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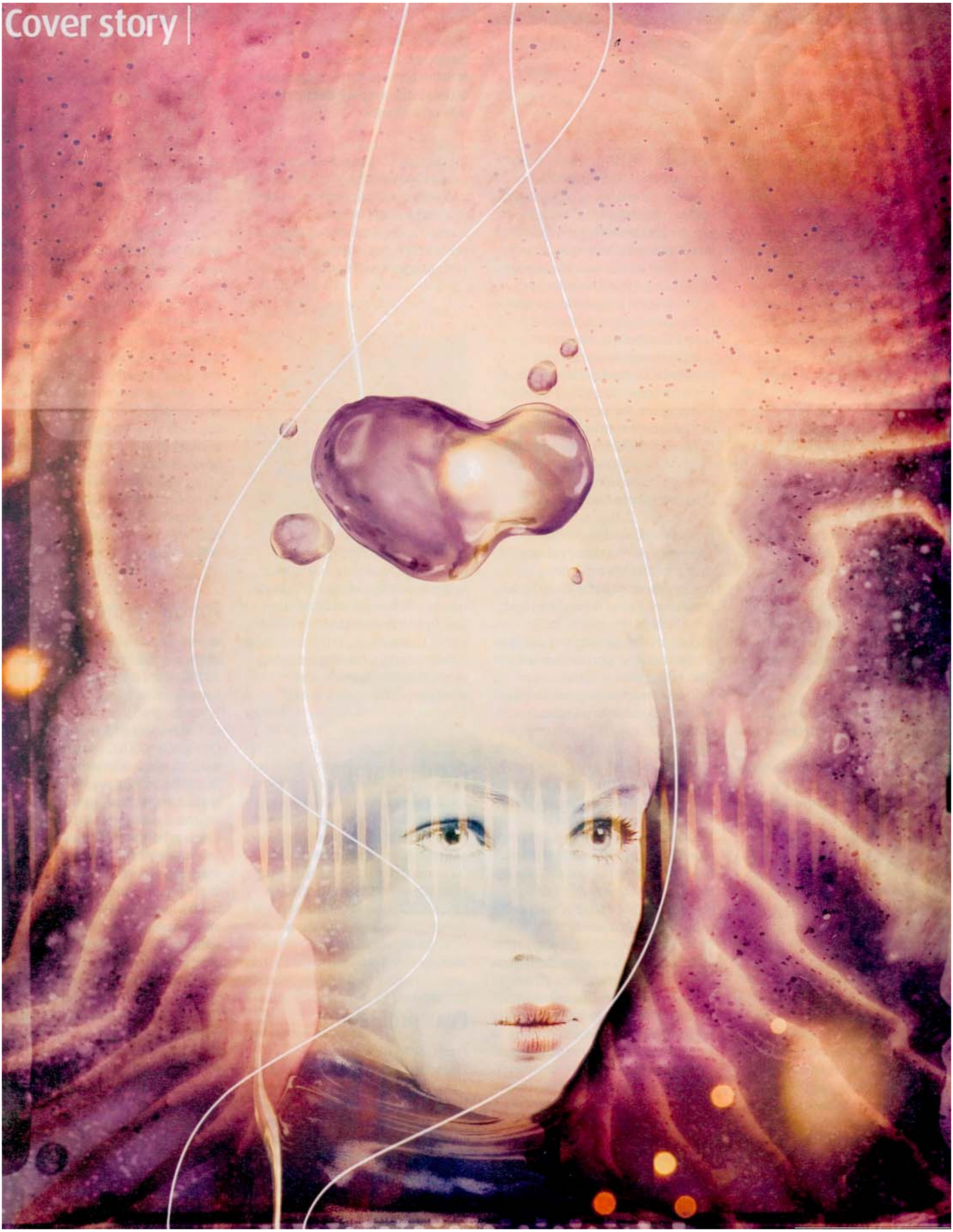


Glooper computer

How do you turn a blob of jelly into a thinking, feeling liquid brain?

Duncan Graham-Rowe reports

MOST of us find a shot of caffeine or a brisk walk does the trick. But when Andrew Adamatzky feels his brain needs a little extra stimulation, he gets a robot to dabble its metal fingers in it.

