THE NEVER-ENDING DAYS OF BEING DEAD

Dispatches from the Front Line of science

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Preface

Ultimate Questions, Ultimate Answers

We've come a long way. Once upon a time we thought the world rested on the back of a turtle and the Sun was a ball of molten iron 'not much bigger than Greece'. Now we have a theory of small things like atoms – quantum theory – which not only explains why the Sun shines and why the ground beneath our feet is solid but has also given us lasers, nuclear reactors and iPod nanos. In addition, we have a theory of big things like the Universe as a whole – Einstein's general theory of relativity – that predicts the existence of black holes and suggests that there was a beginning to time.

Nobody yet knows how the theory of the small meshes with the theory of the big – that's theorists' work-in-progress – but no matter. The point is that previous generations would have killed for the kind of knowledge we now possess about the world. It truly is a privilege to be alive today. For the first time in history, we have a good idea of the extent of the Universe – we can see all the way to the 'light horizon' that forms the boundary of observable space – and we have a good idea of the content of the Universe – we can count up the building blocks of the cosmos, 100 billion or so galaxies like our Milky Way.[*] And not only do we have an idea of the extent and content of the Universe but we also have a strong indication of how it came to be. The Universe burst into being about 13.7 billion years ago in a titanic explosion called the Big Bang and has been expanding and cooling ever since. Our Milky Way – along with all the other galaxies – simply congealed out of the cooling debris of the Big Bang fireball.

Admittedly, we still do not know exactly what the Big Bang was, what drove it or what happened before the Big Bang (or whether this is even a meaningful question). However, the remarkable thing is that we are the first generation with a realistic chance of answering such 'ultimate questions'. And not only these ultimate questions but a host of others, such as:

- What is beyond the edge of the Universe?
- Where does all the complexity we see around us come from?
- What are the limits of what we can 'know'?
- Is the human brain doing more than any computer?
- Where does the everyday world come from?
- Why do we experience a past, present and future?
- Why are loaded fridges difficult to budge?
- Will we ever find ET out in the Universe?
- Can life survive for ever in the Universe?

I address all these questions in this book. To answer them, I have talked to some of the most imaginative and daring scientists in the world. In discovering their extraordinary answers, you will learn – among other things – how the Big Bang might have been spawned by a collision

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[*] The word billion is used in this book for a thousand million, 1,000,000,000.

between 'island universes'; how a single remarkable number contains the answer to every question we could ever ask; how the most widely accepted theory of the Universe's origin implies that Elvis is alive and well and living in another space domain (in fact, an infinite number of other space domains); how nobody can rule out the possibility that the stars are technological artefacts built by extraterrestrial intelligence; how a computer program a mere four lines long could be generating you, me and everything we see around us; how all of us might be resurrected in a computer simulation at the end of time.

The last possibility inspired the title of this book. According to one controversial physicist, when you die, you are fast-forwarded to the dying days of the Universe where you wake up inside the ultimate cyber reality. Stretching before you you will find a subjective eternity of existence – the never-ending days of being dead.*

The ultimate questions I tackle are by no means a definitive selection; they are simply ones that have intrigued me personally. Nevertheless, there are themes which tie many together. I have therefore grouped together the questions into convenient categories. First, there are those whose answers shed light on the 'nature of the universe' – questions such as 'What is beyond the edge of the Universe?' and 'Where does the Universe's complexity come from?'. Second, there are questions whose answers illuminate the 'nature of reality' – 'Where does the everyday world come from?' and 'Why do we experience a present?'. Finally, I address questions which address the place of life (and us) in the Universe – such as 'Will we ever find ET?' and 'Can life survive for ever in the Universe?'.

Some of the ultimate questions I address may at first sight seem

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* Thanks for that line to Jim Crace and his brilliant novel *Being Dead*.

abstract and esoteric. But it is a remarkable feature of such questions that they invariably have significance for our mundane everyday lives. There is no more basic question, after all, than 'Where does the everyday world come from?'. And, even the most esoteric question I ask – 'Does a single number contain the secret of the Universe?' turns out to have a bearing on the origin of human imagination and creativity and whether the brain is doing something more than any computer. I think this is the nature of science at the leading edge. It is ultimately about down-to-earth things we all care about – Where did we come from? Where did the Universe come from? What the hell are we doing here?

One last thing. The answers I present are not necessarily linked to each other. This is characteristic of science at the frontier, where new ideas are so new they have not yet been woven into the tapestry of accepted science. Some will stand the test of time and some will not. Some are even mutually exclusive. All the ultimate questions are hard questions. The hardest questions are always the most interesting ones. Answering them requires journeying to the very frontier of science – and, in fact, way beyond. Have fun!

