
Qu

antum clockwork

Goodbye diodes and wires, hello to the quantum ratchet. Could this weird new piece of electronic machinery be the key to computing's future? Michael Brooks investigates

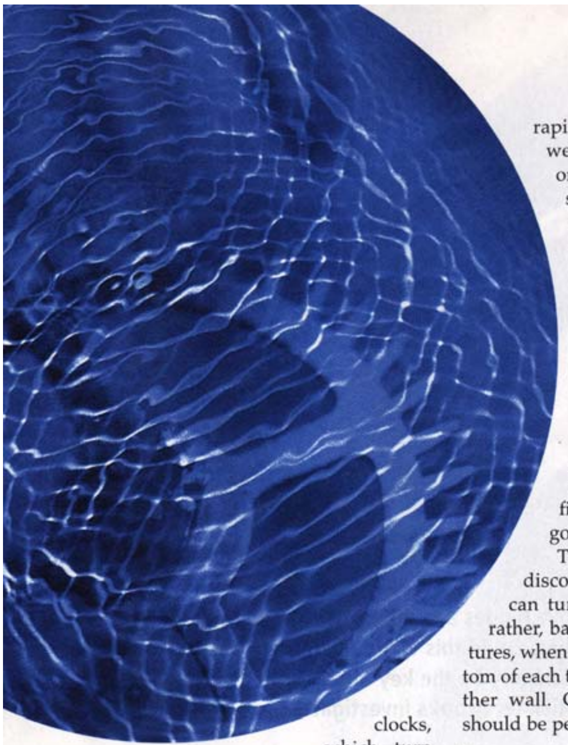
SUPPOSE you lived in a world where you could make a car run uphill by shoving it gently back and forth, or send a pool ball straight into the pocket of your choice just by shaking the table.

Such a world wouldn't seem odd to a small band of researchers in an area that is new even by the standards of frontier physics. The days will soon be over, they believe, when electrons rolled predictably downhill, away from the negative terminal in any circuit. They have discovered how to make electrons move around without any directed voltage.

This is the new science of the quantum ratchet. With an oscillating or randomly varying signal, you can produce useful, directable motion from what seems like chaos. "You can make electrons go round in circles, or up or down, you can make them run uphill. We can do everything with electrons that we do with cars and buses in a city—it's almost like a child's game," enthuses one of the leading players in the field, Peter Hänggi of Augsburg University in Germany.

By making electrons leap from one electrical component to another, we could build electronics without connecting wires. And single electrons shunted around at will could be used to store quantum information, and specially designed compartments could form the logic gates of a generation of quantum computers. As a bonus, quantum ratchets might even help us understand how our muscles turn unfocused chemical energy into directed motion.

Any ratchet produces motion in one direction from a cyclical force. For example, twisting a ratchet screwdriver back and forth drives a screw relentlessly inwards. This relies on a ring of lopsided ratchet teeth: twisting one way drags a sprung peg over the shallow side of each tooth, but twisting in the other direction brings the peg up against the steep side of a tooth, pushing the whole ratchet around. Ratchets appear in bicycle transmissions, turnstiles and the escapements of pendulum



clocks, which turn the pendulum's swing into the one-way motion of the hands.

If you build ratchets on a much smaller scale, things start to get weird. The simplest sort don't even work. Richard Feynman wondered whether a microscopic ratchet would be moved in one direction by the random thermal movements of air molecules. If so, you'd be able to build a perpetual motion machine. Feynman proved, reassuringly, that such a ratchet would move at random back and forth—no directed motion, so no useful work.

But when you actually put some effort into driving a microscopic ratchet, it should work. In 1997, Hänggi and his Augsburg colleague Peter Reimann calculated what should happen to electrons confined in a series of lopsided wells, like the teeth of a ratchet (*Physical Review Letters*, vol 79, p 10). If you add a voltage across the whole series of wells, it pulls on the electrons, raising the potential of the wells at one end and lowering it at the other. And when the wells are lopsided, their shape changes too (see Diagram). A vertical wall, like the left-hand ones in the diagram, isn't affected by the voltage; a sloping wall is made steeper or shallower.

Applying a positive voltage to the ratchet in the diagram makes the right-hand side of each well shallower. The highest energy electrons can then spill rapidly over into the next well. But a negative voltage only makes the right wall steeper, and then electrons are trapped. So if you apply an alternating voltage, the electrons shuffle step by step to the right.

