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Magnetic memory and logic could achieve ultimate energy efficiency

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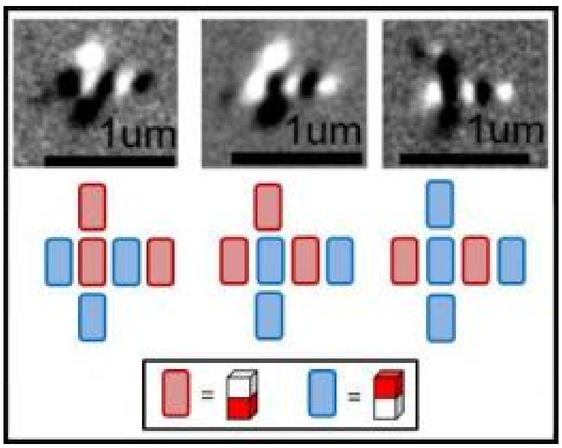


In magnetic contrast images (top) taken by the Advanced Light Source at Lawrence Berkeley National Laboratory, the bright spots are nanomagnets with their north ends pointing down (represented by red bar below) and the dark spots are north-up nanomagnets (blue). The six nanomagnets form a majority logic gate transistor, where the output on the right of the center bar is determined by the majority of three inputs on the top, left and bottom. Horizontal neighboring magnets tend to point in alternate directions, while vertical neighbors prefer to point in the same direction. Credit: Jeffrey Bokor lab, UC Berkeley

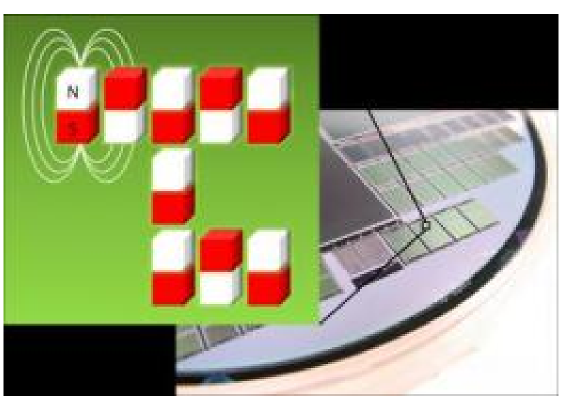
Future computers may rely on magnetic microprocessors that consume the least amount of energy allowed by the laws of physics, according to an analysis by University of California, Berkeley, electrical engineers.

Today's silicon-based microprocessor chips rely on electric currents, or moving electrons, that generate a lot of waste heat. But microprocessors employing nanometer-sized bar magnets – like tiny refrigerator magnets – for memory, logic and switching operations theoretically would require no moving electrons.

Such chips would dissipate only 18 millielectron volts of energy per operation at room temperature, the minimum allowed by the second law of thermodynamics and called the Landauer limit. That's 1 million times less energy per operation than consumed by today's computers.

"Today, computers run on electricity; by moving electrons around a circuit, you can process information," said Brian Lambson, a UC Berkeley graduate student in the Department of Electrical Engineering and Computer Sciences. "A magnetic computer, on the other hand, doesn't involve any moving electrons. You store and process information using magnets, and if you make these magnets really small, you can basically pack them very close together so that they interact with one another. This is how we are able to do computations, have memory and conduct all the functions of a computer."

Lambson is working with Jeffrey Bokor, UC Berkeley professor of electrical engineering and computer sciences, to develop magnetic computers.



Nanomagnetic computers use tiny bar magnets to store and process information. The interactions between the polarized, north-south magnetic fields of closely spaced magnets allow logic operations like those in conventional transistors. Credit: Jeffrey Bokor lab, UC Berkeley

"In principle, one could, I think, build real circuits that would operate right at the Landauer limit," said Bokor, who is a codirector of the Center for Energy Efficient Electronics Science (E3S), a Science and Technology Center founded last year with a $25 million grant from the National Science Foundation. "Even if we could get within one order of magnitude, a factor of 10, of the Landauer limit, it would represent a huge reduction in energy consumption for electronics. It would be absolutely revolutionary."

One of the center's goals is to build computers that operate at the Landauer limit.

Lambson, Bokor and UC Berkeley graduate student David Carlton published a paper about their analysis online today (Friday, July 1) in the journal *Physical Review Letters*.

Fifty years ago, Rolf Landauer used newly developed information theory to calculate the minimum energy a logical operation, such as an AND or OR operation, would dissipate given the limitation imposed by the second law of thermodynamics. (In a standard logic gate with two inputs and one output, an AND operation produces an output when it has two positive inputs, while an OR operation produces an output when one or both inputs are positive.) That law states that an irreversible process – a logical operation or the erasure of a bit of information – dissipates energy that cannot be recovered. In other words, the entropy of any closed system cannot decrease.

In today's transistors and microprocessors, this limit is far below other energy losses that generate heat, primarily through the electrical resistance of moving electrons. However, researchers such as Bokor are trying to develop computers that don't rely on moving electrons, and thus could approach the Landauer limit. Lambson decided to theoretically and experimentally test the limiting energy efficiency of a simple magnetic logic circuit and magnetic memory.

The nanomagnets that Bokor, Lambson and his lab use to build magnetic memory and logic devices are about 100 nanometers wide and about 200 nanometers long. Because they have the same north-south polarity as a bar magnet, the up-or-down orientation of the pole can be used to represent the 0 and 1 of binary computer memory. In addition, when multiple nanomagnets are brought together, their north and south poles interact via dipole-dipole forces to exhibit transistor behavior, allowing simple logic operations.

"The magnets themselves are the built-in memory," Lambson said. "The real challenge is getting the wires and transistors working."

Lambson showed through calculations and computer simulations that a simple memory operation – erasing a magnetic bit, an operation often called "restore to one" – can be conducted with an energy dissipation very close, if not identical to, the Landauer limit.

He subsequently analyzed a simple magnetic logical operation. The first successful demonstration of a logical operation using magnetic nanoparticles was achieved by researchers at the University of Notre Dame in 2006. In that case, they built a three-input majority logic gate using 16 coupled nanomagnets. Lambson calculated that a computation with such a circuit would also dissipate energy at the Landauer limit.

Because the Landauer limit is proportional to temperature, circuits cooled to low temperatures would be even more efficient.

At the moment, electrical currents are used to generate a magnetic field to erase or flip the polarity of nanomagnets, which dissipates a lot of energy. Ideally, new materials will make electrical currents unnecessary, except perhaps for relaying information from one chip to another.

"Then you can start thinking about operating these circuits at the upper efficiency limits," Lambson said.

"We are working now with collaborators to figure out a way to put that energy in without using a magnetic field, which is very hard to do efficiently," Bokor said. "A multiferroic material, for example, may be able to control magnetism directly with a voltage rather than an external magnetic field."

Other obstacles remain as well. For example, as researchers push the power consumption down, devices become more susceptible to random fluctuations from thermal effects, stray electromagnetic fields and other kinds of noise.

"The magnetic technology we are working on looks very interesting for ultra low power uses," Bokor said. "We are trying to figure out how to make it more competitive in speed, performance and reliability. We need to guarantee that it gets the right answer every single time with a very, very, very high degree of reliability."

More information: “Exploring the Thermodynamic Limits of Computation in Integrated Systems: Magnetic Memory, Nanomagnetic Logic and the Landauer Limit”, *Physical Review Letters*. prl.aps.org/pdf/PRL/v107/i1/e010604

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