Memristor minds

What connects our own human intelligence to the unsung cunning of slime moulds? An electronic component that no one thought existed, as **Justin Mullins** explains

EVER had the feeling something is missing? If so, you're in good company. Dmitri Mendeleev did in 1869 when he noticed four gaps in his periodic table. They turned out to be the undiscovered elements scandium, gallium, technetium and germanium. Paul Dirac did in 1929 when he looked deep into the quantum-mechanical equation he had formulated to describe the electron. Besides the electron, he saw something else that looked rather like it, but different. It was only in 1932, when the electron's antimatter sibling, the positron, was sighted in cosmic rays that such a thing was found to exist.

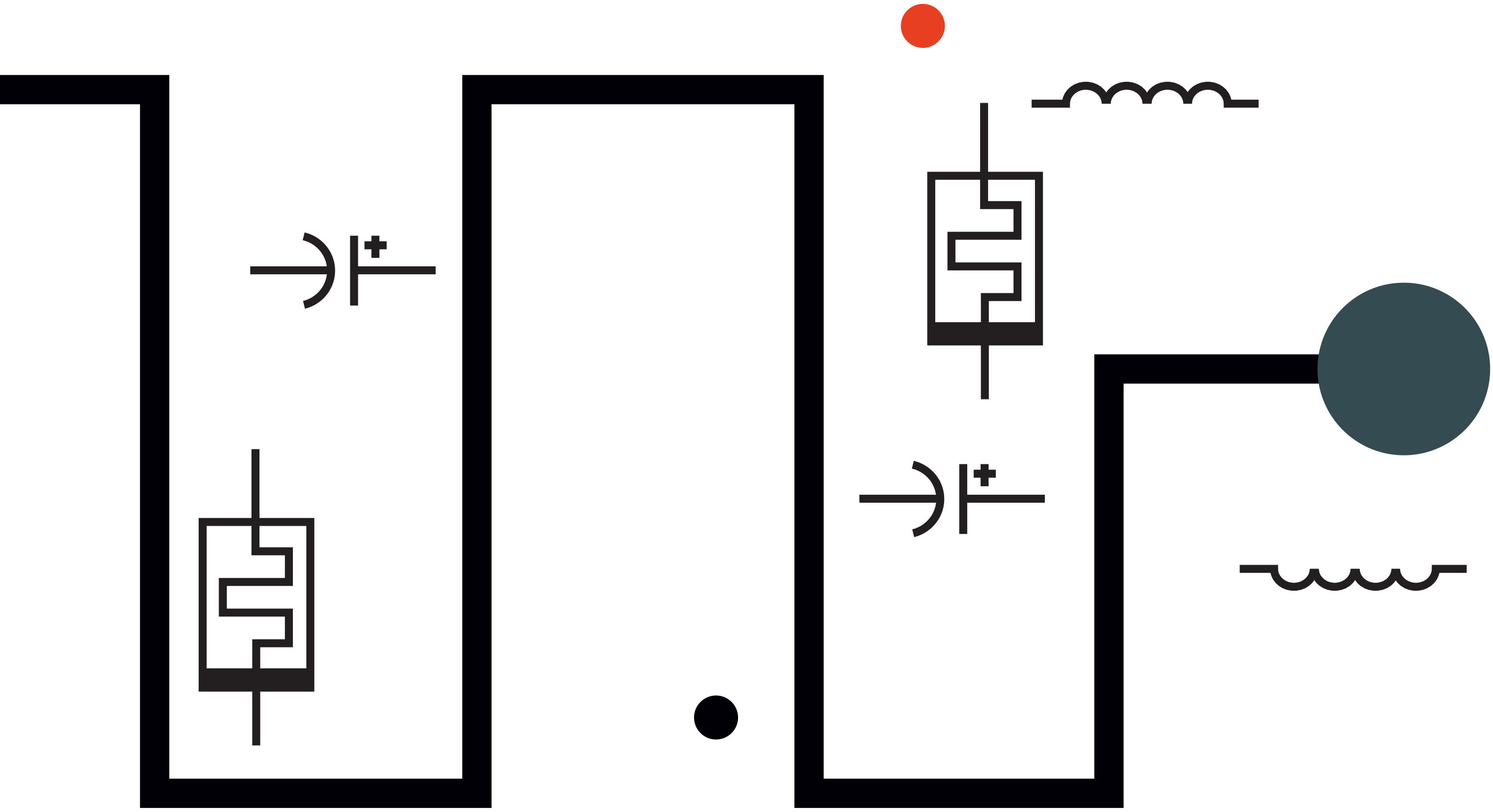
In 1971, Leon Chua had that feeling. A young electronics engineer with a penchant for mathematics at the University of California, Berkeley, he was fascinated by the fact that electronics had no rigorous mathematical foundation. So like any diligent scientist, he set about trying to derive one.

