TERRY PRATCHETT

IAN STEWART & JACK COHEN

The Science of Discworld IV

JUDGEMENT DAY

IT'S WIZARDS VS PRIESTS IN A BATTLE FOR THE FUTURE OF ROUNDWORLD

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About the Book

Order in Court!
On Discworld an almighty row is brewing…

The Omnians want control of Roundworld – its very existence makes a mockery of their religion. The wizards of Unseen University, however, are extremely reluctant to part with it. After all, they created it!

Enter Roundworld librarian, Marjorie Daw (accidentally, through L-space). Perhaps, with her Jimmy Choos and her enquiring and logical mind, she can help? Especially as she's the sort of librarian who thinks that the Bible should be filed under Science Fiction and Fantasy.

Lord Vetinari presides over the tribunal. People on both sides are getting extremely angry. There are some very big questions being asked – and someone's got some explaining to do…

The fourth in the Science of Discworld series, JUDGEMENT DAY *sees Terry Pratchett, Professor Ian Stewart and Doctor Jack Cohen create a mind-mangling mix of fiction, cutting-edge science and philosophy in an attempt to answer the REALLY big questions – this time taking on God, the Universe and, frankly, Everything Else.*

Proceed with caution, you may never look at your universe(s) in the same way again.

About the Authors

Sir Terry Pratchett was the acclaimed creator of the global bestselling Discworld series; the first Discworld book, *The Colour of Magic*, was published in 1983. In all, he was the author of fifty bestselling books. His novels have been widely adapted for stage and screen, and he was the winner of multiple prizes, including the Carnegie Medal, as well as being awarded a knighthood for services to literature. Worldwide sales of his books now stand at 75 million. He died in March 2015.

Professor Ian Stewart is the author of many popular science books and appears frequently on radio and television. He is an Emeritus Professor of Mathematics at the University of Warwick. He was awarded the Michael Faraday Medal for furthering the public understanding of science, and in 2001 became a Fellow of the Royal Society.

Dr Jack Cohen is an internationally renowned reproductive biologist. He has retired to a small thatched cottage in Dorset. He writes, ponders, and plays with microscopes in a rather grand ‘garden shed’. He also throws boomerangs, but doesn’t catch them as often as he used to. In addition, he still enjoyes lecturing and continues to have a passion for the public understanding of science.

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The Science of Discworld IV

Judgement Day

Terry Pratchett
Ian Stewart & Jack Cohen

EBURY PRESS

PROLOGUE

WORLDS, DISC AND ROUND

There is a sensible way to make a world.

It should be flat, so that no one falls off accidentally[fn1] unless they get too near the edge, in which case it's their own fault.

It should be circular, so that it can revolve sedately to create the slow progression of the seasons.

It should have strong supports, so that it doesn't fall down.

The supports should rest on firm foundations.

To avoid an infinite regression, the foundations should do what foundations are supposed to do, and stay up of their own accord.

It should have a sun, to provide light. This sun should be small and not too hot, to save energy, and it should revolve around the disc to separate day from night.

The world should be populated by people, since there is no point in making it if no one is going to live there.

Everything should happen because people want it to (magic) or because the power of story (narrativium) demands it.

This sensible world is Discworld – flat, circular, held up by four world-bearing elephants standing firmly on the back of a giant space-faring turtle and inhabited by ordinary humans, wizards, witches, trolls, dwarves, vampires, golems, elves, the tooth fairy and the Hogfather.

But—

There is also a stupid way to make a world. And sometimes, that is necessary.

When an experiment in fundamental thaumaturgy on the squash court of Unseen University ran wild and threatened to destroy the universe, the computer Hex had to use up a huge quantity of magic in an instant. The only option was to activate the Roundworld Project, a magical force field that – paradoxically – keeps magic out. When the Dean of Unseen University poked his finger in to see what would happen, Roundworld switched on.

Roundworld isn't entirely sure which bit of itself its name applies to. Sometimes the name refers to the planet, sometimes to the entire universe. There have been a few mishaps along the way, but the Roundworld universe has now been running fairly successfully for thirteen and a half billion years; all of it started by an old man with a beard.

In the absence of magic, and lacking natural narrativium, the Roundworld universe runs on rules. Not rules made by people, but rules made by Roundworld itself; which is weird, because Roundworld has no idea what its rules ought to be. It seems to make them up as it goes along, but it's hard to be sure.

