
$e^{-Zr/2a_0}\cos\theta$
$\sin\theta\, e^{\pm i\varphi}$
$Z^2r^2\, e^{-Zr/3a_0}$
$\Delta x\Delta p \geq \frac{\hbar}{2}$

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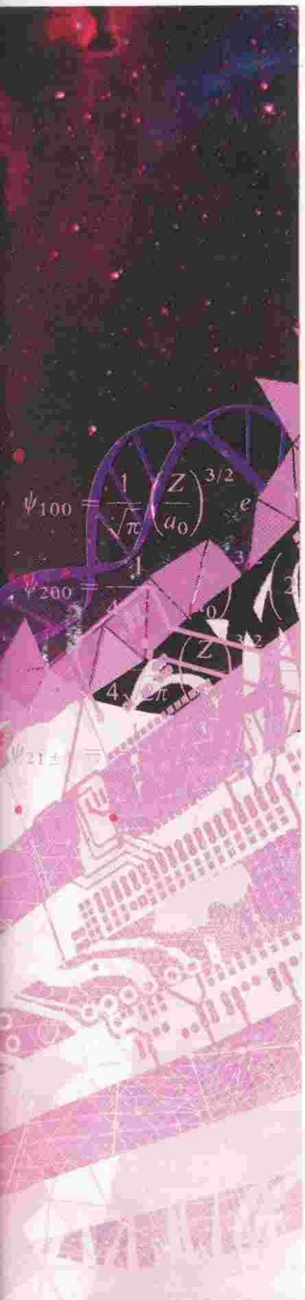

What we'll never know

There are limits to our knowledge, but what are they and how close are we to hitting them, asks **Michael Brooks**

YOU might not expect the UK's Astronomer Royal to make too many pronouncements about what chimpanzees think, but that is one of Martin Rees's favourite topics. He reckons we can learn a lesson from what they understand about the world – or, rather, what they don't. "A chimpanzee can't understand quantum mechanics," Rees points out.

That might sound like a statement of the obvious. After all, as Richard Feynman famously said, nobody understands quantum mechanics. The point, though, is that chimps don't even know what they don't understand. "It's not that a chimpanzee is struggling to understand quantum mechanics," Rees says. "It's not even aware of it." The question that intrigues Rees is whether there are facets of the universe to which we humans are similarly oblivious. "There is no reason to believe that our brains are matched to understanding every level of reality," he says.

We live in an age in which science enjoys remarkable success. We have mapped out a grand scheme of how the physical universe works on scales from quarks to galactic clusters, and of the living world from the molecular machinery of cells to the biosphere. There are gaps, of course, but many of them are narrowing. The scientific endeavour has proved remarkably fruitful, especially when you consider that our brains evolved for survival on the African savannah, not to ponder life, the universe and everything. So, having come this far, is there any stopping us?

The answer has to be yes: there are limits to science. There are some things we can never know for sure because of the fundamental constraints of the physical world. Then there are the problems that we will probably never solve because of the way our brains work. And there may be equivalents to Rees's observation about chimps and quantum mechanics – concepts that will forever lie beyond our ken.

But the limits in knowledge and understanding that we do recognise are, if anything, cause for celebration. They represent some of the most fertile ground for us to explore; ever creative, scientists are learning how to turn obstacles into opportunities. We may never be able to know everything, but discovering what we cannot know usually leads to us knowing more.

Perhaps the most fundamental limitation on knowledge is the cosmic horizon beyond which we will never see. This derives from one of nature's unbreakable rules: nothing can travel faster than light. In 1929, Edwin Hubble discovered that the universe is expanding. Everything is moving away from us, and the expansion is fastest at the most distant reaches of the universe. Any object that is more than 46 billion light years (4×10^{23} kilometres) away is receding at more than the speed of light. (Though nothing can travel through space faster than light, the fabric of the universe itself can expand faster.)

From the moment that an object slips over the horizon, no light it emits will ever arrive at Earth – and the same goes for any other information about it. All we have is the data that has had time to reach us during the › lifetime of the universe. The rest – possibly an infinite amount – is lost to us forever.

