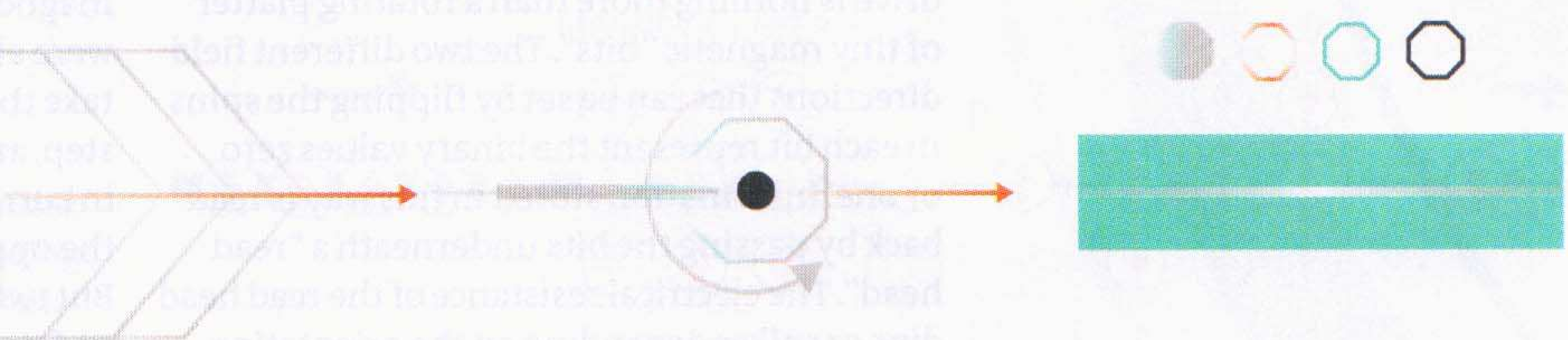
Spin revolution

A much misunderstood quantum property is set to turn computing on its head, says Jon Cartwright



ONE foggy day in early December 1943, a giant awoke. Born in an engineering lab in north-west London, Colossus was the world's first digital, programmable electronic computer – a tower of racks and wires that ate its way through miles of punched-card instructions every hour. Its processing power would enable the Allies to quickly decipher messages from Nazi high command – and help them win the second world war.

Computers have come a long way in the 70 years since, but deep down they work in essentially the same way: by manipulating electrical charge. Guided by its punched cards, Colossus moved charge through thousands of glowing valves. In modern computers, charge passes through millions upon millions of transistors to make the texts, images and sounds that form our digital worlds. It has proved an eminently upscalable approach: the average smartphone today is a million times faster than Colossus, not to mention a hundred thousand times smaller.

But charge is beginning to feel the squeeze. As components have shrunk, they have been handling fewer and fewer moving charges. There is only so far this can go before random charge fluctuations make the operation of the transistors unreliable. "We're simply running out of electrons," says Dan Hutcheson of VLSI Research, a company that analyses technology markets. Add to that the effect of the large amounts of heat generated by very many transistors in a small space, and it is clear we are reaching some fundamental barriers.

But a potential solution is at hand: spin. This peculiar quantum property is already central to the way computer hard drives work. Now it is poised to march into other parts of our digital gadgetry, bringing smaller, faster and more flexible calculating machines – and perhaps even one that can mimic that most powerful of all number crunchers, the human brain. Spin could be the biggest revolution in computing since Colossus.

Spin is a slippery concept to grasp. A quantum property of many sorts of particles, including electrons, it was first proposed in the early 1920s by Wolfgang Pauli, an Austrian theorist so strong-willed it was said he could make experiments fail simply by entering their vicinity. With spin, he didn't have to. Its signature is seen when you send a stream of electrons through an uneven magnetic field. The particles are deflected in opposite directions seemingly at random, as though each one has an intrinstic rotation ›

LEANDRO CASTELAO

"If an electron really were a spinning ball, its surface would be moving at several times the speed of light"

that is somehow "caught" by the magnetic field, causing it to veer off course.

This picture of electrons rotating on their own axes like a spinning ball is useful, but also misleading. A ball can spin by any amount in any direction, whereas an electron is restricted to just the two ways revealed in the magnetic field, dubbed "up" and "down". What's more, if an electron really were a spinning ball of charge, its surface would have to be moving several times faster than the speed of light, defying Einstein's theory of relativity.