Marcus Chown

Part One

THE NATURE OF THE UNIVERSE

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Elvis Lives

What is beyond the edge of the Universe? An infinity of other domains where all possible histories are played out

Whatever spot anyone may occupy, the universe stretches away from him just the same in all directions without limit.
Lucretius, 1st century BC

There are two things you should remember when dealing with parallel universes. One, they're not really parallel, and two, they're not really universes.
Douglas Adams, *The Hitchhiker's Guide to the Galaxy*

Far, far away, in a galaxy with a remarkable resemblance to the Milky Way, sits a star that looks remarkably like the Sun. And on the star's third planet, which looks remarkably like the Earth, lives someone who, for all the world, looks like your identical twin. Not only do they look the same as you but they are reading this exact same book – in fact, they are focused on this very line. Actually, it is weirder than this. A whole lot weirder. There is an infinite number of galaxies that look just like our own galaxy, containing an infinite number of versions of you whose lives, leading up until this moment, have been absolutely identical to yours.

If you think this is pure science fiction, think again. The existence of your doubles is no fantasy. It is an unavoidable consequence of the standard theory of our Universe. And it is no airy-fairy consequence either. If you could voyage far enough across the Universe, it is inevitable that you would run into one of your doubles. In fact, it is even possible to calculate how far you would have to go to meet your nearest doppelgänger. The answer is roughly 10^10^28 metres.

In 'scientific notation', the number 10^28 (10^{28}) is 1 followed by 28 zeroes, which is 10 billion billion billion. Consequently, 10^10^28 is 1 followed by 10 billion billion billion zeroes. It is a tremendously big number. It corresponds to a distance enormously farther than the farthest limits probed by the world's biggest, most powerful telescopes. But do not get hung up on the size of this number. The point is not that your nearest double is at a mind-bogglingly great distance from the Earth. The point is that you have a double at all.

What you have just been let into is cosmology's embarrassing little secret. It is something cosmologists rarely like to mention in public. And who can honestly blame them?

But why does the standard theory of the Universe have such an extraordinary consequence? There are two reasons, it turns out. The first is 'quantum theory', our best description of the microscopic realm of atoms and their constituents. And the second is a popular theory of the first split-second of the Universe's existence, called 'inflation'.

Failures of the Standard Big Bang

Inflation is something which cosmologists have to bolt onto the standard picture of the Big Bang because, to put it bluntly, the standard picture does not work. It predicts things which are not what we see when we look out across the Universe.

According to the Big Bang picture, our Universe began in a dense, hot state about 13.7 billion years ago and has been expanding and cooling ever since. The main evidence for this comes from the galaxies – great islands of stars of which our Milky Way is one among at least 100 billion. They are flying apart from each other like pieces of cosmic shrapnel. The unavoidable conclusion is that they were closer together in the past. In fact, if the expansion of the Universe is imagined running backwards, like a movie in reverse, a moment is reached – about 13.7 billion years ago – when all of the Universe's matter was squeezed into the tiniest of tiny volumes. This was the moment of the Universe's birth – the Big Bang.

When anything is squeezed into a small volume – for instance, when air is squeezed in a bicycle pump – it gets hot. The Big Bang was therefore a 'hot' Big Bang. The evidence for this is in fact all around us today because the heat of the Big Bang was bottled up in the Universe and had nowhere else to go. Every pore of space is therefore still permeated by the 'afterglow' of the Big Bang fireball.* Because this 'heat radiation' has been greatly cooled by the expansion of the Universe over the past 13.7 billion years, it no longer glows as visible light. Instead, it appears as 'microwaves', a type of light invisible to the naked eye but which is familiar to us from radar, mobile phones and, of course, microwave ovens.

Tune your TV between the stations. About 1 per cent of the static, or 'snow', on your screen is due to this 'cosmic microwave background radiation'. Before it was intercepted by your TV aerial, the last time it interacted with matter was in the searing-hot fireball of the Big Bang. Taken together, the fact that the Universe is everywhere glowing with heat, and the fact that it is expanding, strongly supports the idea that, in the very remote past, all of Creation erupted out of a super-dense, super-

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* See my book, *Afterglow of Creation* (University Science Books, Sausalito, California, 1996).

hot state. But, though this 'Big Bang' scenario explains so much, it cannot be the whole story. The reason is that it fails to predict what we observe in the Universe in three major ways.