Certainly, it doesn't know what size it ought to be. From outside, as it gathers dust on a shelf in Rincewind's office, the Roundworld universe – a globe about 20 centimetres in diameter – resembles a cross between a foot-the-ball and a child's snowstorm toy. From inside, it appears to be somewhat larger: a sphere whose radius is about 400 sextillion kilometres. As far as its only known[fn2] inhabitants can tell, it may be much larger still; perhaps even infinite.

Such a huge universe seems to be cosmic overkill, because those inhabitants occupy only the tiniest part of its awe-inspiring volume, namely the surface of an approximate sphere a mere twelve thousand kilometres across.

The wizards call this sphere Roundworld too. Its inhabitants call it Earth, because that's what the surface is usually made of (except for the wet, rocky, sandy and icy bits): a typically parochial attitude. Until a few centuries ago they thought that Earth was fixed at the centre of the universe; the rest, which revolved around it or wandered crazily across the sky, was of minor importance since it didn't contain *them*.

Roundworld the planet, as the name suggests, is *round*. Not round like a disc, but round like a foot-the-ball. It is younger than Roundworld the universe: about one third of its age. Though cosmically minuscule, the planet is fairly big compared to its inhabitants, so that if you live there, and you're stupid, you can be fooled into imagining that it's flat.

To prevent the planet's inhabitants falling off, the rules state that a mysterious force glues them on. Thankfully, there are no world-bearing elephants. If there were, the inhabitants would be able to walk *round* their world to the point where it meets an elephant. This world-bearing beast of immense power would appear to be *lying on its back*, its feet in the air. (Paint the soles yellow and you wouldn't be able to see it floating in a bowl of custard …)

Roundworld's rules are democratic. Not only does this mysterious force glue people to their world: it glues everything to everything else. But the glue is weak, and everything can – and usually does – move.

This includes Roundworld the planet. It does have a sun, but this sun does not go round the planet. Instead, *the planet goes round the sun*. Worse, that doesn't create day and night; instead, it produces seasons, because the planet is tilted. Also, the orbit isn't circular. It's a bit squashed, which is typical of Roundworld's jerry-built construction. So to get day and night, the planet has to spin as well. It works, in its way: if you're really stupid, you can be fooled into imagining that the sun goes round the planet. But – wouldn't you just know it – the spin also prevented Roundworld from being a sensible sphere, because when it was molten it got sort of squashed, just like its orbit … oh, forget it.

As a consequence of this hopelessly bungled arrangement, the sun has to be enormous, and a very long distance away. So it has to be ridiculously hot: so hot that special new rules have to come into play to allow it to burn. And then almost all of its prodigious energy output is wasted, trying to warm up empty space.

Roundworld has no supports. It appears to think it's a turtle, because it swims through space, tugged along by those mysterious forces. Its human inhabitants are not bothered by a sphere that swims, despite the absence of flippers. But then, people turned up at most four hundred thousand years ago, one hundredth of a per cent of the lifetime of the planet. And they seem to have turned up by accident, starting out as little blobs and then spontaneously becoming more complex – but they argue a lot about that. They're not terribly bright, to be honest, and they only started to work out modern scientific rules of the universe they live in four hundred years ago, so they've got a lot of catching up to do.

The inhabitants refer to themselves optimistically as *Homo sapiens*, meaning 'wise man' in an appropriately dead language. Their activities seldom fit that description, but there are occasional glorious exceptions. They should really be called *Pan narrans*, the storytelling ape, because nothing appeals to them more than a rollicking good yarn. They are narrativium incarnate, and they are currently refashioning their world to resemble Discworld, so that things *do* happen because people want them to. They have invented their own form of magic, with spells like ‘make a dugout canoe’, ‘switch on the light’, and ‘login to Twitter’. This kind of magic cheats by using the rules behind the scenes, but if you’re really, really stupid you can ignore that and pretend it’s magic.

The first *The Science of Discworld* explained all that, and much more, including the giant limpet and the ill-fated crab civilisation’s great leap sideways. An endless series of natural disasters established something that the wizards intuitively knew from the word go: a round world is not a safe place to be. Fast-forwarding through Roundworld history, they managed to skip from some not very promising apes huddled around a black monolith to the collapse of the space elevators, as some presumably highly intelligent creatures, having finally got the message, fled the planet and headed for the stars to escape yet another ice age.