What we do know about spin is that it is intimately connected with magnetism. Inside a permanent magnet such as a lump of iron, many of the electrons have the same spin and are locked in place, creating a magnetic field. Apply a large enough opposing magnetic field, and these spins can be made to flip direction, swapping the magnet's north and south poles.

This is a property that has long been harnessed in our computers. A computer hard drive is nothing more than a rotating platter of tiny magnetic "bits". The two different field directions that can be set by flipping the spins in each bit represent the binary values zero or one. Information stored in this way is read back by passing the bits underneath a "read head". The electrical resistance of the read head dips or spikes depending on the orientation of the field, creating pulses of current that are sent on to the computer's processor.

In the early days of digital computers, the route to bigger memory banks was simple: cram more bits into a smaller space. A decade or so ago, that was already running into difficulties. The magnetic fields of the miniaturised bits were getting so small that the change in resistance they caused in the read head was becoming almost undetectabl

In 1988, Albert Fert at the University of Paris South in France and Peter Grünberg at the Jülich Research Centre in Germany independently came up with an inkling of a solution. Electrical currents generally consis of electrons with a random mixture of up and down spins. But send a current into a magnet, and the magnet acts like a strict choreographer: its vast array of fixed spins forces incoming electrons to adhere to the same routine and all spin the same way too.

Fert and Grünberg envisaged sending a current through a stack of two or more magnetic layers. If the spins in these layers were all oriented the same way, it wouldn't take the electrons long to get their spins in step, and there would be only a slight drop in current as electrons carrying spins of the opposite orientation were slowed. But twist one of the magnetic layers around and the moving electrons, having all been compelled to spin in one direction, would

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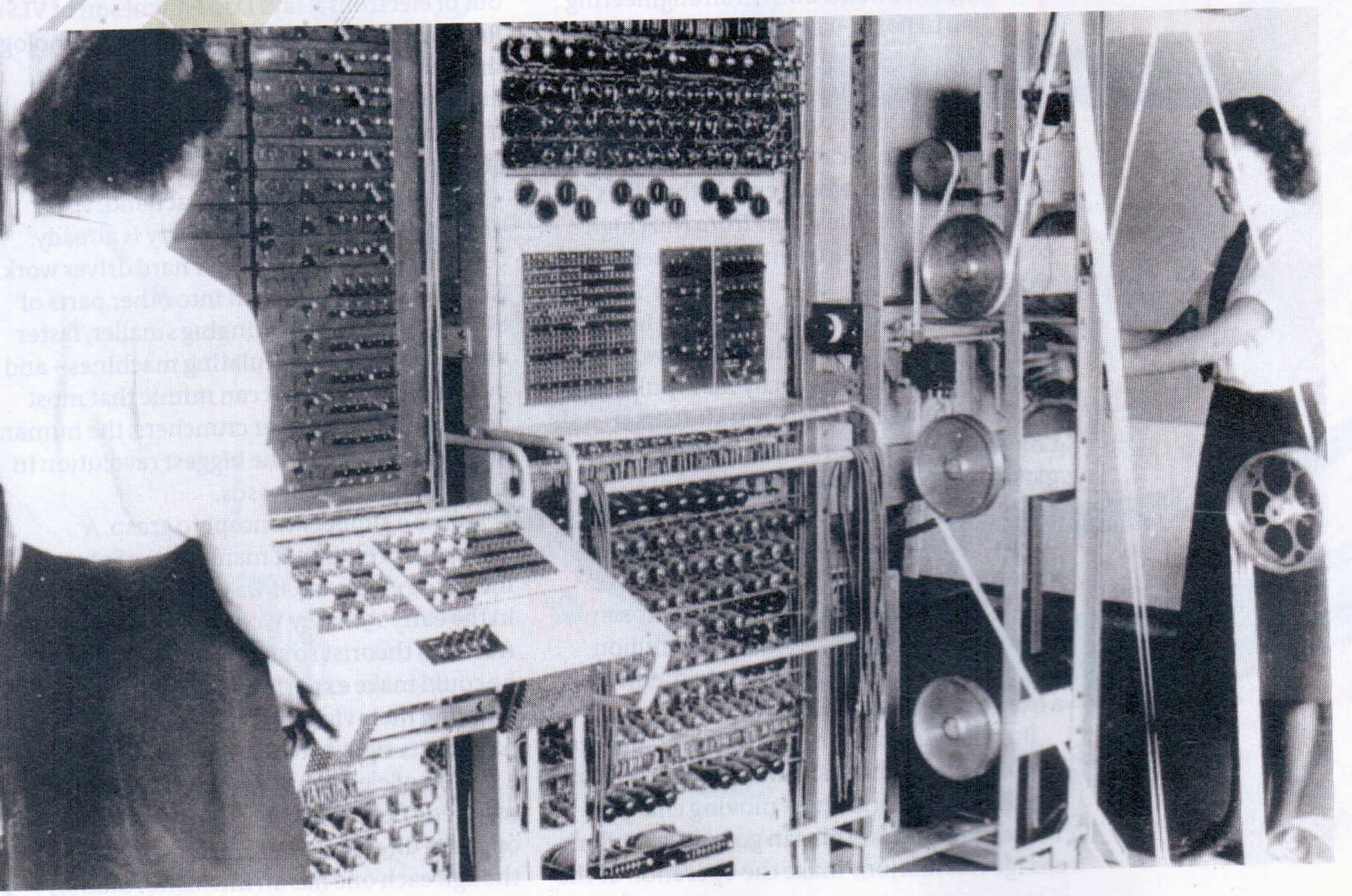