For one thing, the standard Big Bang picture predicts that galaxies like our own Milky Way should not exist. Galaxies are believed to have arisen from regions of gas which in the fireball of the Big Bang were ever so slightly denser than their surroundings. This gave them slightly stronger gravity so that they were able to pull in more matter and grow more effectively than neighbouring regions. But this would have been a painfully slow process. The fully fledged galaxies we see about us today could not possibly have congealed out of the smeared-out matter of the fireball of the Big Bang in a period of time as short as 13.7 billion years. Cosmologists fix the problem by postulating the existence of a vast amount of invisible, or 'dark', matter. The extra gravity it provided would have speeded up galaxy formation by pulling together matter faster so that the galaxies could have formed in the available time.

Even with this fix, however, there is a second major thing which the basic Big Bang model predicts which we do not see. It predicts that the effect of every galaxy pulling with its gravity on every other galaxy should be to 'brake' the Big Bang-driven expansion of the Universe. Contrary to all expectations, however, physicists discovered in 1998 that the expansion of the Universe appears to be speeding up. Here the standard fix is to postulate the existence of 'dark energy', an invisible 'springy' stuff which fills all of space. Its repulsive gravity is said to be countering gravity and so remorselessly driving the galaxies apart.

But, even with the addition of dark energy and dark matter, there is a third thing that the Big Bang model predicts which we do not see. This is a slightly more esoteric matter but it has to do with the 'smoothness' across the sky of the cosmic background radiation.

How the Universe Got to Be All at the Same Temperature

If we imagine the movie of the Universe running backwards, eventually we come to the epoch when the Big Bang radiation originated – a period about 450,000 years after the moment of creation.[*] At that time, the observable Universe was about 18 million light years across.[†] This is unexpectedly large for such an early time. In fact, it is inexplicably large and poses a serious problem for the standard picture of the Big Bang. To understand why, it is necessary to imagine what happened to the Universe as it cooled in the immediate aftermath of the Big Bang.

Things never cool down evenly. So it is likely that parts of the rapidly expanding fireball cooled slightly faster than others. What normally happens in such circumstances – for instance, when a cup of coffee is left on a tabletop – is that any unevenness in temperature that develops gets ironed out. This is because heat continually flows from the hot regions to the cool regions, equalising the temperature.

There is a limit, however, to how fast heat can flow. It is set by the speed of light – the cosmic speed limit. Nothing can exceed it – and that includes heat. The speed limit has no bearing on the flow of heat in something as small as a cup of coffee. But it is hugely significant for

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[*] Actually, the cosmic background radiation comes from an even earlier time than this. After all, it is the relic heat of the Big Bang fireball. Nevertheless, it was only at about 450,000 years after the birth of the Universe – at the so-called epoch of last scattering – that it broke away from matter and was able to fly freely across space. It has space. It has been flying freely across space ever since – the oldest fossil in Creation – carrying with it an imprint of the Universe close to the beginning of time.

[†] A light year is the distance light travels in a year. Since the speed of light in a vacuum is about 300,000 kilometres a second – fast enough to go from the Earth to the Moon in about 1¼ seconds – a light year is about 10 million million kilometres.

something as big as the Universe – even something as big as the shrunken primordial Universe.

Light, by definition, travels at a light year a year. This means that, when the Universe was 450,000 years old, light could have travelled no more than 450,000 light years. But, as pointed out, the Universe at the time was 18 million light years across. Light – and heat – could therefore have spanned only a few per cent of the diameter of the Universe.

It follows, therefore, that, if one side of the rapidly expanding fireball cooled down just a fraction faster than the other, it would have been impossible for heat to have flowed from the hotter side to the cooler side to equalise the temperature. There simply would not have been enough time since the beginning of the Universe.

The standard picture of the Big Bang therefore predicts that the 450,000-year-old Universe must have had an uneven temperature. Furthermore, the cosmic background radiation, because it was mixed in with the matter of the fireball and shared its temperature, should also have an uneven temperature. But this is not at all what astronomers see. When they look at the Big Bang radiation coming from widely separated parts of the Universe – which in practice means pointing a radio telescope in widely different directions in the sky – they see a remarkable constancy in its temperature. In fact, to within much less than 1 part in 10,000, the temperature of the cosmic background radiation is exactly the same in every direction in the sky – a chilly 2.726 degrees Celsius above absolute zero.*

The standard Big Bang picture tells us that heat could not have flowed back and forth across the early Universe and ironed out any temperature

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* Absolute zero is the lowest temperature attainable. When an object is cooled, its atoms move more and more sluggishly. At absolute zero – -273.15 degrees Celsius – they stop moving altogether (apart from a residual jitter which is a consequence of quantum theory).

differences. But our observations say emphatically that it did.