They couldn’t really be descended from those apes, could they? The apes seemed to have only two interests: sex, and bashing each other over the head.

In *The Science of Discworld II*, the wizards were surprised to find that the intelligent star-farers were indeed descended from the apes – a strange new use of the word ‘descend’, and one that caused serious trouble later. They found that out because Roundworld had taken the wrong leg of the Trousers of Time and had therefore deviated from its original timeline. Its ape-derived humans had become barbarians, their society vicious and riddled with superstition. They would never leave the planet in time to escape their doom. Something had interfered with Roundworld’s history.

Feeling somehow responsible for the planet’s fate, much as one might worry about a sick gerbil, the wizards entered their bizarre creation, to find that it was infested by elves. Discworld’s elves are not the noble creatures of some

Roundworld myths. If an elf told you to eat your own head, you'd do it. But going back in time to when the elves had arrived, and kicking them out, just made everything worse. The evil had gone, but it had taken with it any shred of innovation.

Examining Roundworld's history on what ought to have been its correct timeline, the wizards deduced that two key people – prominent among those very few wise ones – had never been born. This omission had to be repaired to get the planet back on track. They were William Shakespeare, whose artistic creations would give birth to a genuine spirit of humanity, and Isaac Newton, who would provide science. With considerable difficulty, and some interesting failures along the way requiring ceilings to be painted black, the wizards nudged humanity back onto the only timeline that would save it from annihilation. Shakespeare's *A Midsummer Night's Dream* tipped the tables decisively by exposing the elves to ridicule. Newton's *Principia Mathematica* completed the job by pointing humanity at the stars. Job done.

It couldn't last.

By the time of *The Science of Discworld III*, Roundworld was in trouble again. Having safely entered its Victorian era, which should have been a hotbed of innovation, it had once more departed from its proper history. New technology was developing, but at a snail's pace. Some vital spur to innovation had been lost, and the gerbil of humanity was sick once more. This time, a key figure had written the wrong book. The Reverend Charles Darwin's *Theology of Species*, explaining the complexity of life through divine intervention, had been so well received that science and religious belief had converged. The creative spark of rational debate[fn3] had been lost. By the time the Reverend Richard Dawkins finally wrote *The Origin of Species (by Means of Natural Selection &c &c &c* …) it was too late to develop space travel before the ice came down.

This time, getting Darwin born was not the problem. Getting him to write the correct book … that was where everything went pear-shaped, and it proved remarkably hard to nudge history back on track. Contrary to the proverb, supplying a missing nail from a horse's shoe does not save a kingdom. It generally has no effect, aside from making the horse feel a bit more comfortable, because hardly anything important has a single cause. It took a huge squad of wizards, making over two thousand carefully choreographed changes, to get Darwin onto the *Beagle*, stop him jumping ship when he was being as sick as a dog, and perk his interest in geology so that he stayed with the expedition[fn4] until it got to the Galápagos Islands.

They wouldn't have succeeded at all, but the wizards eventually realised that something was actively interfering with their efforts to reset history to manufacturer's specifications. The Auditors of Reality are the ultimate Health and Safety officers: they much prefer a universe in which nothing interesting ever happens, and they are willing to go to extreme lengths to ensure that it doesn't. They had been blocking the wizards' every move.

It was a near thing. Even when the wizards successfully arranged for Darwin to visit the Galápagos and notice the finches and mockingbirds and turtles, it took years for him to understand the significance of those creatures – by which time all the turtle shells were long gone, tossed overboard after their contents were eaten, and he'd given away the finches to a bird expert. (He *had* realised that the mockingbirds were interesting.) It took even longer to get him to take the plunge and write *The Origin* instead of *The Ology*; he kept writing scholarly books about barnacles instead. Then, when he had finally managed to write *The Origin*, he still messed up with *Origin II*, calling it *The Descent of Man* – oh dear. *The Ascent of Man* would have been a better marketing ploy.

Anyway, the wizards finally achieved success, even contriving to bring Darwin into Discworld to meet the God of Evolution and admire the wheels on his elephant. The publication of *The Origin* established the corresponding timeline as the only one that had ever happened. (The Trousers of Time are like that.) Roundworld was saved *again*, and could rest undisturbed on its shelf, gathering dust …

Until—

fn1 Falling off deliberately is another matter, about which they can be as imaginative as they wish. See *The Light Fantastic*, *The Colour of Magic* and *The Last Hero*.

fn2 This may be misleading since it is the opinion of the inhabitants concerned.

fn3 That is, insults, name-calling and shameless point-scoring.

fn4 Loosely speaking. He remained on land whenever feasible, about 70% of the entire ‘voyage’.