What is beyond the cosmic horizon? We don't know, but it is generally assumed that the unobservable part of the universe is much the same as the part we can see. However, that assumption has recently been challenged by the discovery of more than 1000 distant galaxy clusters rushing towards the same point in the sky (*New Scientist*, 23 January 2009, p 50). This "dark flow" hints that there might be megastructures beyond the horizon that are unlike anything we have observed.

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Today's unknowns

The limitation imposed by the speed of light means we may never know whether they exist or not. But that dark cloud comes with a silver lining. The discovery of a finite speed of light paved the way for Einstein to twig that everything else in the universe is bound by the speed limit – an idea that revolutionised physics in the form of special relativity.

Another fundamental constraint on our knowledge is the feature of quantum mechanics we know as the Heisenberg uncertainty principle. This has its roots in the discovery that certain things in nature, such as energy, are packaged up in fundamental, indivisible units called quanta. In the 1920s, Werner Heisenberg realised that the measurable characteristics of a quantum object such as an electron do not have a defined value, but many possible values each with a probability attached to it. To pin the value down means taking lots of separate measurements, but doing so blurs our knowledge of another characteristic. The best-known consequence is that we can never simultaneously know a particle's exact position and momentum.

Although Heisenberg unearthed this principle by digging into the mathematics of quantum theory, it has a physical explanation. Bounce a photon off a particle in order to establish its position, and the impact will change the particle's momentum. Thus accurate measurement of both position and momentum simultaneously is impossible.

This places a theoretical limit on our knowledge, but the discovery of the uncertainty principle led to numerous breakthroughs elsewhere. "At first glance, it might seem that uncertainty is 'bad', in the sense that it limits how much we can hope to learn," says Stephanie Wehner of the Centre for Quantum Technologies at the National University of Singapore. "However, the principle isn't really a road block, it's more like a stepping stone. It provides a tool for exploring the quantum world."

> "Chimpanzees aren't struggling to understand quantum mechanics. They aren't even aware of it"

Importantly for you and me, we wouldn't be here without it: the uncertainty principle provides our best explanation for how the entire universe came into being. That's because uncertainty shatters the notion that anything ever has exactly zero energy. So the universe could have come into existence spontaneously when its energy state momentarily flickered away from zero. Heisenberg himself pointed out that uncertainty in time measurements destroys common-sense notions of cause and effect – which perhaps makes the idea of something appearing from nothing a little easier to swallow.

Similar reasoning led Stephen Hawking to propose that black holes must emit a form of radiation – and we have good evidence that they do. Hawking radiation results from apparently empty space gaining some energy due to the uncertainty principle. This is converted into a pair of short-lived particles – one of normal matter and one of antimatter –

that would usually annihilate each other moments after their creation. Near a black hole's event horizon, however, one can float away while the other is swallowed by the black hole. The gradual loss of the energy carried away by these particles will eventually lead to the complete evaporation of the black hole. Analogues of black holes created by shining laser light into a piece of glass have recreated this phenomenon (*New Scientist*, 2 October 2010, p 10) – adding plausibility to the argument that the universe created itself from nothing.

A fundamental limit of mathematics has offered a similarly rich vein of research material. In 1931, Kurt Gödel formulated his incompleteness theorem, which showed that certain mathematical systems cannot prove themselves to be true. Arithmetic, for example, is built on axioms – assumptions, essentially – that can't themselves be proven using arithmetic. That makes the entire edifice of arithmetic in some ways a mathematical equivalent of the sentence "this sentence is false". Other branches of mathematics face a similar problem.

Gödel's insight was a huge blow to the dream of building an unassailable mathematical foundation upon which our description of reality could be built – and it may also place a fundamental limit on how much trust physicists can place in any theory they create. However, here too a limitation has been turned into a source of ideas.

The British mathematician Alan Turing, for example, used Gödel's work to uncover a fundamental characteristic of computing machines: that it is impossible to devise a method that can be applied to any program to predict whether or not it will finish its task and halt. Sometimes you just have to run the program and wait. This "halting problem" may seem arcane but it has come to play a fundamental role in mathematics and computer science. It has turned out to be equivalent to many other problems in pure mathematics, such as deciding whether a "Diophantine equation", a type of algebraic expression involving only whole numbers, has a solution or not. "It tells you when not to attempt the impossible," says Gregory Chaitin, a mathematician at IBM's Watson Research Center in Yorktown Heights, New York.