There are several possible ways to resolve the conflict. All of them involve bolting something new onto the standard picture of the Big Bang.

One possibility is that, in the early Universe, the speed of light was much greater than it is today. Heat would then have had plenty of time to cross the Universe since the birth of everything. Another possibility is that there was a long 'pre-Big Bang' era. The Universe would then have had ample time to come to an even temperature much as a bath with hot and cold water in it ends up uniformly warm if left alone for long enough.

However, the majority of cosmologists favour a third possibility. Early on, they say, the Universe was an awful lot smaller than we naively infer by simply running the movie of its history backwards in time. Because it was much smaller, heat could easily have crossed from one side of the Universe to the other, ironing out any unevenness in temperature.

The Universe, of course, had to achieve its present size in 13.7 billion years. If it started out smaller, it could only have accomplished this if it expanded faster than expected in the beginning. This is what cosmologists believe. In the first split-second of its existence, cosmologists believe the Universe underwent a brief period of super-fast expansion, dubbed 'inflation'. The precise details of inflation are esoteric and, frankly, not very well understood.* However, most are agreed on what caused the period of super-fast expansion of the Universe: the vacuum.

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* Inflation may have been driven by a collision between 'island universes' if our Universe is a 'four-brane' adrift in a ten-dimensional space. See Chapter 3, 'Yoyo Universe'.

The Remarkable Properties of the Quantum Vacuum

According to quantum theory, the vacuum is not empty at all. It is seething with restless energy. Energy is permitted to appear out of nothing – in total violation of the principle of 'conservation of energy', one of the cornerstones of physics, which states that energy can be neither created nor destroyed, only changed from one form to another. The proviso is that it pops into existence and disappears again within a very short interval of time. It is a bit like it being OK for a teenager to borrow their dad's car overnight just as long as it is back in the garage early the next morning before he notices it's gone. If energy is borrowed and paid back quickly enough, the law of conservation of energy does not notice.

The continual appearance and disappearance of energy in this way means that the vacuum is in ceaseless turmoil and, on average, contains more than the zero energy naively expected. And the vacuum also exerts a 'pressure', much like the air in a balloon exerts a pressure on the fabric of the balloon. It is this vacuum pressure that is the key to understanding what drove inflation.

According to Einstein's theory of gravity – the general theory of relativity – gravity is generated by two things: energy, of which the energy of mass is the most familiar kind, and pressure.* To be a little more specific, the gravity of a material depends on its energy density – how much energy is crammed into each tiny volume of the material – plus three times the pressure exerted by the material.

The pressure 'term' has been largely ignored since Einstein came up with his theory of gravity in 1915. And with good reason. The pressure exerted by normal matter is completely negligible compared with its

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* It was Einstein who, in 1905, discovered that mass is just another form of energy – like heat energy or sound energy. Mass energy is the most concentrated of all forms of energy.

energy density. But the possibility has always existed that the Universe might contain hitherto unknown 'stuff' whose pressure is not negligible at all. Enter the vacuum at the beginning of the Universe. According to the proponents of inflation, the vacuum possessed an enormous pressure – in fact, a pressure which was both enormous and negative.

'Negative pressure' sounds a weird concept but, in fact, it is just the opposite of normal, positive, pressure. Stuff with positive pressure wants to expand, like the air in a balloon. Stuff with negative pressure wants to shrink. If it were possible to fill a balloon with it, the fabric of the balloon would simply be sucked inwards rather than blown outwards.

Material with a negative pressure can have a remarkable consequence in Einstein's theory of gravity. Recall that the source of gravity is energy density plus three times the pressure. This means that, if the pressure of a material is negative and big enough, it can completely cancel out the energy density, nullifying gravity altogether. What is more, if the pressure is negative and bigger still, things get even weirder. The 'sign' of the gravity-generating term in Einstein's theory actually reverses. What this means is that, instead of sucking, gravity blows!

Repulsive gravity, it turns out, was the defining characteristic of the 'false vacuum' which existed at the very beginning of the Universe. It was the ultimate driving force behind the super-fast expansion of inflation.[*] But repulsive gravity was only the beginning. The false vacuum possessed an even more astonishing property.

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[*] It seems impossible that a vacuum, which is everywhere trying to shrink, can actually cause the Universe to expand, or inflate. However, the pressure of the vacuum has no direct effect on the Universe because it is the same everywhere. Every piece of the vacuum is trying to shrink but is surrounded by other pieces of the vacuum that are similarly trying to shrink. Consequently, there is a perfect balance everywhere and the vacuum does nothing but sit still. However, the pressure of the vacuum has an indirect effect on the Universe. Through Einstein's general theory of relativity, it generates the repulsive gravity that speeds up the expansion of the Universe.