Colossus opened a
era of charge-base
computing

stumble almost to a halt when forced to spin in the other. The stack's overall resistance would skyrocket (see "All in a spin", right).

Within years, spin "valves" had been developed that used this effect, known as giant magnetoresistance, to switch from a low to a high resistance state using just the tiny fields generated by magnetic bits. Read heads formed of spin valves allowed hard-drive capacities to balloon from megabytes to gigabytes. In 2007, Fert and Grünberg won the Nobel prize in physics for their discovery.

For all that, this first spin computing revolution was limited. Magnetic bits are good for hard-drive storage because once written, they stay written even when the power is off; only when a further magnetic field is applied can they be rewritten. But searching through the magnetic bits on a hard drive for the bits you want to write or retrieve is a slow process. This is why there is a marked delay as your computer retrieves information when you start a program or access a file.

Instant on

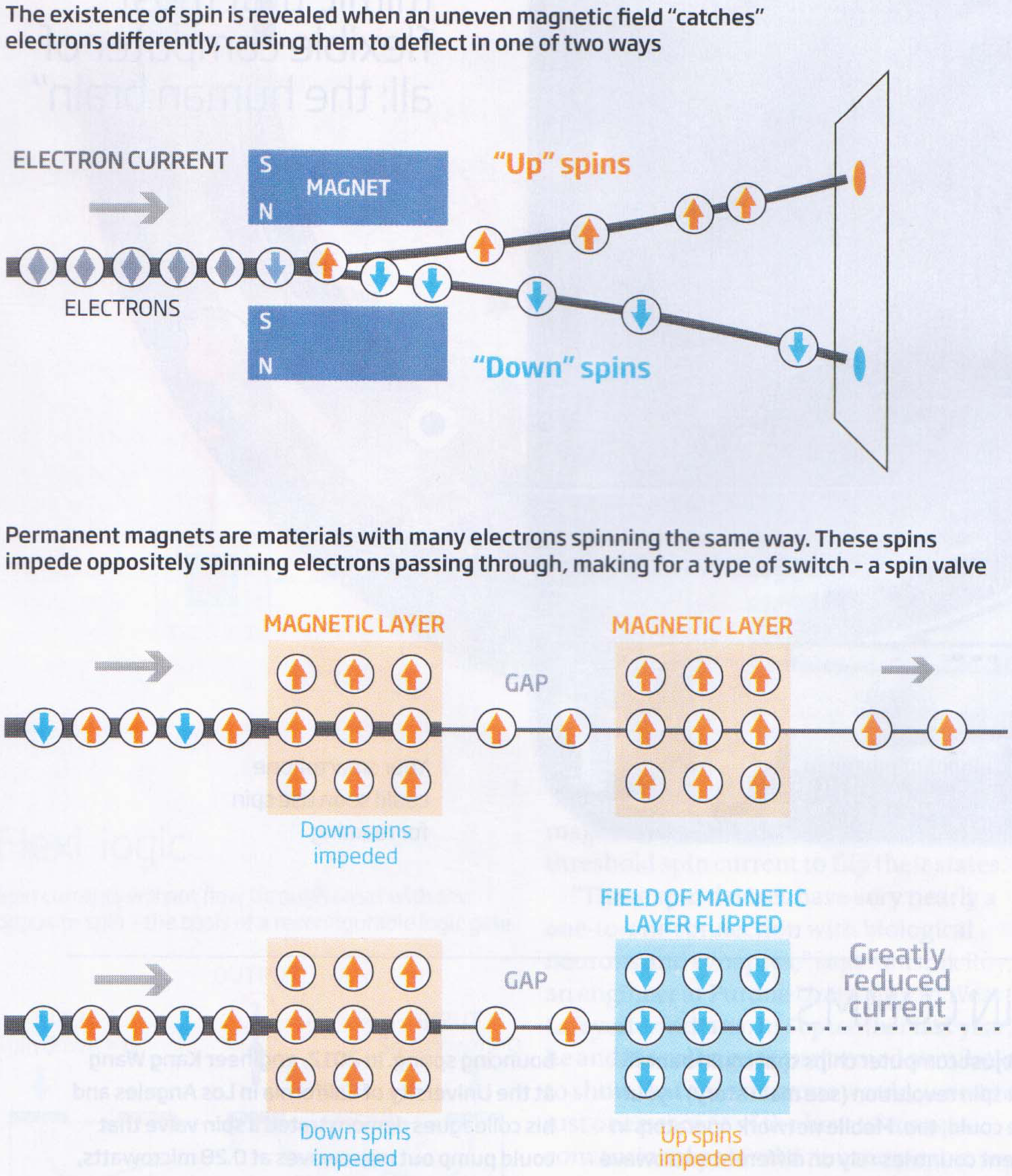
It is also why there has been a lot of time and money invested in finding alternative storage technologies, such as the electrically driven "flash" memories used in smartphones, tablets and, increasingly, in laptops. But no alternative has yet been found that is fast enough to cut the mustard for your computer's other type of memory. Random access memory, or RAM, is where information hauled from a hard drive is stored temporarily while it is used. This is done by charging and discharging capacitors with pulses of current – a process up to 200 times faster than accessing data on a hard drive. But as anyone who has lost work during a blackout will testify, all that information evaporates when the power is switched off.