And he found something missing: a fourth basic circuit element besides the standard trio of resistor, capacitor and inductor. Chua dubbed it the "memristor". The only problem was that as far as Chua or anyone else could see, memristors did not actually exist.

Except that they do. Within the past couple of years, memristors have morphed from obscure jargon into one of the hottest properties in physics. They've not only been made, but their unique capabilities might revolutionise consumer electronics. More than that, though, along with completing the jigsaw of electronics, they might solve the puzzle of how nature makes that most delicate and powerful of computers – the brain.

That would be a fitting pay-off for a story which, in its beginnings, is a triumph of pure logic. Back in 1971, Chua was examining the four basic quantities that define an electronic circuit. First, there is electric charge. Then there is the change in that charge over time, better known as current. Currents create magnetic fields, leading to a third variable, magnetic flux, which characterises the field's strength. Finally, magnetic flux varies with time, leading to the quantity we call voltage.

Four interconnected things, mathematics says, can be related in six ways. Charge and current, and magnetic flux and voltage, are connected through their definitions. That's two. Three more associations correspond to the three traditional circuit elements. A resistor is any device that, when you pass current through it, creates a voltage. For a given voltage a capacitor will store a certain



amount of charge. Pass a current through an inductor, and you create a magnetic flux. That makes five. Something missing?

Indeed. Where was the device that connected charge and magnetic flux? The short answer was there wasn't one. But there should have been.

Chua set about exploring what this device would do. It was something that no combination of resistors, capacitors and inductors would do. Because moving charges make currents, and changing magnetic fluxes breed voltages, the new device would generate a voltage from a current rather like a resistor, but in a complex, dynamic way. In fact, Chua calculated, it would behave like a resistor that could "remember" what current had flowed through it before (see diagram, page 44). Thus the memristor was born.

And promptly abandoned. Though it was welcome in theory, no physical device or material seemed capable of the resistance-with-memory effect. The fundamentals of electronics have kept Chua busy ever since, but even he had low expectations for his baby. "I never thought I'd see one of these devices in my lifetime," he says.

He had reckoned without Stan Williams, senior fellow at the Hewlett-Packard Laboratories in Palo Alto, California. In the early 2000s, Williams and his team were wondering whether you could create a fast, low-power switch by placing two tiny resistors made of titanium dioxide over one another, using the current in one to somehow toggle the resistance in the other on and off.

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Nanoscale novelty

They found that they could, but the resistance in different switches behaved in a way that was impossible to predict using any conventional model. Williams was stumped. It took three years and a chance tip-off from a colleague about Chua's work before the revelation came. "I realised suddenly that the equations I was writing down to describe our device were very similar to Chua's," says Williams. "Then everything fell into place."

What was happening was this: in its pure state of repeating units of one titanium and two oxygen atoms, titanium dioxide is a semiconductor. Heat the material, though, and some of the oxygen is driven out of the structure, leaving electrically charged bubbles that make the material behave like a metal.

In Williams's switches, the upper resistor was made of pure semiconductor, and the ›