So far, this is just like a classical ratchet, where a peg slips over the shallower slope. But transferred to the electronic world, it could be useful. Electrons powered by AC signals could run against a static electric field. "You can make electrons go 'uphill'," says Hänggi.

Then Hänggi and Reimann discovered that quantum theory can turn things upside down—or rather, back to front. At low temperatures, when the electrons sit near the bottom of each trough, they can't get over either wall. Classical physics says they should be permanently trapped.

Escape route

But according to quantum theory, they can sneak out. Because an electron is a probability wave, without a well-defined position, it can never be entirely contained by the walls of the potential. So electrons have a small probability of finding themselves on the other side of a barrier, leaking through in a process called tunnelling.

Electrons can tunnel in both directions through the ratchet. But tunnelling is much more probable through a thin barrier than a thick one. So at low temperatures, Hänggi and Reimann calculated, the overall current must be dominated by electrons leaking through the thin part of the tooth to the left when the voltage is negative (see Diagram). Again, there is net electron movement, but on the other half of the voltage cycle, and in the other direction.

That's the theory. Last month, Heiner Linke of the University of New South Wales in Sydney, and his colleagues from Lund University in Sweden, confirmed it (*Science*, vol 296, p 2314).

Linke started by making a string of triangular quantum dots, each about a micrometre long. A quantum dot is an area of semiconductor which acts like a well for electrons—its walls hold them inside the dot. Because Linke's dots are triangular, electrons get squeezed together at the narrow end. That confinement increases their energy—in other words, it makes the potential higher at the narrow end. So the electrons feel the string of dots as an asymmetrical sawtooth.

Sure enough, Linke saw a current that reversed when he raised the temperature.

But a real surprise, and a potentially very useful one, appears at much lower temperatures. Towards the end of 1998, Linke, then at Lund, and colleagues from the Niels Bohr Institute in Copenhagen, were tinkering with a triangular quantum dot a micrometre across, which they had cooled to just 0·3 kelvin.

With a gentle alternating signal, the researchers saw a directed current. But when they slightly adjusted the strength of the signal, the current went into reverse. Somehow, the small change made the electrons abandon their previous route and come out on the other side. It is as if you could make your clock run backwards by giving its pendulum a nudge.

A delicate quantum effect called interference is responsible. The electron waves, with a wavelength almost as large as the dot, interfere with one another. They combine to cancel out in some places and add in others, so an interference pattern of peaks and troughs sits inside the quantum dot. A peak means there is a high probability of finding an electron in that particular place; a trough means a low probability. So if a peak coincides with one side of the quantum dot, electrons are more likely to escape from that side, and a current will flow in that direction.

A voltage affects how the waves bounce around inside the dot, says Linke, changing the interference pattern. That can turn the current around by making electrons leak from a different side of the dot.

Interference is so sensitive to other factors that Linke cannot even tell which way the ratchet current will flow until he switches the device on. "It's difficult to construct a dot that will only direct the current in one direction. Any little deviation in the shape of the dot on the scale of the electron wavelength—40 nanometres—would affect the interference."

Linke is delighted at the fine degree of control that interference could afford, in theory. Understand how the dot's shape affects the electron current and you could design dots to perform specific tasks. String such dots together and you could build logic gates. Being controlled by very small voltage changes, these gates would be faster and consume less energy than the gates we use today. And because the full quantum state would be preserved, they would be ideal for quantum computers.

But it's not easy. Preserving quantum

coherence in between the dots would need very low temperatures, where the electrons have well-defined energies and there is little confusion from vibrations in the semiconductor material. If the dots can be made much smaller, they might work without expensive cooling, but this is probably a long way off.

In the meantime, devices might be made from quantum ratchets that don't rely on interference. Hänggi and his colleague Igor Goychuk think that two input signals in a tunnelling ratchet might be better than one (*Europhysics Letters*, vol 43, p 503). Like having two oars on a rowing boat, combining two signals could let scientists steer an electron current. Alter the phase difference between the signals, and, says Hänggi, you can control the direction of the motion in two dimensions. This makes many different outcomes possible, so logic gates built on this principle would have a range of outputs, reducing the total number needed.