The dream is to combine the permanence of hard drives or flash memory with the easy access of RAM, allowing for truly instant, loss-free computing. "The calculation would still be there, wherever you left it," says physicist Del Atkinson at Durham University in the UK.

Spin could do it. Magnetoresistive RAM (MRAM) is an idea that dates back to the mid-1990s. It involves the use of tiny spin valves, not as a hard disc's read head, but to form magnetic bits themselves. In MRAM's first incarnations, ones or zeros were written using external magnetic fields to flip the spin orientation in a valve's bottom-most magnetic layer. This information was then read out simply by detecting the electric resistance of the whole valve.

All in a spin

Electrons "spin" in one of two ways: up or down

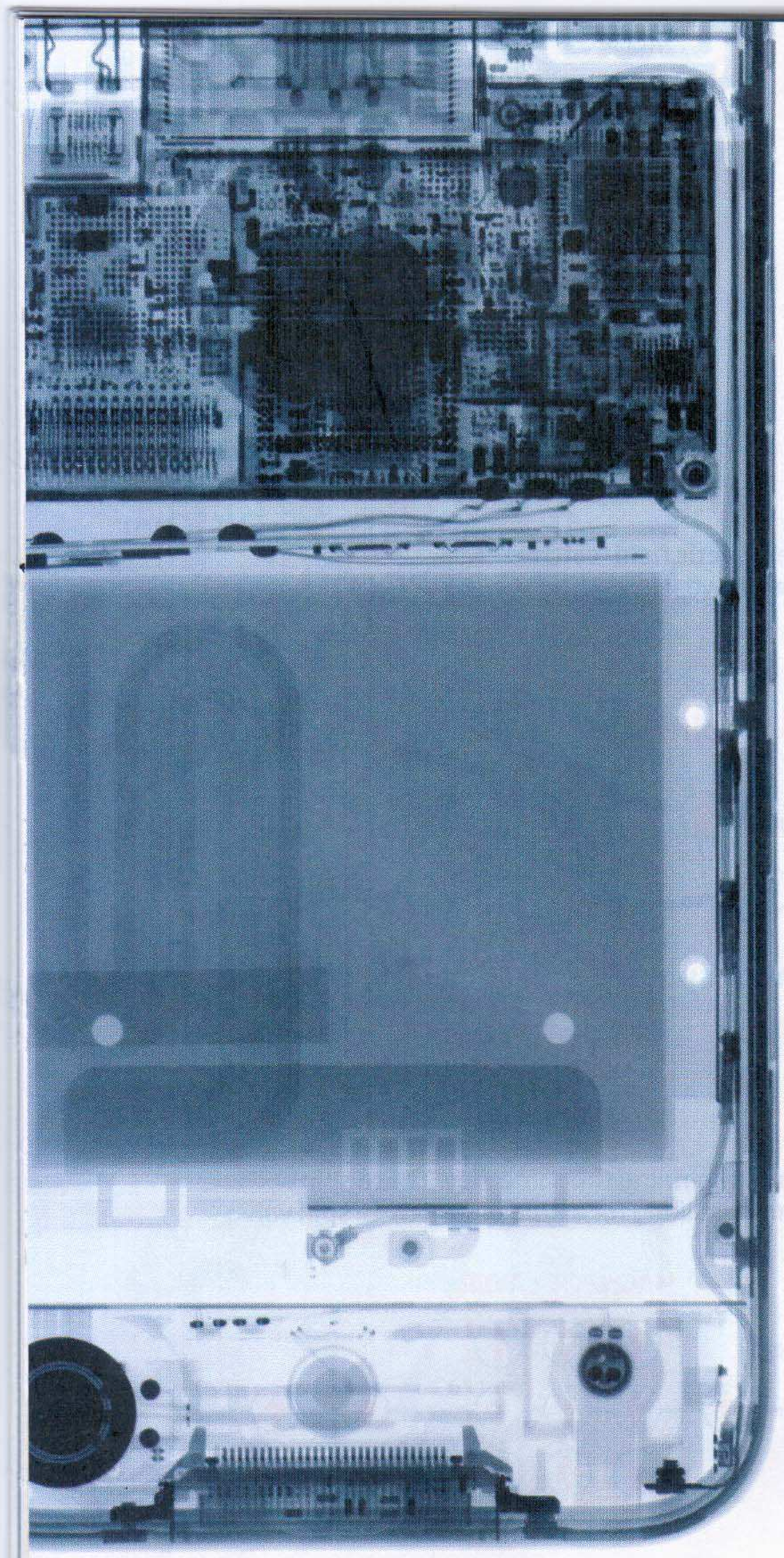


This approach introduced an awkward size limit: the bits had to be big enough that the fields used to write them did not overlap. The first element of the solution came in 1996 with the idea that you could do the writing with electrical currents. You first pass a current through a thick magnet so that all the moving electrons end up with the same spin. If this spin-polarised current is strong enough, it can overpower the fixed spins in the thin first layer of a spin valve, forcing them to reorient.

There was still a problem in making spin-polarised currents that were strong enough to be effective but which didn't melt the materials they passed through. Now, finally, this is possible. Everspin, a company based in Chandler, Arizona, has just started manufacturing spin-torque MRAM with a capacity of 64 megabytes for developers to toy with, while Crocus in Grenoble, France, and Samsung-owned Grandis in California have versions in the pipeline.

Scaling that up to gigabyte capacity is now just a matter of time. In principle, there is no reason why spin-torque MRAM couldn't fill the roles of traditional RAM and permanent data storage, saving time and energy on electrons whizzing between different parts of your circuit board. "There has been a move away generally from any sort of hard disk drives in personal computing, and I suspect this would be the next stage," says Atkinson.