ONE

GREAT BIG THING

Every university must have, sooner or later, a big or, more preferably, a *Great Big Thing*. According to Ponder Stibbons, head of Inadvisably Applied Magic at Unseen University, it was, he said, practically a law of nature; and it couldn’t be too big, and it had to be a thing, and definitely not a small one.

The senior wizards, eyeing the chocolate biscuits on the tray brought in by the tea lady, listened with as much attention as could be expected from wizards momentarily afflicted with chocolate starvation. Ponder’s carefully written and argued speech pointed out that studious research throughout Library-space, or L-space as it is colloquially known, revealed that not to have a Great Big Thing would be a pitiful thing; and the lack of such a thing, indeed, in the academic universe, would make the university they were sitting in right now the butt of jokes and sardonic jibes by people who would be ashamed to be called their fellow academics – said jibes being all the more painful because academics know what *sardonic* actually means.

And when Mister Stibbons finished his last well-tuned argument, Mustrum Ridcully, the Archchancellor, put his hand heavily on the last disputed chocolate biscuit and said, ‘Well now, Ponder, if I know you, and I most certainly *do* know you, then you never put in front of me a problem without having a proposed solution somewhere up your sleeve.’ Ridcully’s eyes narrowed a little as he continued, ‘Indeed, Mister Stibbons, it would be very unlike you not already to have a Great Big Candidate. Am I not right?’

Ponder didn’t bother to blush, but simply said, ‘Well, sir, I do know that we in the HEM[fn1] do think that there are many puzzles presented to us by the universe that we really need to solve. As they say, sir: what you don’t know can kill you! Ha-ha.’

Ponder was pleased with coming up with that remark; he knew his Archchancellor – who had the instincts of a fighter, and a bare-knuckle fighter at that – and so he moved in with, ‘I’m thinking of the fact that we simply don’t know why there is a third slood derivative, which in theory means that at the birth of the universe, in that very first nanosecond, the universe actually began to travel backwards in time. According to Von Flamer’s experiment, that means that we appear to be coming and going at the same time! Ha-ha!’

‘Yes, well, I can quite believe that,’ said Ridcully glumly, looking at his fellows; and because he was the Archchancellor, after all, he added, ‘Wasn’t there something about a cat that was alive and dead at the same time?’

Ponder was always ready for this sort of thing and he said, ‘Yes, sir, but it was only a hypothetical cat, sir, as it turned out – nothing to get pet-owners all upset about – and may I add that the elastic string theory turned out to be just one more unproven hypothesis, as did the bubble theory of interconnecting horizons.’

‘Really.’ Ridcully sighed. ‘What a shame. I rather liked that one. Oh well, I trust that in its short life it gave some theoretical scientists a living, and so happily its little life wasn’t wasted. You know, Mister Stibbons, over the years you have often discoursed with me about the various theories, hypotheses, concepts and conjectures in the world of natural science. You know what? I just wonder, I really do wonder, whether the universe – being of course by its very nature, dynamic, and possibly in some curious sense *sapient* – may now perhaps be trying to escape from your incessant prying, and is possibly driving you into even greater feats of intellect. The little tease!’

There was a pause from the assembled wizards, and for a moment the face of Ponder Stibbons appeared to be made of polished bronze; then he said, ‘What an amazing deduction, Archchancellor. I applaud you! Everybody knows that Unseen University will rise to meet *any* challenge; with your permission, sir, I will set to work on a budget right now. The Roundworld project was only a beginning. Now, with the … Challenger Project, we will explore the fundamental basis of magic in our world!’

He ran to the High Energy Magic building so fast that his progress metamorphosed into a hurtle, which in ballistic terms is exactly the opposite of a turtle and *extremely* more streamlined.

And *that* was six years ago …

Today, Lord Vetinari, tyrant of Ankh-Morpork, glanced up at the Great Big Thing which appeared to be doing nothing but humming to itself. It hovered in the air, appearing and disappearing, and in Vetinari’s opinion looking somewhat smug, a feat indeed for something that had no face.

