Where Have All the Transistors Gone?

R. P. Cowburn

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transport mechanisms. Determining precisely which characteristics of a cage structure drive this choice should prove interesting.

Whatever the answers to these questions, Stagg *et al*. provide us with an intriguing new structure that, like clathrin, helps cells solve the problem of forming capsules of varying size while precisely controlling their formation and contents. Further cryo–electron microscopy maps could tell us the position of other COPII coat components in relation to the cage and, at higher resolutions, define the location of individual Sec13p and Sec31p subunits, and the nature of the interactions that define lattice assembly.

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APPLIED PHYSICS

Where Have All the Transistors Gone?

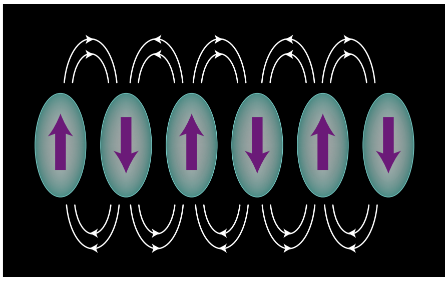
A universal logic gate has been constructed with magnetic nanostructures. Such devices could lead to a new generation of microelectronics.

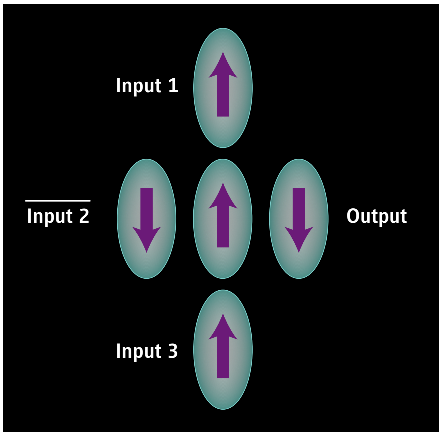
R. P. Cowburn

Today's digital microelectronic circuits are constructed from transistors that switch currents on and off to process the code and data associated with modern information technology. Transistors may not always take center stage, however, as Imre *et al*. (*1*) report on page 205 of this issue. As integrated circuits become ever more dense, the problems in building good transistors multiply. Most researchers attack this problem by advanced optimization of the materials and design of transistors, but Imre *et al.* are part of a group of researchers with a more radical solution: Get rid of the transistors. Imre *et al.* have experimentally demonstrated a universal logic gate, from which all of the logic functions needed in digital microelectronics can be constructed, that is based on magnetic nanostructures and uses no transistors.

Electrons possess the properties of both charge and spin. Charge is responsible for electricity and is the quantity sensed by the transistors in an integrated circuit. Spin, on the other hand, is responsible for magnetism and is not used in most integrated circuits. The blossoming field of spintronics seeks to make use of the spin of the electron in digital microelectronics (*2*). Such a dramatic change at the microscopic level may necessitate an equally dramatic change in the top-level architecture of devices. This will be particularly the case for devices based upon the quantum mechanical interaction of single spins, but may well also be true even for spintronic devices built on classical ferromagnets, such as that proposed by Imre *et al.*

The architecture chosen by Imre *et al.* is based on the concept of cellular automata. Cellular automata are networks of cells with rules that describe how neighboring cells interact; they can, when correctly arranged, perform computations, as previously demonstrated by Amlani *et al*. using single-electron devices (*3*). Although these devices were operational only at cryogenic temperatures, the results opened the tantalizing possibility of computation without conventional transistors, and hence a new approach to the continuation of scaling of microelectronics far into the future.





Chain of logic. (Left) In a simple array of magnetic nanostructures, stray fields couple the magnetization directions (arrows) in an antiparallel fashion from one nanostructure to the next, allowing information to be passed down a chain. **(Right)** Universal logic gate made from five nanostructures. The magnetization of the central nanostructure aligns itself with the net stray magnetic field from the three inputs. This majority state is then communicated to the output nanostructure.

Five years ago, we showed that magnetic nanostructures could allow a physical implementation of a cellular automata architecture that would work at room temperature (*4*): Quantum mechanical exchange within the nanostructure locks all of the spins together, forming a single giant macrospin of enormous moment and hence much greater thermal stability. As Imre *et al.* now show, not only can information propagate across a cellular automata device formed from magnetic nanostructures, but complete logic functions can also be implemented (see the figure).

The choice of demonstration logic gate is important here. Although any of the conventional Boolean functions such as AND or NOT could have been implemented, Imre *et al.* have chosen to implement the less known three-input inverting MAJORITY function. This function simply takes the majority state of its three inputs and then inverts it. This seemingly esoteric function is extremely useful, because with one of the three inputs tied permanently high (that is, the input always has the logic value 1), the gate simply performs the NOR operation on the remaining two inputs. Conversely, if the fixed input is tied permanently low (logic value 0), then the NAND operation is performed on the remaining inputs. Thus, with a single gate, the key functions of NAND and NOR can both be implemented.

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From combinations of these, any arbitrary logic function can then be constructed.