Adamatzky is a computer scientist at the University of the West of England in Bristol, UK, and his prototype brain is a dish of chemicals sitting on a lab bench. Its "thoughts" are waves of ions that form spontaneously and diffuse through the mix. And occasionally, when things get too sluggish, the brain instructs a robotic hand to dip its fingers into the dish and wiggle them about, literally stirring the creative juices.

Designed to do nothing more than mimic the kind of feedback that occurs between our own fingers and brains, this experiment is part of an ambitious programme to develop chemical-based processors that run on ions rather than electrons, and which sit in dishes rather than on circuit boards. Adamatzky calls it gooware: hardware you can store in a bottle.

Now, after more than a decade of development, Adamatzky has worked out how to make liquid logic gates, building arrays that he believes could lead to powerful processors that are infinitely reconfigurable and self-healing. Even computing giant IBM has begun to think along similar lines — they suspect that much the same technology could power a new breed of processor chips.

But that's not to say that chemical computers will replace conventional silicon anytime soon. Besides, for now Adamatzky is focusing his attention on another goal — constructing gooware powerful enough to deserve the description "liquid brain". And to help prove the concept's potential, Adamatzky is building the perfect host for his liquid brain – a jelly robot. Equipped with artificial eyes and synthetic hormones, it might one day sense its surroundings and even feel emotions. Welcome to the world of blobotics.

Chemical computing owes its power to an intriguing but complex piece of chemistry called the Belousov-Zhabotinsky or BZ reaction. It consists of a repeating cycle of three separate sets of reactions, each with its own characteristic mix of ions and molecules (see "Making waves", page 34). Once you combine the ingredients, any local fluctuation in concentration (or a catalyst) will start the first set of reactions. The products of this trigger the second, which starts the third, which starts the first again, and so on. The reactants also change colour through the sequence, typically from red to blue and back again. And because this reaction is self-propagating – reactions in one place diffuse outwards and prompt neighbouring regions to start reacting – it creates alternating waves of red and blue that diffuse outwards from the point where the reaction starts.

Waves in a maze

Researchers have already found ways to exploit light-catalysed BZ reactions to solve problems, such as working out the shortest path through a maze. Solving a maze using a conventional computer is complex as the program has to examine all possible routes to work out which is the shortest. Instead, a team of US researchers used the fact that diffusing reactions like a BZ wave always travel by the shortest path. They built a physical representation of the maze with plastic walls and added the reactants, and when they triggered BZ waves at a point, they found that by recording time-lapse images they could work out the shortest route from any other point in the maze back to the spot where the reaction started.

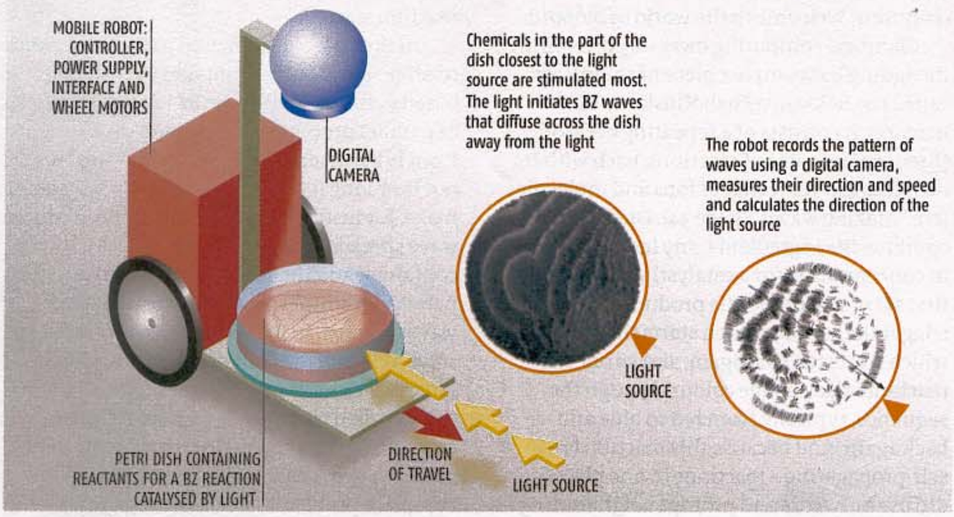
On the face of it, BZ-based processing seems to offer significant advantages over silicon-based systems. Firstly, the BZ reaction is a form of parallel processor: every point on a wave front is like a separate calculation – working out how long it takes to get to that point in the maze, for instance. Computation occurs as the wave spreads or interacts with the walls of the container, and the results can be read out in parallel by simply recording the pattern of waves created. In theory, a BZ reaction could solve a class of difficult problems that have large numbers of possible solutions, such as the so-called travelling salesman problem – computing the shortest loop route between several cities. These tasks, known as NP-complete problems, are extremely time-consuming for conventional computers.