But why stop there? If spin is so good for memory, perhaps it could also help out the very core of your computer: the processor. Today's processors are made up of a ›



Your smartphone could soon use spin for roaming

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> "Spin technology could even be tailored to mimic that most flexible computer of all: the human brain"

billion or so transistor switches that are flipped on and off by applying an electrical field. These switches are combined into logic gates, each of which performs a single operation. A NAND gate, for example, takes two binary inputs and lets a current pass only if at least one is zero. As you write an email or a text document, or play a video or a piece of music, millions of logical operations are performed by flipping these gates in series according to the instructions contained in the program you are using.

This way of working requires a lot of logic gates to do relatively little. As more and more logic gates have been crammed into processor chips, they have been generating more and more heat, raising a significant barrier to reducing processor size further.

All this makes operating transistors with electron spins, rather than electrical currents, an attractive idea. Unlike currents, spins do not need sustaining: once flipped they stay flipped, meaning less power is used and less heat wasted.

In 2007, Ian Appelbaum, then at the University of Delaware in Newark, and his colleagues demonstrated the principle of spin processing with the first spin transistor, which used a combination of electric and magnetic fields to switch a current according to the value of its spin. But this was little more than a conventional transistor translated into the language of spin. The same year, Hanan Dery of the University of Rochester in New York state and his colleagues suggested a different, potentially much more powerful, scheme (*Nature*, vol 447, p 573). Their spin-logic device uses two spin-polarised input currents and two magnetic contacts whose spin direction can be flipped to produce a gate whose logic operation can be changed on the fly (see "Flexi-logic", opposite).

