found lots of narrow growth rings, suggesting that *Majungasaurus* had become large over a prolonged period.

"I was very surprised," he says. The next dinosaur he examined, a similar-sized beast called *Ceratosaurus*, was the opposite — a big dinosaur that grew fast during its growth spurt, says D'Emic.

Bone growth rings

Over a decade, D'Emic and his colleagues amassed bone growth-ring measurements from 42 theropod species to see which strategies led to large and small bodies. They found that 31% of theropod species were larger than their ancestors because of faster growth and 28% because of prolonged growth. Meanwhile, 21% became smaller than their ancestors by shortening their growth spurts, and 19% by slowing growth.

The study covered theropod species that lived between 230 million years ago and the end of the Cretaceous period 66 million years ago, when a mass-extinction event wiped out the non-avian dinosaurs. It's "a huge evolutionary timescale" to include in an analysis, says Vera Weisbecker, an evolutionary biologist at Flinders University in Adelaide, Australia. "That is really impressive," she says. "It's just fascinating that there are so many developmental ways to become big or small."

Palaeontologist Kevin Padian at the University of California, Berkeley, says the analysis is the kind of work that needs to be done, animal group by animal group, to understand how body size evolves.

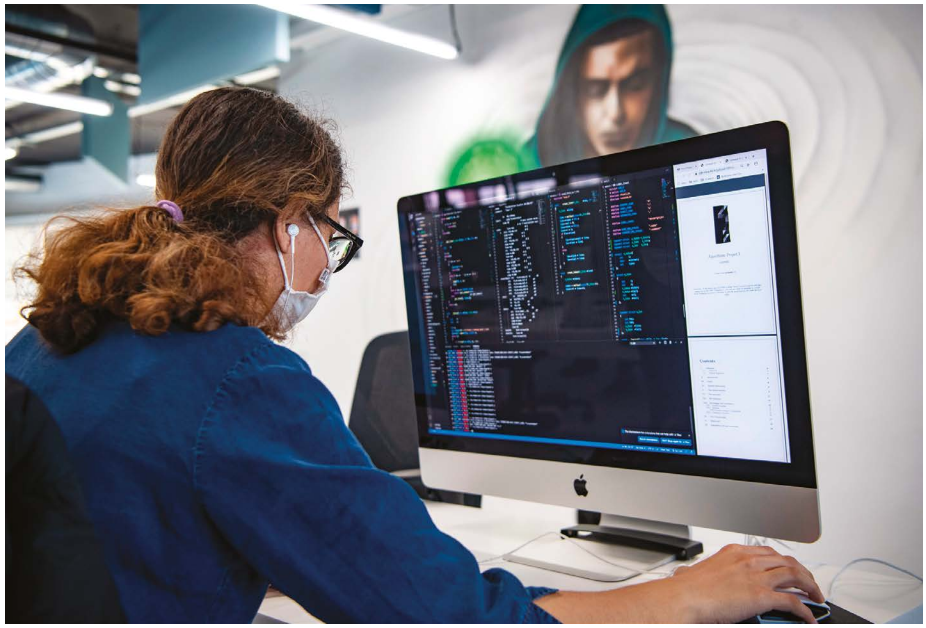
Drivers of change

But Meike Köhler, an evolutionary palaeobiologist at the Catalan Institution for Research and Advanced Studies in Barcelona, Spain, says the findings are not surprising because previous work has shown a range of growth strategies across animal species. Köhler would like to see an analysis that considers what ecological circumstances influenced how animals changed in size over time.

Weisbecker says that the growth strategy used might be related to evolutionary pressures. "If you looked at all the ones with explosive early growth, you might be able to test if they happen to be the ones that are more likely to be predated on, for example," she says.

For each species, the growth strategy that led to its individual body size probably related to its unique environment, says Padian. "It's not a one-size-fits-all, which is a good thing for us to learn," he says. "We might have thought that, but they've documented it."