Unfortunately, chemical computers also have one major drawback: you need to translate your problem into a physical representation, such as a maze, add the reactants and let the waves diffuse through. Simply designing and constructing a maze to solve a complex problem could take months. To most researchers it seemed like a dead end.

But in the mid-1990s Adamatzky began to suspect that the BZ reaction might have potential for computing. In 1996 he met Ben De Lacy Costello, a chemist at the University of the West of England, and the pair set out to try something rather ambitious: build their own chemical-based processor. By 1999 they had teamed up with Nicolas Rambidi, a physicist at Moscow State University in Russia, and proved the concept by making a ▶

ANATOMY OF A CHEMICAL CONTROLLER

A chemical processor based on the Belousov-Zhabotinsky (BZ) reaction can control a robot, steering it towards light, for example



Making waves

The most common recipe for the Belousov-Zhabotinsky reaction uses bromide and bromate ions, malonic acid, and a cerium catalyst that also acts as a visual indicator for the reaction. Mix the ingredients together and three separate sets of reactions start. First, bromate ions oxidise bromide ions, forming bromine:

$BrO_3^- + Br^- + 2H^+ \rightarrow HBrO_2 + HOBr$

$HBrO_2 + Br^- + H^+ \rightarrow 2HOBr$

$HOBr + Br^- + H^+ \rightarrow Br_2 + H_2O$

As the bromide ion concentration drops, the second set of reactions kicks in, creating BrO_2 radicals that oxidise the cerium and change the mixture's colour from red to blue:

$BrO_3^- + HBrO_2 + H^+ \rightarrow 2BrO_2 + H_2O$

$BrO_2 + Ce(III) + H^+ \rightarrow HBrO_2 + Ce(IV)$

Then the third set of reactions begins: malonic acid, cerium and bromine react to create bromomalonic acid and bromide ions. The cerium is reduced, the blue mixture turns red and the cycle begins again:6

$MA + Br_2 \rightarrow BrMA + Br^- + H^+$

$Ce(IV) + MA + BrMA \rightarrow Br^- + Ce(III)$ (other products are formed but this reaction set is still being investigated)

robot controlled by little more than a dish of chemicals (see Diagram, above).

Spurred on, they created a menagerie of strange mechanical-chemical hybrids. One used robotic fingers and a BZ-based "brain" to mimic interactions between human hands and brains – the BZ reaction controlled the fingers, while the fingers themselves were tipped with catalysts that could stimulate the BZ reaction. Another was a bot with two BZ-based brains that could navigate through a furniture-filled room. One brain guided the robot towards its destination while the other steered round obstacles en route.

Although the chemical processors worked well enough for relatively simple tasks like these, Adamatzky quickly realised that for more complex processing he would have to find a way to build the chemical equivalent 2333333333of a programmable computer. And for that he needed logic gates.

Logic gates perform the operations on which all conventional processors depend. A NOT gate, for example, turns a digital 0 into a digital 1, and vice versa. An OR gate outputs a 1 as long as at least one of its two input numbers is a 1. And if you can build OR and NOT gates, then provided you can link them together, it should be possible to construct all other kinds of logic circuit.

Other researchers had already attempted this. They built circuits with physical channels to carry the BZ waves – the equivalent of wires – and junctions between channels where the waves could interact — the equivalent of logic gates. But to Adamatzky this represented a return to the problems of the original BZ processors. Miniaturisation would be difficult, and routing one wire over another would be well nigh impossible. "You would simply get a poor imitation of conventional computer architecture," he says.