As the Universe ballooned in size during inflation, the energy density of the vacuum stayed doggedly the same. It meant that, when the Universe doubled in size, the total energy in the vacuum doubled. When the Universe tripled in size, the energy in the vacuum tripled. In fact, for as long as the breakneck expansion of inflation kept going, the total energy in the vacuum just kept going up and up.

Imagine holding a stack of bank notes between your hands, pulling your hands apart and discovering that ever more bank notes fountain out of nothing to fill the gap. That was how vacuum at the beginning of time was. As the Universe grew, energy was literally conjured out of nothing. Inflation, as many physicists have remarked, was the 'ultimate free lunch'.

Eventually, after the merest split-second, inflation ran out of steam. No one knows why or how. But the false vacuum 'decayed'. It transformed itself into normal, well-behaved vacuum.

A split-second, by human standards, is brief. But so violent was inflation that, in that split-second, the Universe grew phenomenally in size, doubling and redoubling its volume perhaps as many as eighty times over. Consequently, by the time inflation came to an end, there was an enormous amount of energy in the false vacuum.

As pointed out above, energy can be neither created nor destroyed, only transformed from one form into another. The energy of the false vacuum therefore had to go somewhere. Where it went was into creating matter and heating it to a ferocious temperature. In short, it generated the blisteringly hot inferno we have come to call the Big Bang.

If the Big Bang is compared with the explosion of a stick of dynamite, the brief epoch of inflation that preceded it can be likened to the explosion of a hydrogen bomb. A billion billion hydrogen bombs. In fact, so violent was inflation that no adequate words exist to describe it.

Inflation and the Never-ending Universe

With inflation bolted onto the basic Big Bang idea, there emerges a new picture of the origin of the Universe. In the beginning, it turns out, was the false vacuum. Driven by repulsive gravity, it underwent a period of extraordinary expansion. The false vacuum was inherently unstable, however, and eventually decayed into normal vacuum. It did not decay everywhere at once, though. The process was far more chaotic than that. Instead, the false vacuum decayed unpredictably at widely separated locations while all the time it was continuing to inflate.

It may help to picture the false vacuum as a vast liquid with tiny bubbles forming spontaneously all over it. The bubbles were regions where inflation had come to an end and the false vacuum had decayed. One such bubble contained our Universe. The energy dumped into this bubble-universe from the false vacuum created matter and heated it to a tremendous temperature. It created the fireball of the Big Bang.

But our Universe was not alone. All the other bubbles continually forming all over the liquid also contained universes. And the energy dumped into these other bubble-universes also created matter and heated it to a tremendous temperature. It drove their very own Big Bangs.

It is a stupendously grand vision of creation. If it is correct, as many cosmologists believe, then the Big Bang was not a one-off event. It was simply one Big Bang among an uncountably huge number of Big Bangs going off like firecrackers across the length and breadth of false vacuum.

People thought the Universe was immense. But, if inflation is correct, it was far more immense than anyone imagined. Douglas Adams was *so* right in *The Hitchhiker's Guide to the Galaxy*, when he wrote: 'Space is big. You just won't believe how vastly, hugely, mind-bogglingly big it is.'

One of the most striking features of the inflationary picture is that the new false vacuum is created by the tremendous expansion of inflation far faster than it can ever decay into normal vacuum. So, despite being constantly eaten away, the false vacuum is never destroyed. Quite the opposite. It keeps on growing and growing. If money behaved like the false vacuum, it would accumulate in your bank account far faster than you could spend it. No conceivable spending spree you could embark on, no matter how extravagant, could prevent you becoming richer and richer. For this reason inflation is unstoppable. It is eternal.

According to 'eternal inflation', our bubble-universe is hopelessly lost in a vast and ever-growing ocean of false vacuum. Although there are other bubble-universes out there in the void, the ever-inflating false vacuum which separates us from them is remorselessly driving them farther and farther away from us. There is no way, not even in principle, that we could communicate with other bubble-universes or even have the slightest knowledge of them.

One of the most remarkable features of bubble-universes like ours is how big they appear to their occupants. Although each bubble-universe has an edge – it is a bubble, after all – to all intents and purposes the space inside extends for ever.

This takes a bit of getting your head around. But it is of key importance for understanding why it is you have a double – in fact, an infinite number of doubles.