D'Emic says he and his team are conducting similar analyses on other groups, including mammals — a group that contains many more species to sample — to see whether the diversity is found in other branches of the evolutionary tree.



FADEL SENNA/AFP/GETTY

AI tools have allowed researchers to solve complex mathematical problems.

HOW WILL AI CHANGE MATHEMATICS?

AI tools already help formulate new theories and solve problems. But they're set to shake up maths even more.

By Davide Castelvecchi

As interest in chatbots spreads like wildfire, mathematicians are beginning to explore how artificial intelligence (AI) could help them to do their work. Whether it's assisting with verifying human-written work or suggesting new ways to solve difficult problems, automation is changing the field in ways that go beyond mere calculation, researchers say.

"We're looking at a very specific question: will machines change math?" says Andrew Granville, a number theorist at the University of Montreal in Canada. A February workshop at the University of California, Los Angeles (UCLA), explored this question, aiming to build bridges between mathematicians and computer scientists. "Most mathematicians are completely unaware of these opportunities," says one of the event's organizers, Marijn Heule, a computer scientist at Carnegie Mellon University in Pittsburgh, Pennsylvania.

Akshay Venkatesh, a 2018 winner of the prestigious Fields Medal who is at the Institute for Advanced Study in Princeton, New Jersey, kick-started a conversation on how computers will change maths at a symposium in his honour last October. Two other recipients of the medal, Timothy Gowers at the Collège de France in Paris and Terence Tao at UCLA, have also taken leading roles in the debate.

"The fact that we have people like Fields medallists and other very famous big-shot mathematicians interested in the area now is an indication that it's 'hot' in a way that it didn't used to be," says Kevin Buzzard, a mathematician at Imperial College London.

AI approaches

Part of the discussion concerns what kind of automation tools will be most useful. AI comes in two major flavours. In 'symbolic' AI, programmers embed rules of logic or calculation into their code. "It's what people would call 'good old-fashioned AI'," says Leonardo de Moura, a computer scientist at Microsoft Research in Redmond, Washington.

The other approach, which has become extremely successful in the past decade or so, is based on artificial neural networks. In this type of AI, the computer starts more or less from a clean slate and learns patterns by digesting large amounts of data. This is called machine learning, and it is the basis of 'large language models' (including chatbots such as ChatGPT; see page 20), as well as the systems that can beat human players at complex games or predict how proteins fold. Whereas symbolic AI is inherently rigorous, neural networks can only make statistical guesses, and their operations are often mysterious.

De Moura helped symbolic AI to score some early mathematical successes by creating a system called Lean. This interactive software tool forces researchers to write out each logical step of a problem, down to the most basic details, and ensures that the maths is correct. Two years ago, a team of mathematicians succeeded in translating an important but impenetrable proof – one so complicated that even its author was unsure of it – into Lean, thereby confirming that it was correct.

The researchers say the process helped them to understand the proof, and even to find ways to simplify it. "I think this is even more exciting than checking the correctness," de Moura says.

As well as making solitary work easier, this sort of 'proof assistant' could change how mathematicians work together by eliminating what de Moura calls a "trust bottleneck". "When we are collaborating, I may not trust what you are doing. But a proof assistant shows your collaborators that they can trust your part of the work."

Sophisticated autocomplete

At the other extreme are chatbot-esque, neural-network-based large language models. At Google in Mountain View, California, former physicist Ethan Dyer and his team have developed a chatbot called Minerva, which specializes in solving maths problems. At heart, Minerva is a very sophisticated version of the autocomplete function on messaging apps: by training on maths papers in the arXiv repository, it has learnt to write down step-by-step solutions to problems in the same way that some apps can predict words and phrases. Unlike Lean, which communicates using something similar to computer code, Minerva takes questions and writes answers in conversational English. "It is an achievement to solve some of these problems automatically," says de Moura.