When balls collide

Then Adamatzky stumbled across some theoretical work by two American physicists, Tommaso Toffoli and Edward Fredkin from Boston University in Massachusetts. They suggested that you could create a simple form of processor using little more than billiard balls. They set up a scheme in which each ball represents either a digital 1 or 0. Computation occurs when the balls collide, and the exact logical operation performed depends on how the balls collide and the direction in which they rebound. In other words, collisions could create the equivalent of logic gates. Adamatzky began to wonder whether he could collide BZ waves to create a chemical processor.

Conventional BZ waves certainly wouldn't do the trick. Instead of moving in a straight line, they radiate out, making it difficult to see how individual waves interact. So Adamatzky started to ask colleagues and experts in BZ systems whether anyone knew how to create the chemical equivalent of a billiard ball.

In 2002 his efforts finally paid off. He discovered that a team of Spanish and American researchers had created a light-sensitive BZ mixture containing chemical inhibitors that suppressed the formation of the usual BZ wave patterns. With just the right amount of stimulation – provided by light – the mixture generated wavefront fragments that travelled through the reactor dish in straight lines, without spreading out.

Last year Adamatzky tried it himself: he introduced a BZ mixture into a thin layer of gel loaded with silver halide ions. The viscous gel slows the diffusion reaction and the halide ions act as chemical inhibitors. Instead of forming circular waves, it spontaneously generated wave fragments less than a millimetre long that didn't grow or shrink, and which travelled in straight lines. He nicknamed them BZ bullets (see Diagram, page 35).

Experiments showed that these bullets seem to behave more like quasi-particles than waves, sometimes even bouncing off one another like billiard balls, so he realised they really could be used to create the logic gates. In experiments he found that when two bullets collide at a certain angle, they create a single "output" bullet travelling in a specific direction. With only one input, there was no output in that direction, creating an AND gate – one that outputs 0 unless both inputs are 1. Adamatzky also created other gates called NOT and XOR. Now he plans to begin combining different gates together to create more complex logic circuits.

Although his work is still at an early stage, Adamatzky is confident he can control and organise BZ bullets to form circuits, and he already has a good idea of how to construct them. He can create BZ bullets by illuminating a light-catalysed BZ reaction, and is now working on how to steer the bullets and send the output from the gates to specific points such as sensors. He hopes to use fixed impurities in the gel layer to act like mirrors, bouncing the bullets in specific directions.

Since there is no need for wires, you can route multiple signals through the same volume by controlling their timing. And you can read out the results of a calculation using a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high-resolution digital camera or sensors mounted around the edge of the dish. "Potentially we can pack a very complicated circuit in a very small volume," says Adamatzky. And rather than using simple binary logic, it might be possible to employ a more complex, multi-valued logic, based on the relative sizes of the bullets.

Adamatzky compares his chemical controllers to conventional parallel processors such as neural networks, and believes they can perform any function these other systems can. "All algorithms previously implemented in 'conventional' parallel processors can be adapted to liquid chemical processors," he says. But he admits he has a lot of work to do before his chemical computers become useful. They have one big limitation too, he says: they are not suited to real-time processing because the bullets move at just a few millimetres per minute.

> "Could they ever replace conventional chips? Perhaps, if researchers can learn to create waves on a nanoscale"

However, Adamatzky and his colleague Tetsuya Asai, now at Hokkaido University in Sapporo, Japan, have come up with a possible solution: they are making waves in silicon. Asai has created silicon chips that generate the solid-state equivalent of BZ waves, and used them to make simple logic gates. The key is a form of diode called a p-n-p-n junction. When there is a voltage across it, a single "seed" electron will trigger the build-up of more and more electrons inside the diode. When the charge accumulates to a critical level, the diode "opens", releasing a flood of electrons.

Asai has built a two-dimensional array of these diodes in silicon and shown that the electron cascade at one diode triggers electron avalanches from neighbouring diodes in turn. The result is a wave that sweeps through the array much like a conventional BZ wave, only a million times as fast. It is also far easier to get signals in and out of a silicon processor, so in the long term this work might produce new types of parallel-processing silicon chips, says De Lacy Costello, or perhaps even hybrid silicon-chemical systems.

