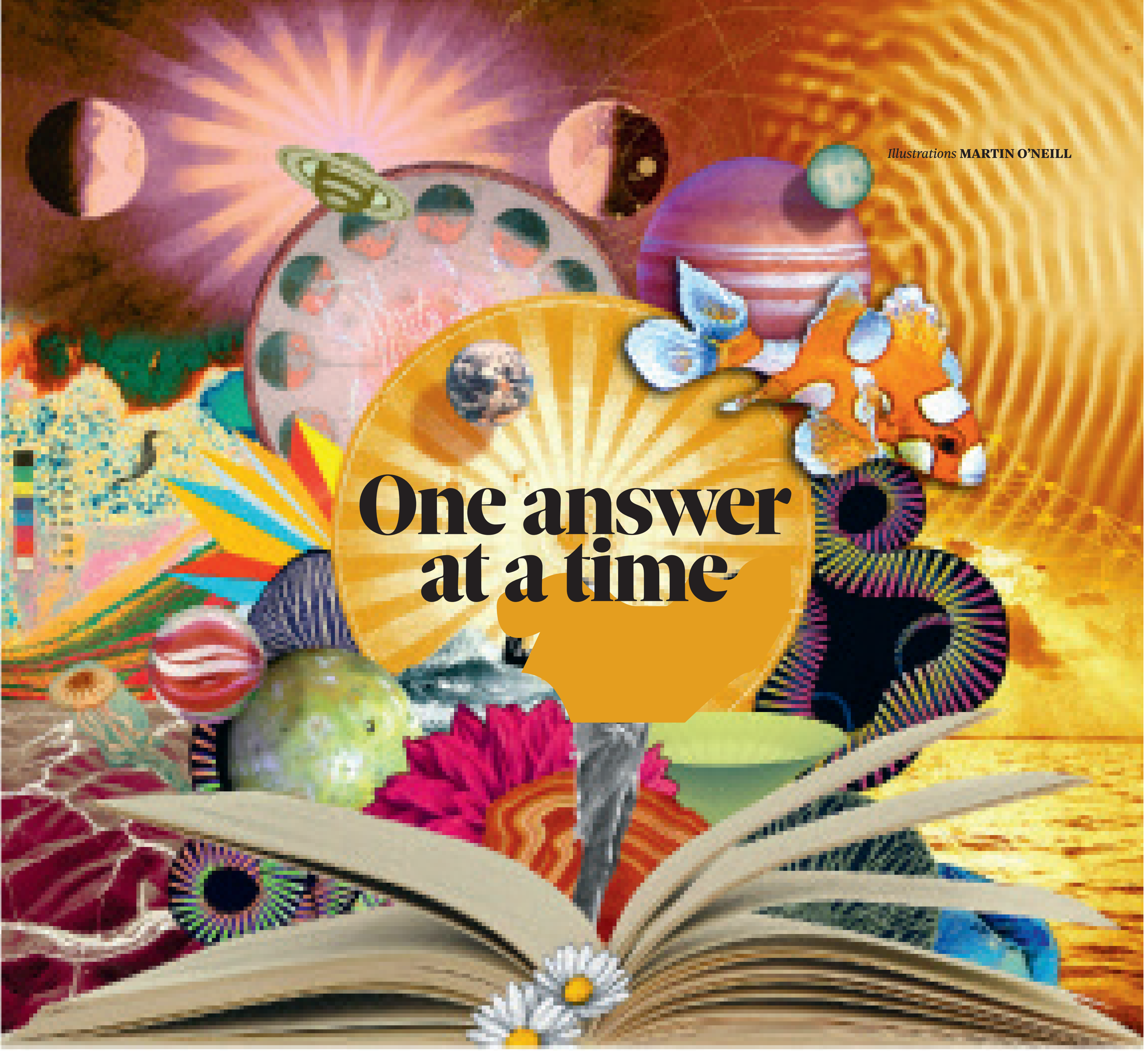

Illustrations **MARTIN O'NEILL**

One answer at a time

Baffled by black holes? Exasperated by evolution? Confused by quantum theory? Science writer Marcus Chown breaks down the mysteries of the universe into manageable chunks you can get your head around

Evolution

Why are race horses so suited to running fast? Because horse breeders selected the fastest horses from a population and bred them together. And repeated the process. Over and over. Why are living things so suited to surviving in their environment? Charles Darwin's genius was to realise the answer is similar. Just as humans artificially select horses for speed, something naturally selects wild creatures for compatibility with their environment.

The "something" is deceptively simple. Creatures produce far too many offspring to be supported by the available food. Only those with the traits required to outcompete others for food will survive to reproduce and pass on those traits to the next generation. This straightforward idea came to Charles Darwin after his five-year stint as ship's naturalist on board HMS Beagle. "How extremely stupid not to have thought of that," said Thomas Huxley, Darwin's friend and champion, when he heard the idea.