The important thing to realise is that, although our bubble-universe is a piece of decayed false vacuum which is no longer inflating, it is nevertheless surrounded by false vacuum which is continuing to inflate at breakneck speed. From where we are sitting, the inflation of that vacuum is happening faster than the speed of light. This means that the boundary between our bubble-universe and the false vacuum must also be receding faster than light.* Since it is impossible for any material object to travel faster than light, the boundary is unreachable – even in principle – by us or any other occupants of our bubble-universe. And, if it is unreachable, the edge of our bubble-universe, for all practical purposes, is an infinite distance away.

This appears to be confirmed by observations of the cosmic background radiation. Slight variations in the temperature of the afterglow of the Big Bang from place to place in the sky turn out to be sensitive to the type of Universe we live in. And the variations appear to strongly favour a Universe that marches on for ever in all directions.

Despite the evidence from the Big Bang radiation, however, our Universe does not 'look' infinite. Far from it. With our most powerful telescopes we can pretty much see all the way to the 'edge' of space and make a rough count of all the galaxies – at last count about 100 billion. But the edge turns out not to be the real edge of our Universe, only the edge of the 'observable' Universe. And this is only a tiny portion of our bubble-universe.

Our view of the bubble-universe is restricted by two things. First, light, though it travels extremely fast, does not travel infinitely fast. And, second, the Universe has not existed for ever but was 'born' a mere 13.7 billion years ago. Taken together, these things mean that the only objects we can see are those whose light has taken less than 13.7 billion years to reach us. Objects farther away than this we cannot yet see because their light is still on its way to Earth. There are whole hosts of objects, for

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* Though matter and energy cannot travel faster than light, according to Einstein's general theory of relativity, space – the backdrop against which the cosmic drama is played out – can expand at any rate it likes. Inflation is a prime example of this faster-than-light expansion. After all, it ensured that the Universe at 450,000 years old was far bigger than 450,000 light years across, the maximum size it could have attained if its expansion had been limited merely to the speed of light.

instance, whose light would take 14.7 billion years to travel across space to us. However, they will not become visible from Earth for another billion years.

Actually, this is not completely true. Because the expansion of the Universe in the past was faster than it is today, the ‘light horizon’, which defines the edge of the observable Universe, is farther away than 13.7 billion light years. It means that we can see the light from all objects that are closer than 42 billion light years away (4 × 10^26 metres).

The Universe’s horizon has much in common with the horizon seen from a ship at sea. Just as we know there is more sea over the horizon, we know there is more of the Universe over the cosmic horizon – in fact, an infinite amount, according to inflation.

Of course, our observable Universe is not the only region in our bubble-universe bounded by a light horizon. If the space within our bubble-universe is effectively infinite in extent, it follows that there must be an infinite number of similar regions, each bounded by their own horizon. So, what is it like in these other regions? Here, quantum theory has something very startling to say.

Quantum Theory and the Graininess of Universe

According to quantum theory, matter is not continuous but grainy. If you picked up a branch or a rock and cut it in half, then in half again, you could not go on in this manner for ever. Sooner or later, you would come to a tiny, hard grain of matter that could not be divided any more. In the 5th century BC, the philosopher Democritus called such a grain an ‘atom’, from the Greek words *a-tomos* meaning ‘uncuttable’. Nowadays, we know that the truly uncuttable motes of matter – quarks and electrons – are even smaller than atoms. But this does not change the central truth. Matter, on the smallest scales, is fundamentally grainy, like a newspaper photograph looked at too closely.

And it is not just matter. According to quantum theory, everything – energy, space, even time – ultimately comes in tiny, indivisible chunks, or 'quanta'.

The basic building blocks of today's Universe – the fundamental grains of matter – are protons and neutrons.* Essentially identical in size, these two particles are the principal constituents of the 'nuclei' at the heart of atoms.

The protons and neutrons of the Universe are distributed very unevenly. For instance, there is a whole bunch of them over here making up the Earth and a whole bunch over there constituting the Sun. What is more, the protons and neutrons which make up the Earth and Sun are spread very thinly. This is because atoms – apart from the tiny, hard motes of their nuclei – are overwhelmingly made of empty space.

No one has provided a better mental picture of an atom than the playwright Tom Stoppard in *Hapgood*: 'Now make a fist, and if your fist is as big as the nucleus of an atom then the atom is as big as St Paul's, and if it happens to be a hydrogen atom then it has a single electron flitting about like a moth in an empty cathedral, now by the dome, now by the altar.'

It is easy to imagine other possible universes in which the protons (and neutrons) of ordinary matter are distributed in different ways. A pointless exercise, you might think. And you would be right if the other possible universes were merely hypothetical. But they are not!