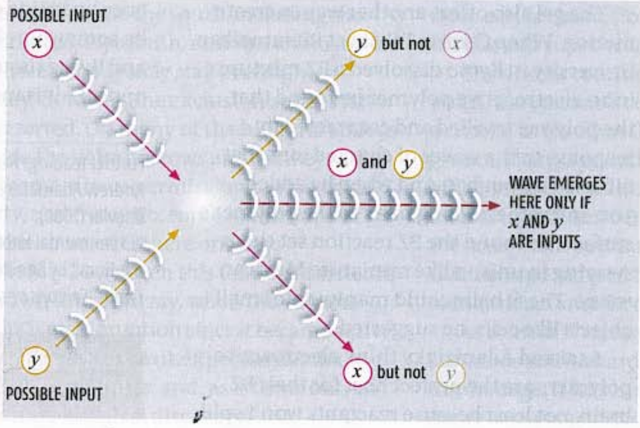
Could they ever replace conventional silicon chips? Perhaps, if researchers can learn

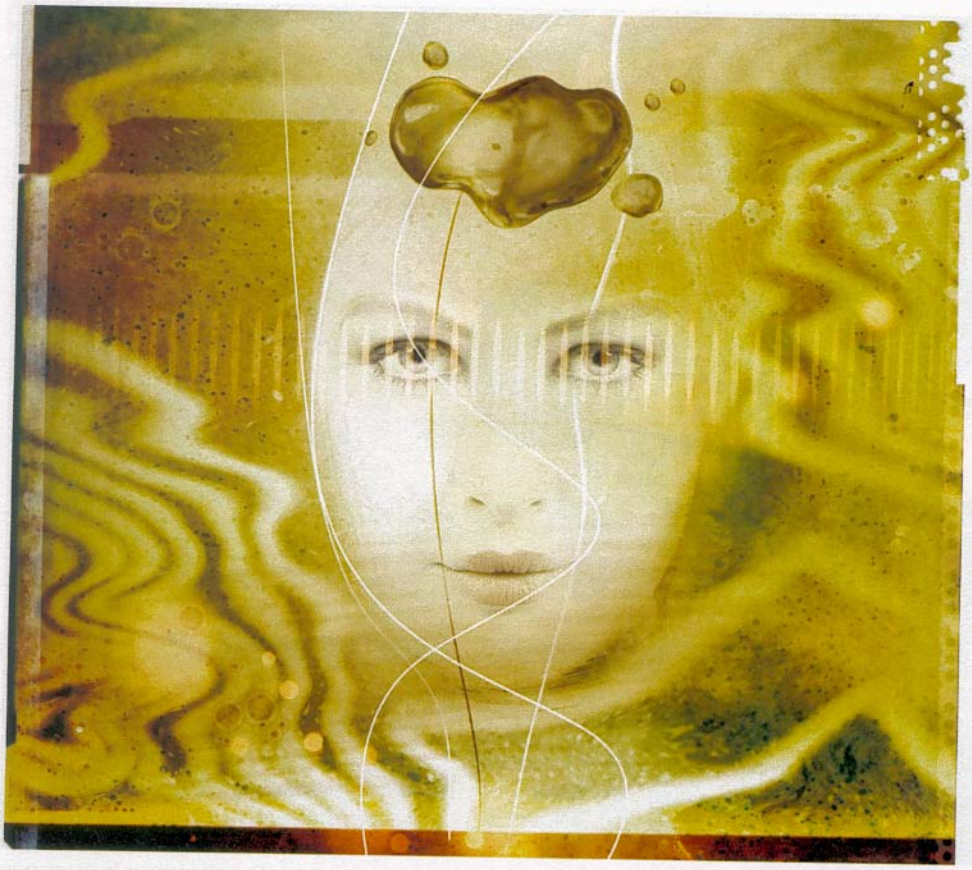
LIQUID LOGIC GATES

Add chemical inhibitors to a Belousov-Zhabotinsky reaction and it creates small wave fragments that travel in straight lines. When the fragments collide, they interact, rebounding or even annihilating each other. This behaviour can be used to make logic gates, providing, say, the equivalent of an AND gate

AND GATE

INPUT x	INPUT y	OUTPUT
0	0	0
1	0	0
0	1	0
1	1	1





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how to create waves on a nanoscale, so packing the logic gates close together. And there is no reason why you can't create the equivalent of chemical waves using individual molecules or atoms, says Kenneth Showalter, an expert on BZ systems at West Virginia University in Morgantown. "There are reaction-diffusion waves on a much smaller scale," he says.