It was, in fact, a rather amorphous blob that seemed to twist magical equations with arcane symbols and squiggles that clearly meant *something* to those who knew about such things. The Patrician was not, on his own admission, a lover of technical things that spun and, indeed, hummed. Nor of unidentifiable squiggles. He saw them as things with which you couldn't negotiate, or argue; you couldn't hang them either, or even creatively torture them. Of course, the dictum *noblesse oblige* came to the rescue as always – although those who knew Havelock Vetinari well knew that he sometimes wasn't all that obliging.

On this occasion Lord Vetinari was being introduced to excitable and occasionally spotty young wizards in white robes – though still of course in pointy hats – who made a great fuss about large conglomerations of mindless and humming machinery behind the blob. Nevertheless, he did his best to look enthusiastic, and managed to drum up some conversation with Mustrum Ridcully, the Arch-chancellor, who it seemed was just as much in the dark as himself; and he congratulated Ridcully because it was clearly the thing to do, whatever the thing *did*.

'I'm sure you must be very proud, Archchancellor. It's extremely good, clearly a triumph, most certainly!'

Ridcully chuckled and said, 'Bravo! Thank you *so* much, Havelock, and do you know what? *Some* people said that if we turned the experiment on it would bring the world to an end! Can you imagine that? Us! The psychic protectors of the city, and indeed of the world throughout history!'

Lord Vetinari took an almost imperceptible step back and carefully enquired, 'And precisely when was it that you *did* turn it on, may I ask? It seems to be humming along quite adequately at the moment.'

'As a matter of fact, Havelock, the humming is going to end very shortly. The noise you are hearing is coming from a swarm of bees in the garden over there, and the Bursar hasn't had enough time to instruct them to get back to work. In fact, we were hoping that you would do the honours after lunch, if it is all right by you, of course?'

The expression on the face of Lord Havelock Vetinari was, for a moment, a picture: and it was a picture painted by a *very* modern artist, one who had been smoking something generally considered to turn the brain to cheese.

But *noblesse oblige* was a crushing imperative even for a tyrant, especially one who valued his self-esteem, and therefore, two hours later, a well-fed Lord Vetinari stood in front of the huge humming thing, feeling rather concerned. He made a small oration on the need for mankind to further its knowledge of the universe.

'While it is still there,' he added, looking very pointedly at Ridcully.

Then, after posing for the iconographer's lenses, he looked at the big red button on its stand in front of him and thought, I wonder if there *is* any truth in the rumours that this could end the world? Well, it's too late now to protest, and it would be quite remiss for me to draw back at this point. He brightened up and thought, If indeed it's me who blows up the known world, then it might just be good for my image anyway.

He pressed the button to the kind of applause people make when they understand that something important has happened while at the same time having no idea what they are really cheering. After checking, Vetinari turned to the Archchancellor and said, 'It would seem, Mustrum, that I have not destroyed the universe, which is something of a comfort. Is anything else supposed to happen?'

The Archchancellor slapped him on the back and said, 'Don't fret, Havelock: the Challenger Project was started up yesterday evening by Mister Stibbons over a cup of tea, just to make certain that it would start; and seeing that it was warmed up, he left it on. This of course in no way demeans *your* part in the ceremony, I promise you. The formality of the *significant* opening is at the heart of the whole business, which I am proud to say has all gone swimmingly!'

And *that* was six minutes ago …

fn1 High Energy Magic department.

TWO

GREAT BIG THINKING

Great Big Things have a seductive allure, to which Roundworld’s scientists are by no means immune. Most science requires relatively modest equipment, some is inherently expensive, and some would finance a small nation. Governments worldwide are addicted to big science, and often find it easier to authorise a ten-billion dollar project than one costing ten thousand – much as a committee will agree to a new building in five minutes, but then spend an hour debating the cost of biscuits. We all know why: it takes an expert to evaluate the design and price of a building, but everyone understands biscuits. The funding of big science is sometimes depressingly similar. Moreover, for administrators and politicians seeking to enhance their careers, big science is more prestigious than small science, because it involves more money.

However, there can also be a more admirable motive for huge scientific projects: big problems sometimes require big answers. Putting together a faster-than-light drive on the kitchen table using old baked bean cans may work in a science fiction story, but it’s seldom a realistic way to proceed. Sometimes you get what you pay for.