Just as the impossibility of building a perpetual motion machine led to the discovery of the laws of thermodynamics, the limits of mathematics and computing can teach us some basic rules about how the mathematical world works. "I used to be a pessimist about incompleteness, but not any more," Chaitin says. "You can say, 'Oh my god there's a wall', but you can also say, 'Look: there's a door in the wall'."

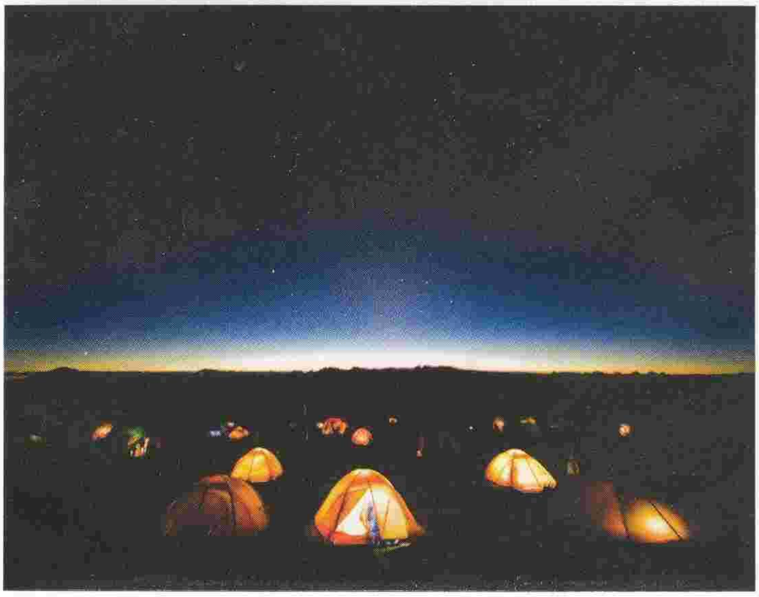
"Even if we can create a second genesis in the lab, it won't tell us how life on Earth began 3.8 billion years ago"

Chaitin is now applying incompleteness to evolution – something he calls "metabiology". The idea stems from his considerations of Turing's work. The halting problem led Chaitin to formulate a number, known as omega, that defines the probability of whether a randomly chosen program will halt or not in terms of a string of 0s and 1s. Omega is infinitely long and irreducibly complex, and Chaitin has described it as the DNA of mathematics. Now he is working out how to use omega to examine real DNA.

If you think of DNA as a program for building and operating an organism, Chaitin says, you might be able to discover the mathematics by which the information in DNA operates. Doing this, he says, may show that evolution is the analogue of omega: infinitely complex and thus endlessly creative. "A way of looking at Gödel and Turing's work is that they were opening the door from pure mathematics to biology," Chaitin says.

When it comes to biology, there is only one sure limit, according to evolutionary biologist Jerry Coyne of the University of Chicago. Knowing how life began will be forever beyond our reach, he says – it is biology's cosmic horizon. That is because the molecules involved didn't get fossilised. Even if we can create a "second genesis" in the laboratory, that won't tell us exactly how it happened on Earth 3.8 billion years ago, Coyne says. "There are so many different scenarios for how life got going and they all involve molecules that don't get fossilised. It's a clear limit." ›

Advances come from studying the horizons of science



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Another area of biology that some say lies beyond the limits of science is consciousness. Decades have passed without any real progress, says Russell Stannard, emeritus professor of physics at the Open University in the UK, and author of *The End of Discovery*. That may mean it is beyond us, he concludes. "Consciousness is a very good candidate for us having exhausted all that can be said about it."

