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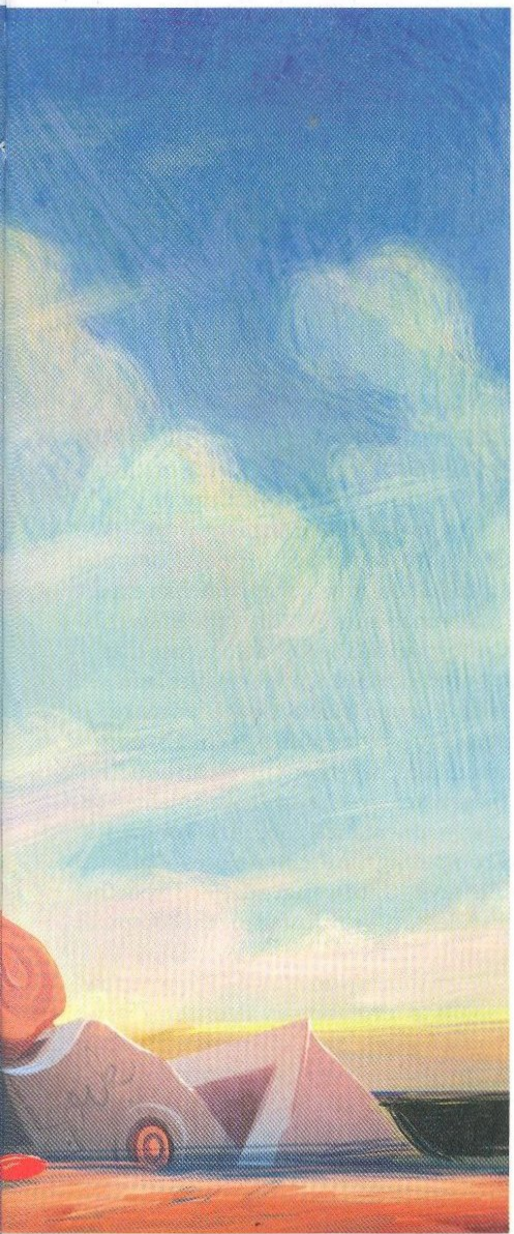
Rise of the robogeeks

Forget the likes of Terminator and Wall·E – the first intelligent robot to stalk this earth could be seriously square, says **Michael Brooks**



"Human brains don't work by magic, so whatever it is they do should be doable by machine"

IN December, philosopher and artificial intelligence expert Aaron Sloman announced his intention to create nothing less than a robot mathematician. He reckons he has identified a key component of how humans develop mathematical talent. If he's right, it should be possible to program a machine to be as good as us at mathematics, and possibly better.

This is no mad quest, insists Sloman, of the University of Birmingham in the UK. "Human brains don't work by magic, so whatever it is they do should be doable in suitably designed machines," he says.

Sloman's creature is not meant to be a mathematical genius capable of advancing the frontiers of mathematical knowledge: his primary aim, outlined in the journal *Artifical Intelligence* (vol 172, p2015), is to use such a machine to improve our understanding of where our mathematical ability comes from. Nevertheless, it is possible that such a robot could take us beyond what mathematicians have achieved so far. Forget robot vacuum cleaners and android waitresses; we're talking about a machine that could spawn a race of cyber-nerds capable of creating entirely new forms of mathematics.

The field of artificial intelligence has promised much before, of course. Early researchers thought it might open a fast-track to understanding consciousness, and there were claims that artificially intelligent computers and robots would change the world. The truth has been more prosaic. AI has done some clever things, such as give us great chess players and voice recognition software, but it hasn't delivered a revolution.

But when it comes to mathematics, we can't rule one out yet, says Alison Pease, who researches the philosophy of mathematics at the University of Edinburgh, UK. Pease teaches computers to do mathematics using AI programs, and thinks a computer really could astonish its programmer with a new mathematical insight. "Ours hasn't yet, but there is no reason why one shouldn't in the future," she says.

The first concrete step towards this scenario came with a program written by Simon Colton, now at Imperial College London. The program was named HR, in honour of the mathematicians Godfrey Harold Hardy and Srinivasa Ramanujan. It looked for "interesting" sequences of numbers (*New Scientist*, 24 February 2001, p 13).

Some of HR's discoveries have even been published – and HR, rather than Colton, got the credit. Though they might not look like cutting-edge advances, they could yet prove important. "I always refer to HR's work in number theory as recreational mathematics, but things that look insignificant can end up being hugely significant and interesting," Colton says.

Pease and her colleagues Alan Smaille and Markus Guhe have recently taken things further. In their Edinburgh computing laboratory they have been running virtual mathematics conferences, populated entirely by digital mathematicians (see "Reinventing the conjecture", page 36). So where might that lead?

All the way to significant new mathematics, Sloman hopes. His idea is that our key mathematical capabilities are formed in childhood. So rather than engineering a fully fledged mathematician's brain, Sloman thinks we should build a robot with a child-like brain and let it grow into its mathematical destiny.

There's just one problem. How do we know which of our childhood capabilities equip us for a life of juggling numbers?

Sloman is busy gathering clues. The answer, he reckons, lies in the spatial awareness skills that children must acquire in order to negotiate their world: skills such as knowing that a toy train pushed into a tunnel will come out the other side. Or that a jigsaw puzzle piece fits its gap only when correctly oriented. Or that the number of toys on the sofa does not depend on the order in which you count them.