Big science can be traced back to the Manhattan project in World War II, which developed the atomic bomb. This was an extraordinarily complex task, involving tens of thousands of people with a variety of skills. It stretched the boundaries of science, engineering and, above all, organisation and logistics. We don’t want to suggest that finding really effective ways to blow people to smithereens is necessarily a sensible criterion for success, but the Manhattan project convinced a lot of people that big science can have a huge impact on the entire planet. Governments have promoted big science ever since; the Apollo Moon landings and the human genome project are familiar examples.

Some areas of science are unable to function at all without Great Big Things. Perhaps the most prominent is particle physics, which has given the world a series of gigantic machines, called particle accelerators, which probe the small-scale structure of matter. The most powerful of these are colliders, which smash subatomic particles into stationary targets, or into each other in head-on collisions, to see what gets spat out. As particle physics progresses, the new particles that theorists are predicting become more exotic and harder to detect. It takes a more energetic collision to spit them out, and more mathematical detective work and more powerful computers to compile evidence that they were, for an almost infinitesimal moment of time, actually present. So each new accelerator has to be bigger, hence more expensive, than its predecessors.

The latest and greatest is the Large Hadron Collider (LHC). ‘Collider’ we know about, ‘hadron’ is the name of a class of subatomic particles, and ‘large’ is fully justified. The LHC is housed in two circular tunnels, deep underground; they are mostly in Switzerland but wander across the border into France as well. The main tunnel is eight kilometres across, and the other one is about half as big. The tunnels contain two tubes, along which the particles of interest – electrons, protons, positrons and so on – are propelled at speeds close to that of light by 1,624 magnets. The magnets have to be kept at a temperature close to absolute zero, which requires 96 tonnes of liquid helium; they are absolutely enormous, and most weigh over 27 tonnes.

The tubes cross at four locations, where the particles can be smashed into each other. This is the time-honoured way for physicists to probe the structure of matter, because the collisions generate a swarm of other particles, the bits and pieces out of which the original particles are made. Six enormously complex detectors, located at various points along the tunnels, collect data on this swarm, and powerful computers analyse the data to work out what's going on.

The LHC cost €7.5 billion – about £6 billion or $9 billion – to build. Not surprisingly, it is a multinational project, so big politics gets in on the act as well.

Ponder Stibbons has two reasons for wanting a Great Big Thing. One is the spirit of intellectual enquiry, the mental fuel on which the High Energy Magic building runs. The bright young wizards who inhabit that building want to discover the fundamental basis of magic, a quest that has led them to such esoteric theories as quantum thaumodynamics and the third slood derivative, as well as the fateful experiment in splitting the thaum that inadvertently brought Roundworld into existence in the first place. The second reason opened the previous chapter: every university that wants to be *considered* a university has to have its very own Great Big Thing.

It is much the same in Roundworld – and not only for universities.

Particle physics began with small equipment and a big idea. The word 'atom' means 'indivisible', a choice of terminology that was a hostage to fortune from the day it was minted.

Once physicists had swallowed the proposition that atoms exist, which they did just over a century ago, a few began to wonder if it might be a mistake to take the name literally. In 1897 Joseph John Thomson showed that they had a point when he discovered cathode rays, tiny particles emanating from atoms. These particles were named electrons.

You can hang around waiting for atoms to emit new particles, you can encourage them to do so, or you can make them an offer they can't refuse by bashing them into things to see what breaks off and where it goes. In 1932 John Cockroft and Ernest Walton built a small particle accelerator and memorably 'split the atom'. It soon emerged that atoms are made from three types of particle: electrons, protons and neutrons. These particles are extremely small, and even the most powerful microscopes yet invented cannot make them visible – though atoms can now be 'seen' using very sensitive microscopes that exploit quantum effects.

All of the elements – hydrogen, helium, carbon, sulphur and so on – are made from these three particles. Their chemical properties differ because their atoms contain different numbers of particles. There are some basic rules. In particular, the particles have electrical charges: negative for the electron, positive for the proton, and zero for the neutron. So the number of protons should be the same as the number of electrons, to make the total charge zero. A hydrogen atom is the simplest possible, with one electron and one proton; helium has two electrons, two protons and two neutrons.

The main chemical properties of an atom depend on the number of electrons, so you can throw in different numbers of neutrons without changing the chemistry dramatically. However, it does change a bit. This explains the existence of isotopes: variants of a given element with subtly different chemistry. An atom of the commonest form of carbon, for instance, has six electrons, six protons and six neutrons.