Minerva shows both the power and the possible limitations of this approach. For example, it can accurately factor integer numbers into primes – numbers that can't be divided evenly into smaller ones. But it starts making mistakes once the numbers exceed a certain size, showing that it has not 'understood' the general procedure.

Still, Minerva's neural network seems to be able to acquire some general techniques, as opposed to just statistical patterns, and the Google team is trying to understand how it does that. "Ultimately, we'd like a model that you can brainstorm with," Dyer says. He says it could also be useful for non-mathematicians who need to extract information from the specialized literature. Further extensions will expand Minerva's skills by studying textbooks and interfacing with dedicated maths software.

Dyer says the motivation behind the Minerva project was to see how far the machine-learning approach could be pushed; a powerful automated tool to help mathematicians might end up combining symbolic AI techniques with neural networks.

Maths v. machines

In the longer term, will programs remain part of the supporting cast, or will they be able to conduct mathematical research independently? AI might get better at producing correct mathematical statements and proofs, but some researchers worry that most of those would be uninteresting or impossible to understand. At the October symposium, Gowers said that there might be ways of teaching a computer some objective criteria for mathematical relevance, such as whether a small statement can embody many special cases or even form a bridge between different subfields of maths. "In order to get good at proving theorems, computers will have to judge what is interesting and worth proving," he said. If they can do that, the future of humans in the field looks uncertain.

Computer scientist Erika Abraham at RWTH Aachen University in Germany is more sanguine about the future of mathematicians. "An AI system is only as smart as we program it to be," she says. "The intelligence is not in the computer; the intelligence is in the programmer or trainer."

Melanie Mitchell, a computer scientist and cognitive scientist at the Santa Fe Institute in New Mexico, says that mathematicians' jobs will be safe until a major shortcoming of AI is fixed – its inability to extract abstract concepts from concrete information. "While AI systems might be able to prove theorems, it's much harder to come up with interesting mathematical abstractions that give rise to the theorems in the first place."

US LAWSUIT THREATENS ACCESS TO ABORTION DRUG

Nature explains the science behind the case, which could weaken the FDA's regulatory authority.

By Mariana Lenharo

A lawsuit in Texas not only has the potential to ban a popular abortion drug across the United States – but could also set a dangerous precedent by overturning the approval of a medication by the US Food and Drug Administration (FDA).

Following the reversal of *Roe* v. *Wade* last year, some US states have banned abortions, driving more pregnant people to seek medication abortions. The lawsuit against the FDA, brought by anti-abortion groups and physicians, seeks to overturn the agency's approval of the abortion drug mifepristone, which happened in 2000. The plaintiffs allege that mifepristone, which is used in combination with another drug, misoprostol, is not safe – a claim that is not corroborated by the scientific evidence, say researchers who spoke to *Nature*. Legal specialists think there is a good chance that the judge deciding the case, Matthew Kacsmaryk in the US District Court for the Northern District of Texas, will rule in favour of the plaintiffs. Appointed by former US president Donald Trump, who promised to help overturn *Roe*, Kacsmaryk "has deep ties to the religious right, and he has issued rulings that are based on very, very conservative ideologies", says Amanda Allen, an attorney and director of The Lawyering Project, an organization based in New York City that works to improve abortion access.

The effects of this case might reverberate across the country, further affecting health care for pregnant people. "If the plaintiffs get what they're asking for, mifepristone will be banned in all states – it doesn't matter if the state has a law in place that protects access to abortion," Allen says.

Here, *Nature* explains the evidence in the case, what's on the line and what abortion options will be available to people in the United States if the FDA loses.

Is mifepristone safe?

All the evidence suggests that the answer is yes, contrary to what the plaintiffs argue. A 2013 systematic review published in the journal *Contraception*, for example, found that failure to terminate a pregnancy occurred in fewer than 5% of pregnant people who had taken mifepristone combined with misoprostol, and