Darwin's courage was in proposing his theory knowing it was missing two key ingredients. The first was the mechanism of variation. What creates the array of new traits from which natural selection then selects? The second was the mechanism of inheritance.

Now, we know that both missing ingredients are related. The building block of all life – the atom of biology – is the cell, a tiny bag of gloop packed with molecular machines. At the heart of each cell is a mini cell or nucleus, containing chromosomes made of a giant molecule called deoxyribonucleic acid, or DNA. The traits we inherit from our parents are associated with stretches of the DNA known as genes. And, for those traits to be inherited, their DNA must be copied. In the case of human DNA, this requires the faithful duplication of 3bn letters of the genetic code. Inevitably, mistakes occur. A letter may be incorrectly copied. Or mutations, changes in genes, can also be caused by ultraviolet light, viruses, cancer-causing chemicals and nuclear radiation. Together, these provide the array of new traits from which evolution by natural selection does its selecting.

Special relativity

Light is a wave like a ripple on a pond, a fact which is not obvious because the ripples are far smaller than the width of a human hair. At 16, Albert Einstein wondered what it would be like to ride alongside such a light wave. He realised it would appear not to be moving, just as a car travelling at 70mph would appear stationary if you drove alongside it at 70mph. But – this is the point – the Scots physicist James Clerk Maxwell's theory of light said there was no such thing as a stationary light wave. Einstein, therefore, concluded that if catching a light wave would allow you to see something impossible, it too must be impossible. Light is uncatchable. In our universe, it plays the role of infinite speed, a speed that can never be reached.

Something travelling infinitely fast seems infinitely fast no matter how rapidly you are travelling because, compared with infinite speed, any other speed is so negligible it might as well be zero. Since light plays the role of infinite speed, everyone must, therefore, measure the same speed for a light beam. Now, speed is defined as the distance something travels in a given time – the car just mentioned, for instance, was travelling 70 miles in an hour. So, if everyone is to measure the same speed for light, no matter how fast they are moving, something odd must happen to their measurements of distance and time. There must be some huge cosmic conspiracy.

The conspiracy is noticeable only at speeds approaching that of light's 300,000 kilometres a second, which is why we never notice it in daily life and it took the genius of Einstein to recognise it. But if someone were to fly past you at close to the speed of light, you would see their time slow so that they appeared to be wading through treacle and their space compress in the direction of their motion so they appeared flat as a pancake. "Moving clocks run slow," goes the mantra, and "moving rulers shrink". This, in a nutshell, is Einstein's special theory of relativity.

Global warming

Several kinds of molecules floating in the Earth's atmosphere have the property of trapping heat given off from the surface. Between them, the molecules keep the planet from freezing solid and make life possible. In fact, without the most important of all the heat-trapping molecules – water vapour – the planet would be a giant ball of ice with an average temperature of only -18C.

The fact that the air warms in the presence of sunlight was discovered in 1856 by the little-known American scientist Eunice Foote. She inserted thermometers into long glass tubes that she filled with gases such as oxygen and hydrogen. When she exposed the tubes to sunlight she discovered that, of all the gases, water vapour and carbon dioxide warmed the most. If the amount of these two gases in the atmosphere varied, she speculated, it might change the climate, making her the first person in history to make this connection.

Unaware of Foote's work, the Irish physicist John Tyndall confirmed her discovery three years later. Tyndall determined that water vapour and carbon dioxide are not heated directly by visible light from the Sun but by heat in the form of invisible infrared light, radiated by the surface of the Earth after it has been heated by the Sun. "The atmosphere admits the entrance of the solar heat, but checks its exit and the result is a tendency to accumulate heat at the surface of the planet," wrote Tyndall. This is the famous "greenhouse effect".

In general, infrared light is absorbed by simple molecules made of two or more atoms because the energy of such light is just right to set the molecules vibrating. Naively, you can think of the atoms inside a molecule such as water (H_20) or carbon dioxide (CO^2) as connected by springs that can alternately compress and expand. The most abundant molecules in the atmosphere are nitrogen (N^2), which accounts for 78.08% of air, and oxygen (O^2), which makes up 21.95%. If they acted as greenhouse gases, however, the Earth would be as hot as an oven. Fortunately, they lack a crucial property known as a dipole moment, and so do not absorb infrared light.

Foote and Tyndall's discovery was surprising because it showed that molecules with concentrations as tiny as carbon dioxide, which makes up a mere 0.04% of the atmosphere, have a huge effect. Although both scientists suspected a link between carbon dioxide and climate, it was the Swedish chemist Svante Arrhenius who in 1896 suggested that, at the end of ice ages, an increase in carbon dioxide had helped warm the Earth. He also demonstrated that burning fossil fuels, such as coal and oil, could create large enough quantities of carbon dioxide and a "hot-house effect", a phrase that did not catch on, but which today we would recognise as the greenhouse effect. Arrhenius was the first to show that human activity could change the climate.