This idea has already caught the attention of researchers at IBM, who are experimenting with a processor that performs simple calculations using rows of carbon monoxide molecules on a metal surface. When one molecule moves forwards, it knocks into its neighbour and produces a cascade effect "very much like dominoes", says Bernie Myerson, IBM's chief technologist. By altering the way rows intersect, it is possible to create basic logic gates that work in a similar way to Adamatzky's colliding bullets. It's still early days, says Myerson, but future generations of computers could well be chemical-based.

"He wants to use his gooware to create a liquid robot in which metal and wire are replaced by jelly"

Building the blob

Adamatzky is not particularly interested in taking on the chip industry, however. He has a far more ambitious plan. He wants to use his gooware to create a hugely powerful parallel processor: a liquid robot brain in which metal and wire are replaced by a blob of jelly. The host material he has in mind is an electroactive gel, a jelly-like polymer. Not only can BZ waves travel through electroactive gel without being slowed down, but the gel also expands and contracts in response to electric fields. The stuff is already used as artificial muscles, and researchers have used it to make a starfish that moves in response to an electric field (*New Scientist*, 6 July 2002, p 19).

The gel also offers another way to create motion. When Osamu Tabata at Ritsumeikan University in Kyoto dissolved a BZ mixture in an electroactive polymer he found that the polymer swelled and contracted in response to the waves of charged ions that diffused through it. And when he added 300-micrometre-long hairs to the polymer's surface, he found the BZ reaction set them swaying in unison like miniature Mexican waves. These hairs could manipulate small objects like cells, he suggested.

Asai and Adamatzky think electroactive polymers are the perfect host for their BZ brain, not least because reactants won't spill out if the robot makes sudden movements – a problem Adamatzky experienced with some of his earliest designs. They plan to copy Tabata's BZ-impregnated electroactive polymer, and by giving their blob a hairy coat they hope the Mexican waves could propel the blob along, just as starfish walk using small "legs". The hairs could even help it sense its surroundings, avoid obstacles or find things. And Rambidi has used a light-sensitive BZ reaction to create a kind of artificial retina that can perform basic image-processing – in particular, edge-detection, one of the fundamental abilities of the human retina.

Gooey on the inside yet rigid enough to keep its shape, their robot would be a double for the creeping, wobbling monster in the 1950s B-movie *The Blob*, a film that Adamatzky admits he watched with great interest. Without a rigid skeleton, this robot could squeeze into tight spaces or change its shape. "It will be completely flexible," says Adamatzky – an intelligent, shape-changing, crawling blob. And almost every component they need is in place. The challenge now, Adamatzky says, is bringing these elements together, a task he and his colleagues have begun in earnest. They estimate it will take them about five years.

And beyond that? Could his liquid brain ever become sentient? Adamatzky believes so. He has even begun work on computer simulations of emotional states created by reagents in chemical solutions. So far the results are impressive, he says. Insert a set of synthetic hormones into a powerful parallel processor and a machine might even feel or express emotions, he suggests.

Peter Bentley, an expert in artificial intelligence at University College London, thinks that Adamatzky's plans for a chemical brain might be over-ambitious – but not completely crazy. "I'm not sure you could get the same sort of complexity within a gel," says. "But there's a lot of potential here."

Even if Adamatzky doesn't succeed, he's likely to uncover new ideas that could help create better processors or reveal something about the way our brain works. After all, says Showalter, BZ-based chemistry is one of the best models we have for the processing that goes on inside our heads. "Chemistry seems to be somewhere between electronic hardware and living tissue," he says. "That's part of the appeal – it is moving closer to biology." ●

Further reading: *Reaction-Diffusion Computers* by Andrew Adamatzky, Ben De Lacy Costello and Tetsuya Asai, Elsevier (2005).

"Experimental implementation of collision-based gates in BZ medium" by Ben De Lacy Costello and Andrew Adamatzky, in *Chaos, Solitons and Fractals*, in press.