'Quantum ratchets are a revolution waiting in the wings'

Axel Lorke and his colleagues at the Ludwig-Maximilians University in Munich are looking at another way to steer electrons. They created an array of triangular "antidots", small areas of a semiconductor surface where electrons cannot enter. Infrared radiation shakes the electrons so they crash against the antidots rather like balls hitting the obstacles on a pinball table (they are too warm to behave like quantum-mechanical waves). They tend to get funnelled into the narrowing gaps between the dots. So the array turns the jiggling of the infrared radiation into a well-directed beam of electrons.

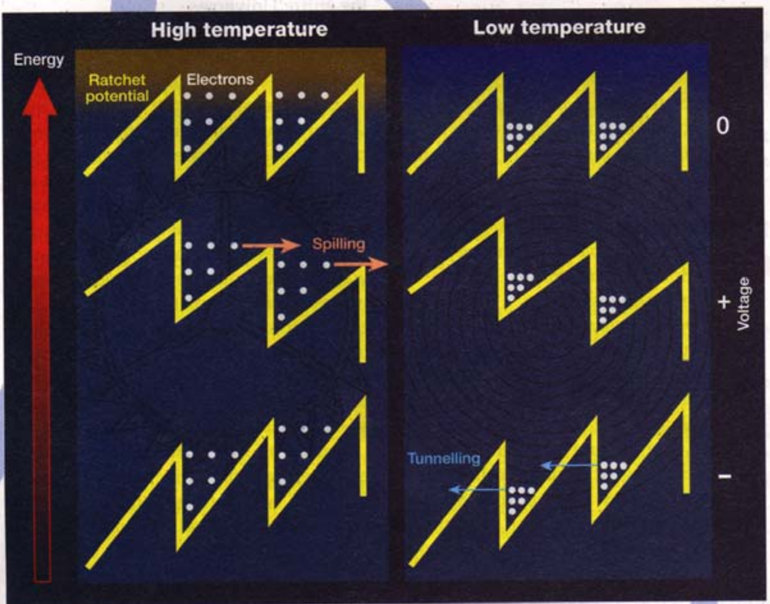
This could lead to wireless electronics. Just arrange your blocks of antidots to point in different directions, and bathe the lot with infrared. Electrons will then whizz around, following the arrows whichever way they point— and you can even send several electron beams across one another. No more need for a nightmare of connecting wires.

What's more, it only takes one step to carve an array of antidots from a piece of semiconductor, compared with the 20 or more needed to make the complicated structures of modern electronics.

Lorke has already made an antidot rectifier that works at up to 77 kelvin. And, because these devices are classical not quantum in nature, they should work at even higher temperatures. "If you think this is something that might find uses in a market then you can start to tweak up the temperature," he says.

Charles Marcus of Stanford University in California believes that quantum ratchets are a revolution waiting in the wings, but he says it's too soon to tell just how big it is going to be. "We're two steps away from making it useful. We don't even know what it is we've got, and the rules of the game are not yet known," Marcus says.

But electronics isn't the only game in town. Linke points out that as electrons carry heat, quantum ratchets could be used as heat pumps, perhaps for cooling single microscopic components on a chip.



Quantum ratchets might even help researchers understand molecular motors. These tiny engines are biology's ratchets (*New Scientist*, 13 December 1997, p 38). They take the directionless energy released in a chemical reaction, and somehow produce motion in one direction. Our muscles are huge arrays of molecular motors working in concert. Although it seems very unlikely that muscles really are quantum ratchets, they may have quantum effects operating within them.

Muscles contract when layers of two different protein fibres, actin and myosin, slip over one another. Each myosin fibre has branching "heads" which attach to sites along the actin fibre and walk along from site to site. To do this, the myosin heads change their shape, driven by electron transfer inside the protein. As all this happens at the atomic scale, quantum effects are probably involved, says Linke.

Whatever the truth about real biomotors, Hänggi is sure that those looking to build machines on the nanoscale had better take note of quantum ratchets. "Any machine on a microscopic level cannot neglect quantum laws," he says.

Hänggi points out that we are now building ratchets of every size from just a few micrometres to the human scale. Ratchets that work in the quantum world could soon be used in electronics. Biologists are developing narrow sawtooth channels to separate DNA fragments of different weight. Hänggi is building a ratchet that can separate different-sized microscopic particles in suspension (ideal, he says, for segregating healthy cells from sick ones). And then, in the macroscopic world, there's your ratchet screwdriver.

Strangely enough, turning the screw relies on muscles whose mechanism might be explained by the quantum ratchets. It's a complete circle, you might say. But it only turns one way. □

Michael Brooks is a science writer based in Sussex