Quantum theory

At the start of the 20th century, a myriad of baffling experiments had revealed that light waves could behave as particles – a stream of tiny, bullet-like photons – and even more unbelievably that particles, such as the electrons in atoms, could behave as waves, like ripples on a pond. Quantum theory – our best description of the submicroscopic world of atoms and their constituents – merely spells out the consequence of this strange dual nature of the world's fundamental constituents.

Consider the consequence of waves behaving as particles. Look out of a window. You will see the scene outside, but also a faint reflection of your face. This is because glass is not perfectly transparent. Most of the light passes right through while a small portion is reflected back, showing your face. But how is this possible if light is a stream of photons? Since they are identical, either 100% should be transmitted or 100% reflected. The only way physicists could make any sense of this was to accept that an individual photon has a certain chance of being transmitted and a certain chance of being reflected. In other words, they had to give up on the idea of ever knowing for certain what a single photon will do.

And it is not just photons that are fundamentally unpredictable. So, too, are all the denizens of the submicroscopic world, from electrons to atoms. Ultimately, the universe is founded on random chance – arguably the most shocking discovery in the history of science. But, of course, the world *is* predictable. This is because what nature takes with one hand, it grudgingly gives back with the other. The universe may be fundamentally unpredictable. But its unpredictability is predictable. And this is what quantum theory is: a recipe for predicting unpredictability.

Black holes

These were predicted by a man dying of a skin disease in a First World War field hospital. Karl Schwarzschild's prediction used Einstein's recently presented theory of gravity, but Einstein never believed in black holes. And, for much of the 20th century, physicists believed they were too ridiculous to exist. Or, if they did exist, they would be so small and so black against the black of space as to be impossible to spot. What nobody realised was that black holes would be blindingly bright.

What changed everything was the discovery by British astronomers Paul Murdin and Louise Webster of a black hole in the star system Cygnus X-1 in 1971. Matter ripped from a companion star by the gravity of the black hole swirled down through an "accretion disk" like water down a plug hole, heating up to millions of degrees and shining brilliantly as it did so. Actually, black holes had been spotted years earlier, but had not been recognised. In 1963, Dutch astronomer Maarten Schmidt discovered quasars, beacons at the edge of the universe pumping out 100 times the energy of a normal galaxy. Eventually, it was realised their prodigious luminosities derived from superheated matter swirling down though an accretion disk on to a black hole. But not a stellar-mass black hole as in Cygnus X-1 but a "supermassive" black hole, weighing tens of millions or even tens of billions of times the mass of the Sun.

Cygnus X-1 represents the endpoint of the life of a massive star. When it runs out of fuel, it can no longer generate the heat to push against the gravity trying to crush the star. The star shrinks catastrophically, its gravity increasing until it is so strong that light can no longer escape and it winks out of existence as a black hole. As for supermassive black holes, we do not know how they form or why there is one in the centre of every galaxy. There is even a 4.3m solar mass "tiddler" in the heart of our Milky Way.

At first no one realised that black holes would be blindingly bright

The Big Bang

The greatest discovery in the history of science is that there was a day without a yesterday. The universe has not existed forever, but was born. About 13.82bn years ago all matter, energy, space – and even time – erupted into being in a fireball called the Big Bang. The fireball expanded and, out of the cooling debris, there congealed the galaxies – about 2tn of them – of which our Milky Way is one.

The evidence for the Big Bang is all around. Take the light from the fireball. It was bottled up in the universe and the universe, by definition, is all there is. So it had nowhere to go. Greatly cooled by the expansion of the universe over the past 13.82bn years, this afterglow of the big bang appears today not as visible light but as microwaves. In fact, if you could see the universe with eyes sensitive to microwaves, you would see the whole of space glowing white. Amazingly, 99.9% of the photons in the universe are tied up in this relic of the Big Bang and only 0.1% come from the stars and galaxies.

Although the basic Big Bang idea that the universe started hot and dense and has expanded and cooled ever since is beyond doubt, other things have to be bolted on to make the theory work. These include dark matter, mysterious invisible stuff that outweighs the visible stars and galaxies by a factor of six, and dark energy, yet more mysterious invisible stuff with repulsive gravity that accounts for two thirds of the mass of the universe. And fundamental questions – such as what was the Big Bang? What drove it? And what happened before? – remain to be answered. ■

The One Thing You Need To Know by Marcus Chown is published by Michael O'Mara at £16.99. Buy it from guardianbookshop.com for £14.95