There are a number of attractive reasons to consider using spintronics in general, and magnetic logic in particular, for digital microelectronics devices. Magnetic systems tend to be nonvolatile—they retain data when power is removed—which is an increasingly important trait in a world of mobile and wearable computing. Devices based on spintronics can be very dense and continue to operate well when scaled to small sizes; in particular, they do not exhibit leakage current when small (although there are some new challenges for very small magnetic particles, known collectively as the superparamagnetic limit).

The work of Imre *et al.* has two particularly noteworthy features. First, they used an adiabatic clocking scheme in which the energy barriers between discrete data states are gradually lowered and then raised again; this allows the system to move gradually from one computational state to another without the wasted energy that is inherent in conventional architectures (*5*). Given that one of the most pressing problems in the future scaling of microelectronics is how to manage the waste heat, it is of interest that "hot clocking" (as it is sometimes known) is intrinsic to the architecture. Second, the convenience of having a single universal gate goes deeper than simply saving the effort of designing others. It also opens the possibility of reconfigurable logic, in which the actual function of the gate can be changed after the hardware has been built. At the very least, this allows a single chip to be used for many different applications, reducing both costs and time to market. In principle, the hardware could be reconfigured within a few nanoseconds, allowing the microprocessor to adapt its very architecture to the best form for the computation in hand at that instant (*6*).

Challenges still remain before magnetic logic can be widely used. Imre *et al.* have not yet addressed any issues of speed, although their work is closely related to the emerging memory technology known as MRAM (magnetic random-access memory), where subnanosecond switching speeds are commonplace (*7*). Perhaps the greatest challenge facing magnetic logic is the identification of specific applications where its strengths will be most keenly felt. There would be little advantage in constructing an entire microprocessor from magnetic logic elements; there may be great benefit to implementing a specific functional block within a hybrid system on a chip. Many people believe that the future of microelectronics lies in a diverse hybrid of technologies on a single platform, each doing what it does best. Imre *et al.* have brought us one step closer to having a valuable new technology to add to the menu.

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PHYSIOLOGY

Running a Clock Requires Quality Time Together

The strictly timed disassembly of a protein complex before entry of its constituents into the nucleus influences the 24-hour period of the circadian clock.

Jay C. Dunlap

A defining characteristic of circadian clocks, the biological timekeepers that control metabolic and behavioral activities through the cycle of day and night, is their ~24-hour period length, and all models for circadian clocks must explain how to construct a feedback loop that takes about a day to close. The cellular transcription regulators PERIOD (PER) and TIMELESS (TIM) are essential components of the fruit fly (*Drosophila melanogaster*) clock mechanism, and the model for the *Drosophila* clock has assumed that a major aspect of the ~24-hour time constant is the long time it takes for PER and TIM to associate in the cell cytoplasm before they enter the nucleus. On page 226 in this issue, Meyer *et al.* (*1*) report that this long-assumed lag in PER-TIM association does not exist. Rather, PER and TIM bind to each other right away, so a lag in their association cannot contribute to the 24-hour time constant (see the figure). Instead, it now appears that the entry of TIM and PER into the nucleus is delayed through the action of an interval timer whose existence comes as a complete surprise, and whose pace, moreover, is influenced by PER.

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Half a century ago when scientists asserted that the molecular basis of circadian rhythms would be found in biochemical feedback loops that closed within the confines of a cell, one point of disbelief was the long time constant. Everyone accepted that feedback regulation could feature in networks, but everyone knew that these closed right away. How could a biochemical feedback loop be the basis of a biological clock characterized by a ~24-hour period length? Many early models for circadian clocks simply ignored the conundrum of the long time constant and settled for a plausible description of a feedback loop. But those models that took it seriously tried every imaginable solution (*2*), including counting functions (where a simple step happens over and over again), tape loop models (where a series of events plays out, the last of which reinitiates the series), models that relied on slow diffusion of clock proteins to take up time, and even (early on) models derived from the cellular sensing of subtle geophysical variables (the mysterious Factor X) (*2*). It led some to believe that even though clocks in unicellular organisms might be confined to cells, fundamentally different mechanisms might be at work in multicellular organisms (*3*).

Inevitably, as the problem of biological timing gradually gave way to the continued onslaught of genetics and biochemistry, it became apparent that daily expression of clock proteins, often apparently driven by negative-feedback loops involving activation and repression of gene expression, was a central feature of the circadian rhythm mechanism in eukaryotes (*2*). Stability of period length is conferred by the way these loops, of which there are usually two or more, are assembled and interlocked. In the fungus *Neurospora crassa*, for instance, a heterodimeric complex of the transcription factors WHITE COLLAR-1 and -2 (WC-1 and -2; collectively the WCC) activates expression of the transcription factor FREQUENCY (FRQ). FRQ then dimerizes and associates with a FRQ-interacting RNA helicase, the complex acting to reduce activity of the WCC (one loop). At the same time, the complex promotes the synthesis of more WC-1 (a second loop) (*4*, *5*). In *Drosophila*, a heterodimeric complex of the transcription factors CLOCK (CLK) and CYCLE (CYC) acti-

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