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* Protons and neutrons are actually triplets of quarks bound together. This is because quarks, despite being the ultimate indivisible grains of matter, are not able to roam free in today's Universe. This was possible only in the super-hot conditions which existed in the first split-second of the Big Bang.

Consider the question of how the galaxies – the dominant structures in today's Universe – came to be. Inflation, it turns out, provides an answer.

In the beginning, recall, was the quantum vacuum. Now, it is a fundamental property of anything quantum that it is seething with restless energy. Consequently, on the smallest scales, the quantum vacuum was like a boiling cauldron. (On large scales everything averaged out. The quantum vacuum was like an ocean that looks flat from an airliner flying high above, but close up is seen to be choppy.)

The choppiness of the quantum vacuum should have been of no consequence. It was a feature, after all, of impossibly tiny regions. But inflation changed everything. Not only did it inflate the vacuum, it inflated the choppiness of the vacuum too. As a result, the choppy regions became stretched to tremendous size.

Now, the choppiest regions of the vacuum contained the most energy. And energy, as Einstein recognised in his theory of general relativity, warps space, creating gravity. Warped space and gravity are one and the same thing. So, when inflation finally spluttered to a halt, and the energy of the false vacuum was dumped unceremoniously into matter and normal space, it was the regions where the vacuum was choppiest that became the places where gravity was strongest. And, on account of their enhanced gravity, these regions were the most effective at dragging in and piling up matter from their surroundings. They would grow into the great clusters of galaxies which we see snaking like daisy chains across today's Universe.

The inflationary picture therefore tells us that giant collections of trillions upon trillions of suns were actually 'seeded' by regions of the vacuum far smaller than an atom!

But the quantum contortions of the primordial vacuum that spawned galaxies were more than just small. They were utterly random. This may not seem very significant. But it is. It means that everything in the observable Universe – the distribution of galaxies seen by our telescopes – is ultimately the result of random processes that went on in the first split-second of the Universe's existence. And what is true of our observable Universe must also be true of all other regions the size of the observable Universe in our bubble-universe. The way their galaxies are distributed must also be the result of random processes in the first split-second of the Universe.

This is crucial. It means that all the possible arrangements of protons in a volume the size of our observable Universe are not merely hypothetical. They will in fact occur – in other regions of the bubble-universe.

There is of course a stupendously large number of ways that protons could be arranged in a volume the size of the observable Universe. But the hugeness of this number is not important. The important thing is that it is finite. This follows from the fact that protons are tiny grains so there is only a finite number of places in space where they can be located, and a finite number of ways they can be arranged. Think of a chessboard with a limited number of squares where chess pieces can be located and a limited number of ways of arranging those pieces. According to quantum theory, the observable Universe is like a giant three-dimensional chess board.

Because there is only a finite number of ways of arranging protons in a volume the size of our observable Universe, and the bubble-universe, according to inflation, is effectively infinite in extent, it follows that every possible arrangement must occur somewhere. In fact, it is even more incredible than this. Every possible arrangement must occur an infinite number of times, in an infinite number of other places.

The implication for our own observable Universe is as obvious as it is shocking. It cannot be unique. Worst still, there must be an infinite number of other regions exactly like our observable Universe.

How Far Away are Regions Identical to Ours?

How far away is the nearest region that is identical in all respects to our observable Universe? Well, this depends on how many different Universes are possible. Which is, of course, the same as asking how many different ways protons can be arranged within a volume the size of our observable Universe.[*]

Think of protons as being like tiny oranges that can be stacked together, row on row, layer on layer. Just as it is possible to calculate how many oranges will fit in a box, it is possible to estimate how many protons will fit in the 'box' of the observable Universe. The answer turns out to be about 10^118.[†]

The observable Universe is not, of course, chock-a-block full with protons and neutrons. Nevertheless, because of its quantum graininess, it has 10^118 distinct locations, each of which may or may not be occupied by a proton.

In estimating how many different ways in which protons can be distributed around these 10^118 locations, it helps first to consider a drastically cut-down Universe with a more manageable number of locations for protons – say four. Location 1 can either contain a proton or no proton, making two possibilities. For each of these possibilities, location 2 can either contain a proton or no proton. That makes a total of $2 \times 2 = 4$ possibilities. For each of these, location 3 can have either a

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[*] For this elegant argument I am indebted to Max Tegmark of the Massachusetts Institute of Technology ('Parallel Universes', *Scientific American*, May 2003, p 31).