From the minds of babes

You might be surprised to learn, for instance, that you grasped the topological concept called "the transitivity of containment" when you were still a toddler. Stacking cups, one inside the other, you learned that the small cup would fit not only in the medium-sized cup, but also inside the big one.

Transitivity of containment, like other geometrical and topological concepts, is learned through experience. "There are hundreds, if not thousands more examples of things a child learns empirically, that are later seen to be theorems in topology, geometry and arithmetic," Sloman says.

At some point, children make that jump for themselves. As toddlers, we soon translate our experiences into general theorems which we use to make predictions.

Take the train-through-a-tunnel example. By repeated experiences like this, toddlers >

learn the basic properties of rigid rods. That's why a 3-year-old carrying a long broom handle can negotiate a narrow corridor, turn a corner at the end without getting the broom handle caught in the vertical bars of a stair-gate, then make adjustments so that the handle will go through the next doorway. "There is a switch from learning empirically to realising it has 'simply got to be like that'," Sloman says.

And here is the key to the emergence of the mathematical mind. "The mechanisms that make that possible in a child are related to what makes it possible for them to go on to become a mathematician," Sloman says. "A lot of abstract maths has its roots in our ability to think about space and time, processes, and interactions between processes and structures."

Sloman has gone back to basics, to watch how children learn to navigate the world around them. He is building an archive of observations of children performing pseudo-mathematical tasks. These navigational and object manipulation skills – or at least the ability to acquire them quickly – must be encoded in the genome, Sloman reckons. And that means they could be encoded in a machine.

Sloman is still a long way from designing his robot toddler. Once he has catalogued the abilities of children at various stages of development, he still has to work out how to understand the mathematical implications of those abilities, then represent them in some form of computer code. "Information needs to be encoded in some form in order to be usable," he says. The gargantuan scale of the task means his aims are necessarily modest: at this stage he is simply trying to show a link between spatial manipulations and the basics of mathematics. Anything more would be a bonus. But just how big could that bonus be? Could a robot mathematician really do something interesting?

"In principle, yes, absolutely," Pease says. But, she adds, the story-so-far tempers her optimism. "Of all the scientific and mathematical discovery programs I've looked at, nothing has yet made a big discovery." At the very least, she says, that means there is a long way to go.

Colton thinks there is every reason to believe computers could produce something interesting to mathematicians. "Software is already producing theorems of value to maths," he points out. "Not of huge value, I admit – but then the average student or mathematician isn't producing anything of huge value either."

He and his team are convinced that computers can be genuinely creative. "Creativity is a very loaded word: people like to think it's a uniquely human attribute," he says. "The fact is, computers doing maths are more likely to be creative than, say, an undergraduate student, in many ways."

Others are sceptical of this view. Computers are a useful tool, says Rafael Núñez an expert on mathematical cognition at the University of California, San Diego, but the sense that computers can invent mathematics is an illusion. Though it looks like we can make progress by programming machines to do mathematics, he reckons there can be nothing in these machines that isn't pre-ordained by human mathematical concepts. "For me, it's like computing the decimal places of pi," Núñez says. "Once we have decided what the right rules are, we're just using the computer to crunch numbers."

Sloman thinks Núñez's view is too narrow. He points to "evolutionary algorithms" as a reason for optimism. This innovation allows a computer to evolve its own programs by producing lots of them, testing them against a goal criteria, and then selecting and "interbreeding" the best ones. It has allowed computers do things that nobody programmed them to do. "In some cases no human even knows how they do what they do," Sloman says. Aerospace and automobile designers have been using evolutionary algorithms since the late 1980s to optimise aircraft parts and streamline their designs. Even city traders are using them to buy and sell shares (*New Scientist*, 28 July 2007, p 26).

Evolution has a few million years head start on us in developing brilliant mathematicians, of course, but at least we're now in the race. "Our big discovery would be how do we do mathematics, rather than how do we write a program that can generate really new mathematics," says Pease. "But hopefully one would lead on from the other."

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Reinventing the conjecture

The traditional view of mathematics sees it as a set of some eternally existing rules that describe the universe. Doing maths involves exploring this abstract, ethereal domain.

Though appealing to many, this notion of mathematicians as intrepid explorers is nothing more than a romantic myth, according to Alison Pease of the University of Edinburgh, UK. "Maths is not discovery," she says. "It's a thing that we invent."

It is something that her computers can invent too, she insists. Pease runs an AI program called HRL, which puts together "agents" in a student-teacher relationship.

The students are programmed to take some input information, make inferences from it and try to assess just how "interesting" those inferences are. If sufficiently interesting, the teacher gets involved, calling a group brainstorm designed to develop the ideas further.

One of HRL's early successes was the independent invention of a mathematical proposition called Goldbach's conjecture. One of the students was given the concept of integers and divisors, and instructed to use these to play around with the integers 1 to 10, looking for interesting relationships. A second student had the same concepts and instructions, but played with the integers 11 to 20.

Student two generated two new concepts: "even numbers" and "the sum of two primes". Then it generated a conjecture: that all even numbers can be expressed as the sum of two primes. It thought this was interesting, and sent its work to the teacher to be placed on the agenda for discussion.

The response was positive. "The teacher sent a request for modifications to this conjecture, and student one found the counterexample," Pease says. That counterexample is the number 2: the conjecture was modified to "all even numbers except 2 are the sum of two primes".

The fact that Christian Goldbach came up with this still unproven conjecture in 1742 makes it a little less impressive, but the point is made. Even if computers are a few centuries behind, it seems that machines really can do what human mathematicians do.