There are other isotopes, which have between two and sixteen neutrons. Carbon-14, used by archaeologists to date ancient organic materials, has eight neutrons. An atom of the commonest form of sulphur has sixteen electrons, sixteen protons and sixteen neutrons; 25 isotopes are known.

Electrons are especially important for the atom's chemical properties because they are on the outside, where they can make contact with other atoms to form molecules. The protons and neutrons are clustered closely together at the centre of the atom, forming its nucleus. In an early theory, electrons were thought to orbit the nucleus like planets going round the Sun. Then this image was replaced by one in which an electron is a fuzzy probability cloud, which tells us not where the particle *is*, but where it is *likely* to be found if you try to observe it. Today, even that image is seen as an oversimplification of some pretty advanced mathematics in which the electron is nowhere and everywhere at the same time.

Those three particles – electrons, protons and neutrons – unified the whole of physics and chemistry. They explained the entire list of chemical elements from hydrogen up to californium, the most complex naturally occurring element, and indeed various short-lived man-made elements of even greater complexity. To get matter in all its glorious variety, all you needed was a short list of particles, which were 'fundamental' in the sense that they couldn't be split into even smaller particles. It was simple and straightforward.

Of course, it didn't *stay* simple. First, quantum mechanics had to be introduced to explain a vast range of experimental observations about matter on its smallest scales. Then several other equally fundamental particles turned up, such as the photon – a particle of light – and the neutrino – an electrically neutral particle that interacts so rarely with everything else that it would be able to pass though thousands of miles of solid lead without difficulty.

Every night, countless neutrinos generated by nuclear reactions in the Sun pass right through the solid Earth, and through you, and hardly any of them have any effect on anything.

Neutrinos and photons were only the beginning. Within a few years there were more fundamental particles than chemical elements, which was a bit worrying because the explanation was becoming more complicated than the things it was trying to explain. But eventually physicists worked out that some particles are more fundamental than others. A proton, for example, is made from three smaller particles called quarks. The same goes for the neutron, but the combination is different. Electrons, neutrinos and photons, however, remain fundamental; as far as we know, they're not made out of anything simpler.[fn1]

One of the main reasons for constructing the LHC was to investigate the final missing ingredient of the standard model, which despite its modest name seems to explain almost everything in particle physics. This model maintains, with strong supporting evidence, that *all* particles are made from sixteen truly fundamental ones. Six are called quarks, and they come in pairs with quirky names: up/down, charmed/strange, and top/bottom. A neutron is one up quark plus two down quarks; a proton is one down quark plus two up quarks.

Next come six so-called leptons, also in pairs: the electron, muon, and tauon (usually just called tau) and their associated neutrinos. The original neutrino is now called the electron neutrino, and it is paired with the electron. These twelve particles – quarks and leptons – are collectively called fermions, after the great Italian-born American physicist Enrico Fermi.

The remaining four particles are associated with forces, so they hold everything else together. Physicists recognise four basic forces of nature: gravity, electromagnetism, the strong nuclear force and the weak nuclear force. Gravity plays no role in the standard model because it hasn't yet been fitted into a quantum-mechanical picture. The other three forces are associated with specific particles known as bosons in honour of the Indian physicist Satyendra Nath Bose. The distinction between fermions and bosons is important: they have different statistical properties.

The four bosons 'mediate' the forces, much as two tennis players are held together by their mutual attention to the ball. The electromagnetic force is mediated by the photon, the weak nuclear force is mediated by the Z-boson and the W-boson, and the strong nuclear force is mediated by the gluon. So that's the standard model: twelve fermions (six quarks, six leptons) held together by four bosons.

Sixteen fundamental particles.

Oh, and the Higgs boson – *seventeen* fundamental particles.

Assuming, of course, that the fabled Higgs (as it is colloquially called) actually existed. Which, until 2012, was moot.

Despite its successes, the standard model fails to explain why most particles have masses (for one particular technical meaning of 'mass'). The Higgs came to prominence in the 1960s, when several physicists realised that a boson with unusual features might solve one important aspect of this riddle. Among them was Peter Higgs, who worked out some of the hypothetical particle's properties and predicted that it should exist. The Higgs boson creates a Higgs field: a sea of Higgs bosons. The main unusual feature is that the strength of the Higgs field is not zero, even in empty space. When a particle moves through this all-pervasive Higgs field it interacts with it, and the effect can be interpreted as mass. One analogy is moving a spoon through treacle, but that misrepresents mass as resistance, and Higgs is critical of that way of describing his