Philosopher Daniel Dennett of Tufts University in Medford, Massachusetts, doesn't buy this argument. "There are limits to science but this isn't one of them," he says. "I know of no reason to expect that a brain couldn't understand its own methods of functioning." Dennett also reckons that there is plenty of progress. "I can't keep up with it," he says. It's a tough problem to be sure, but the sceptics are seeing the problem from the wrong perspective. Just because the brain is complex, with 100 million cells and a quadrillion synaptic connections, that doesn't mean we can't figure out what is going on within it.

However complex the human brain, Dennett points out, we are quite capable of augmenting its capabilities in order to understand it. In the past we used conversations, books and letters; now we use computers to store, access and process vast amounts of data. We have become extremely successful at sharing that data too, in a way that connects many minds together to solve the toughest of questions. That is how we reached the point where we can understand and even predict the movement of stars and electrons. There is no reason to think consciousness cannot be conquered in the same way, Dennett says.

"The history of the early cosmos is lost forever, yet we have still pieced together a detailed account of what happened at that time"

Science and technology don't just allow us to augment our brains and senses to see further. They can also open doors to worlds we can never directly experience. The early history of our cosmos is lost to us forever because it was only after 100,000 years that light became detached from matter and was free to fill the universe, carrying information with it. That hasn't stopped us from piecing together a detailed account of what happened before that time.

Don't underestimate science

A combination of creative thinking and rigorous checks against what information we do have available has proved an astonishingly powerful tool. While we will never know for sure that the big bang theory is correct, we have lots of reasons to think it is. For example, the amounts of the elements hydrogen, helium and lithium present in the universe exactly match the predictions of our theories describing the beginning of everything.

It is also possible to use well-tested theories to see beyond what we can experience directly. For example, we have never carried out an experiment in a black hole and probably never will, but we can still be confident what happens inside one. "Einstein's theory of gravity has been tested in a number of ways, and therefore we take seriously what it has to say about the inside of black holes," Rees says.

Perhaps the biggest workaround will have to be in our search for a "theory of everything". The most promising candidate is string theory, which conjures what we think of as nature's fundamental forces and particles from the vibrations of tiny bundles of energy. Unfortunately, string theory only works if there are extra, unreachable dimensions of space. These dimensions are, string theorists suggest, "compactified" – rolled up too small for us to be able to interact with them.

Though we cannot access these dimensions, we already have circumstantial evidence that they exist. In 1999, for example, Lisa Randall and Raman Sundrum at Harvard University came up with an explanation for why the gravitational force is so much weaker than the other fundamental forces of nature. Their calculations looked at a five-dimensional universe and the way forces

Gravitational waves should exist, though we haven't seen them

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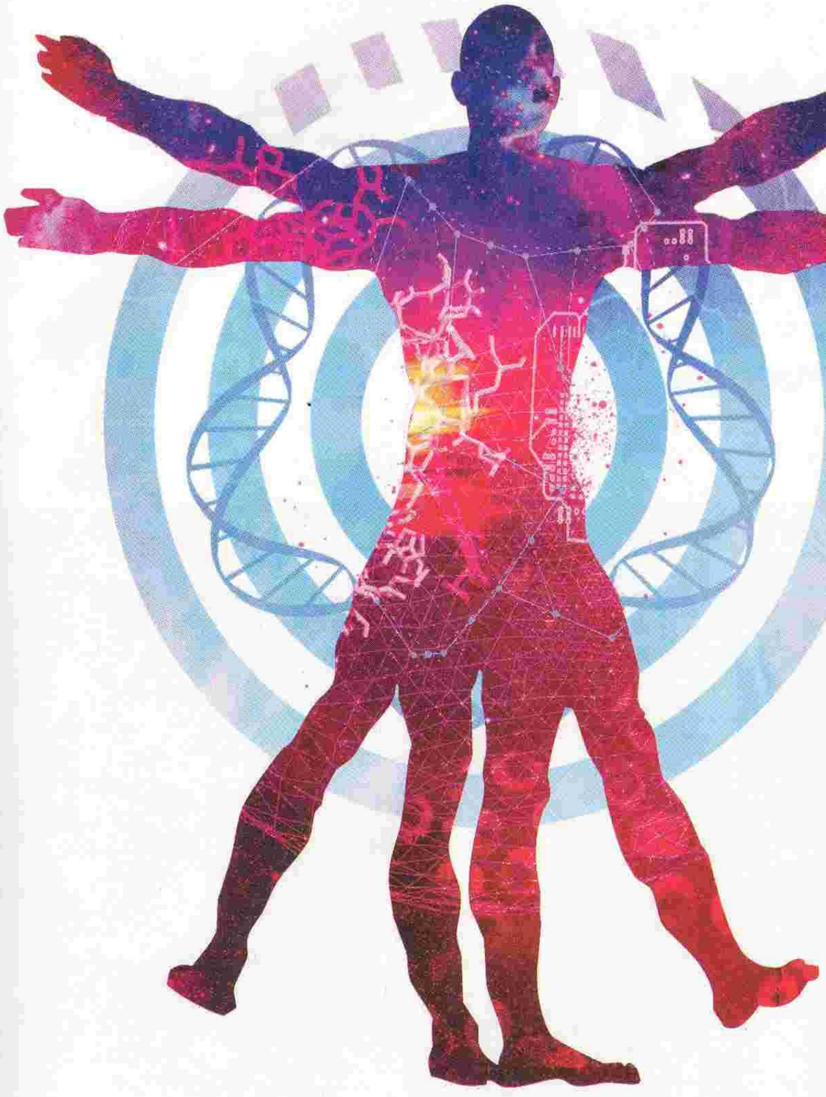