This is radical stuff. In a normal processor, the type of each logic gate is set during manufacture, and engineers have to build in numerous different gates to accommodate the needs of different programs. Gates that can rewire themselves would radically reduce the amount of hardware needed to produce the same performance and versatility. "It's like a factory doing something on a jacket's lining so the customer can wear it inside out, too," says engineer Behtash Behin-Aein of the computer chipmaker Global Foundries in Milpitas, California, who has worked on a similar proposal for spin logic.

Implementing spin logic is no cakewalk: one problem is keeping output currents strong enough that they don't fade away

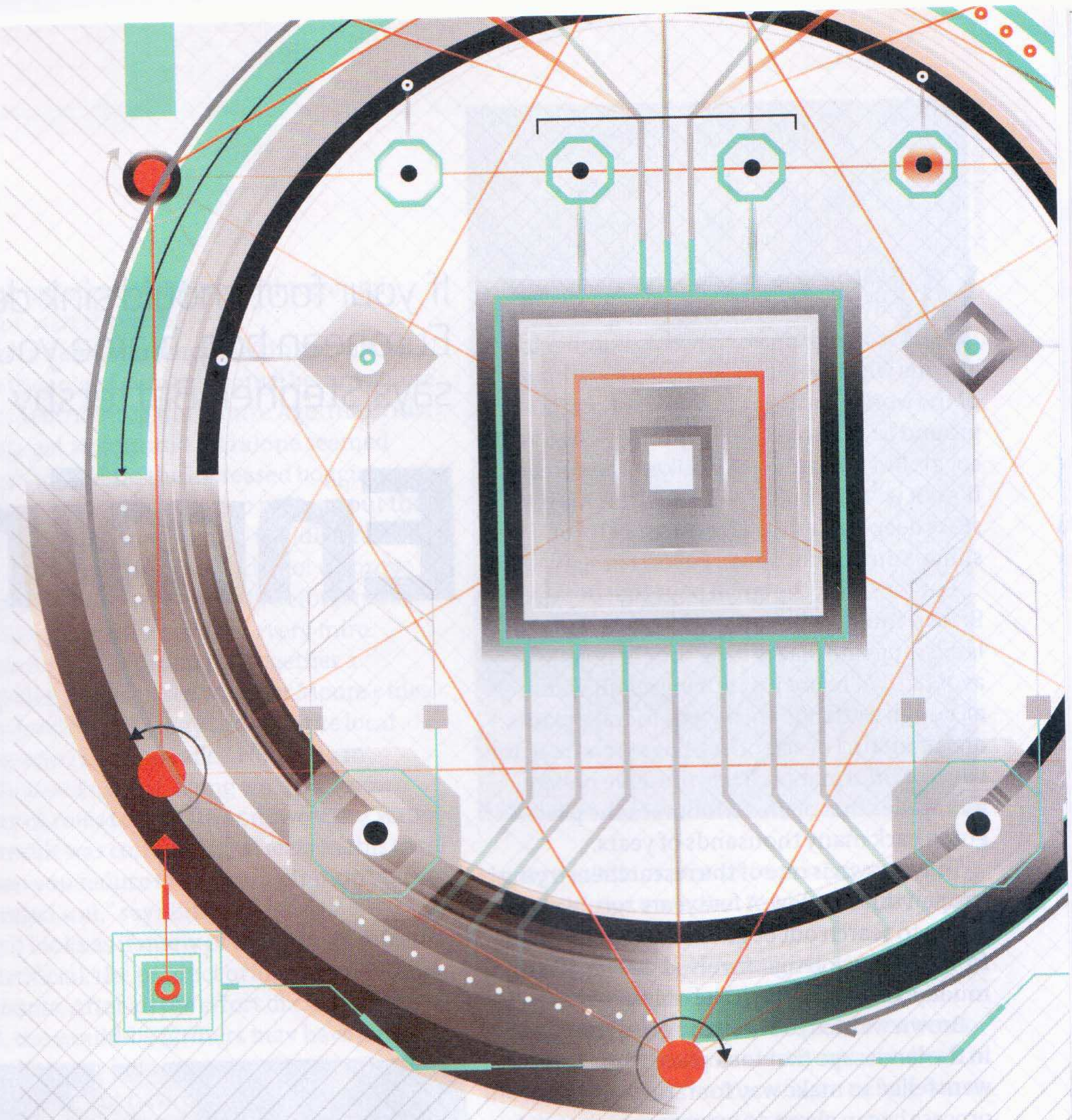
SPIN COMMS

It's not just computer chips that could benefit from a spin revolution (see main story) – your phone could, too. Mobile network operators in different countries rely on different microwave frequencies to carry signals. To go "roaming", your phone needs separate microwave generators – silicon devices that oscillate electronic current to create fields of the right frequencies.

These oscillators could all be replaced by a single spin device thousands of times smaller. A current of electrons all with a particular spin creates magnetic forces that cause the spins in nearby magnetic materials to try to align. Get the strength of current right, and the magnet spins will begin to rotate, but not quite flip. Send in pulses of current, and the spins will begin to oscillate, sending out pulses of energy at microwave frequency.

This frequency is easily tuned by introducing a second electrical current that makes the magnetic material flick back quicker or slower, an effect rather like changing the mass on a bouncing spring. In 2012, engineer Kang Wang at the University of California in Los Angeles and his colleagues demonstrated a spin valve that could pump out microwaves at 0.28 microwatts, close to the power needed for mobile telecoms. A spin-valve oscillator could be inside smartphones within the next five to 10 years (*ACS Nano*, vol 6, p 6115).

Fibre-optic telecoms could also use a spintronic makeover. Currently, the pulses of laser light used to encode signals are generated by shifting electrons back and forth. That is one of the factors that limits the rate at which information can be sent to about 50 gigahertz. In 2011, Nils Gerhardt at the Ruhr University Bochum in Germany and his colleagues showed that this speed limit could be overcome by generating laser light by flipping electron spins (*Applied Physics Letters*, vol 99, p 151107). This process can produce pulses at nearly three times the frequency of a conventional laser – a turbo boost that might dramatically improve your internet bandwidth within the next decade.



before they reach the next gate. Given the amount of investment in existing computing architectures and fabrication processes, spin logic will probably only be able to take off when conventional transistors finally reach their limit, which they are predicted to do in a decade or so.

All in the mind

Once this spin revolution begins, some physicists believe the technology could even be tailored to mimic that most flexible computer of all: the human brain. Logic gates in today's computer chips process information in sequence, each one taking its input from the previous gate's output. The brain, by contrast, does things in parallel. An input – the reading of a word, say – causes a bunch of neurons to fire, sending electrical pulses through junctions called synapses, which cause further neurons to fire. Rather than being "on" or "off", neurons only fire if the signals within them overstep a certain threshold. That allows them collectively to perform subtle and complex tasks such as text recognition.

Last October, the chipmaker Qualcomm, which has its headquarters in San Diego, California, announced that it is using the standard method for manufacturing electrical transistors in an attempt to create brain-like "neuromorphic" chips. Grouped in complex circuits, these transistors can be made to switch only when a certain level of input current is reached.

But this approach is inherently problematic says physicist Julie Grollier of Unité Mixte de Physique CNRS/Thales near Paris. You need dozens of transistors to represent a single neuron, and dozens again to represent a single synapse. Even if you could somehow squeeze all these components together, you still face that most exhausting of computing problems: overheating.

In 2011, Grollier, Fert and others exposed the bare bones of an alternative approach. The spin memristor is a device whose resistance can be set with a spin current to any value you like. It is rather like a more elaborate spin valve that instead of just being off or on can be off, on, or anything in between (*Nature Physics*, vol 7, p 626).

Grollier believes that a single spin memristor could function as a synapse, with its programmable resistance offering a way to set the strengths of connections between neurons. Meanwhile, the neurons themselves would be other types of spin valve with thicker magnetic layers that would need a certain threshold spin current to flip their states.

"These spin devices have very nearly a one-to-one connection with biological neurons and synapses," says Kaushik Roy, an engineer at Purdue University in West Lafayette, Indiana. In September last year, he and his colleagues performed simulations to show that spin neurons would generate just one per cent of the heat of more conventional potential neuromorphic technologies, removing a big barrier to getting a brain-like computer working in practice (arxiv.org/abs/1309.3303).

It is still very early days, and Roy is cautious about how far spin can take us in building a brain. "It's not exactly what the brain does," he says. "First of all, we don't know exactly what the brain does."