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would manifest within it. They found that while electromagnetism and the strong and weak nuclear forces exert their full strength in all dimensions, gravity is strongly bound to the hidden fifth dimension and only a small fraction of it "leaks" into the four we inhabit. Is gravity's feebleness a result of hidden extra dimensions?

> "The human brain is vastly complex. Yet we may still understand it by augmenting its capabilities"

Proof of string theory faces other, even bigger obstacles. Even with the extra dimensions in place, there remains the problem of getting to the energies at which string theory could be tested. Probing things on such small scales requires working at extremely high energies – to smash them into ever-smaller pieces takes ever more energy. That is why particle accelerators need to get more powerful to delve deeper into the nature of matter. "To test string theory you'd need a collider the size of a galaxy," Stannard says. The chances of building such a machine are slim.

Yet there is still hope. Many of the equations governing high-energy physics turn out to be the same as those that govern the behaviour of electrons and other particles whizzing about within solids. That has led to suggestions that tabletop experiments on humble crystals might yield some of the answers we seek.

There are still doubters, of course. Some have suggested that our final theory would be so complex as to be beyond human comprehension, or even beyond human capabilities for discovering it. Mathematician Roger Penrose at the University of Oxford thinks that unlikely, however. "I don't see why it should be," he says.

Marcelo Gleiser, a philosopher and physicist at Dartmouth College in New Hampshire, takes the opposite view. He has argued that the notion of a theory of everything rests on an unproven assumption that the universe is inherently neat and symmetrical. The very fact that the universe contains energy and matter is evidence against such symmetry, he says. Nothingness is neater than something, so the fact that the universe is full of stuff could mean that it is surprisingly messy at heart (*New Scientist*, 8 May 2010, p 28).

In the end, though, the consensus is that it is well worth pressing on. Thanks to the incompleteness theorem, we will never be sure any theory of everything is mathematically true, but that shouldn't bother us unduly. It didn't worry Gödel, who considered intuition more important than formal proof. Contemporary mathematicians are following suit, Chaitin says, and are throwing new, unprovable axioms into their subject all the time.

A little over 100 years ago, nobody had the slightest idea that the quantum world even existed. Now it lies at the heart of our understanding of the universe. Today's unknowns sometimes become tomorrow's great theories. A hundred years from now, who knows what we will know?

Rees remains circumspect, however. We can dream of a final theory, but we need to keep those chimps in mind, he says, even if the ultimate limits of science are not yet on our radar. "The limits won't necessarily be something we're struggling to solve now," he says. "It's not the unified theory. It's going to be a problem we are not even aware of." ■

Michael Brooks is a consultant for *New Scientist* and author of *13 Things that Don't Make Sense* (Profile, 2008) and *The Big Questions: Physics* (Quercus, 2010)