What's certain, though, is that from small beginnings, spin is starting to worm its way into all aspects of our electronic devices. The spin revolution is only just dawning – and no one is quite sure where it will end. "It's one of those things that has been waiting at the gates," says Hutcheson. "And all of a sudden we're starting to move really quickly." ■

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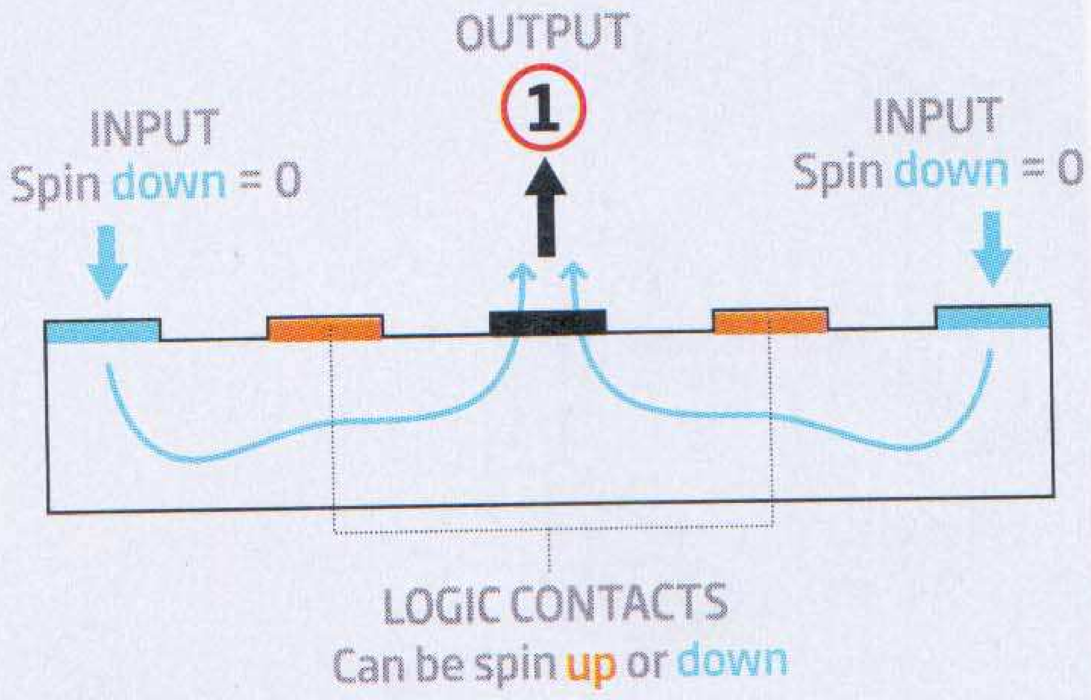
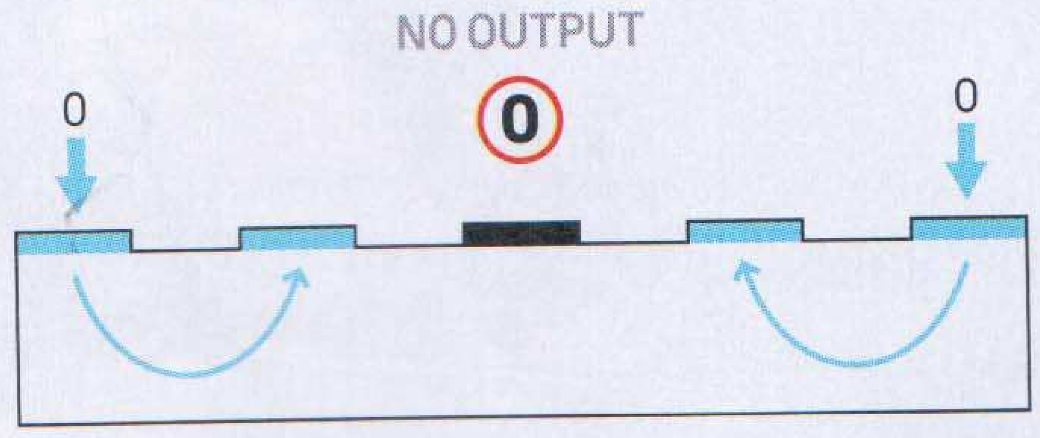
Flexi-logic

Spin currents will not flow through areas with the opposite spin – the basis of a reconfigurable logic gate



When a logic contact has the opposite spin to an input current, the current bypasses it and flows to the output. If both logic contacts are spin up, the gate is a NAND gate, producing an output only if at least one input is zero (spin down)



Flip the contacts to spin down and the gate becomes an OR gate, producing an output only if at least one input is one (spin up)