[†] There are actually only about 10^80 protons in the observable Universe, which gives an indication of how mind-bogglingly thinly matter is smeared through space. Each atom is so empty that there actually is room for another million billion protons inside it. And so empty is the observable Universe that there is room for another ten thousand billion atoms. In fact, there is so much empty space about that it is as if we live in a ghost Universe!

proton or no proton. That makes 2 × 2 × 2 = 8 possibilities. By now, the pattern should be clear. For a universe with four possible locations, protons can be arranged in 2 × 2 × 2 × 2 = 2^4, or 16, different ways.

It is easy to generalise. If there are *n* possible locations for protons, the protons can be arranged in 2^*n* different ways. In other words, a total of 2^*n* different universes are possible. In our Universe, *n* = 10^118, so there are 2^10^118 possible ways the basic building blocks could have been arranged. This is approximately equal to 10^10^118.[*]

Now we are in a position to address the original question. How far away is the nearest region which is identical in all respects to our observable Universe?

Think again of that cut-down universe with only four locations for protons. There are 2^4 = 16 possibilities, after which universes start repeating. If these are arranged in a three-dimensional space, the first repeating Universe is only twice the width of the Universe away. In general though, the distance is 2^(*n*-3) × the diameter of the observable Universe. Since the diameter of the Universe is about 8 × 10^26 metres, the nearest region identical to our observable Universe is about 10^10^118 metres away.[†]

This is a fantastically long way away. However, things are not quite this bad. Although we would have to travel 10^10^118 metres to find a region identical to our observable Universe, it would not be necessary to travel so far to find a region identical to our local neighbourhood. Take,

[*] 2^10^118 ~ (10^3)^10^117 = 10^(3 × 10^117) ~ 10^10^118 (where '~' means approximately equal to)

[†] For *n* = 10^118 and *d* = 8 × 10^26 metres,
D = 2^(10^118-3) × 8 × 10^26 metres
~ 2^10^118 × 8 × 10^26 metres
~ 10^10^118 × 8 × 10^26 metres (see previous footnote)
= 10^10^118 × 10^26 metres
= 10^[10^118 × 26] metres
~ 10^10^118 metres

for instance, a sphere 100 light years across and centred on the Earth. How far would we have to travel to find another identical sphere?

Well, a sphere 100 light years across is roughly a billionth the diameter of the observable Universe, which means it contains only a billion billion billionth the number of possible locations for protons, which comes to 10^91. That means that, instead of there being 10^10^118 possible arrangements, there are only about 10^10^91. So, after 10^10^91 spheres 100 light years across have been exhausted, things start to repeat. That puts the nearest 100-light-year sphere of space identical to our own at about 10^10^91 metres from the Earth.

That is still a fantastically long way away. But your nearest double is still not that distant. All that is really necessary is an assemblage of matter identical to you. Roughly speaking, that means about 10^28 particles. So, how far would we have to travel to find another identical assemblage? Well, if there are 10^28 possible locations for protons, there are 10^10^28 possible arrangements of those protons. And this means your nearest double is just 10^10^28 metres away.

In reality, your nearest copy is probably much closer. This is because the processes of planet formation and biological evolution may conspire to create planets like Earth and intelligent creatures like humans. Astronomers suspect that there may be at least 10^20 habitable planets in the volume of the observable Universe. And some of them may look like Earth.

Could You Ever Meet Your Double?

Could you ever meet your double? Remarkably, there is no problem – at least in principle. After all, the horizon of the Universe moves outwards by roughly a light year every year, so the observable Universe gets ever bigger, eating ever more into the bubble-universe. It is easy to imagine a time when the volume of our observable Universe finally overlaps an identical region.

Unfortunately, because of the enormous distances currently separating identical regions, our observable Universe will not merge with its double until far, far into the future. By that time, the human race will be long gone and all the stars will have gone out. So, for all practical purposes, it will not matter one way or another whether it happens or not.

There is another possibility, however. Similar regions may never overlap. Currently, the expansion of the Universe is speeding up because of the presence of dark energy. If dark energy continues to speed up the expansion, then it will become more and more difficult for light from distant galaxies to reach us. Even as the light is en route, the space between us and the galaxies will be stretching. A light beam trying to reach the Earth will be in the position of a 100-metre runner trying to reach the finishing line when the finishing line is continually being moved farther away.

The effect will be to cause the horizon of the Universe eventually to stop moving outwards into the bubble-universe and begin moving inwards. The observable Universe, instead of growing, will begin shrinking. If this is the case, our observable Universe will never overlap with a similar region – not even in principle.

However, we do not know for sure that this is what will happen. This is because the expansion of the Universe began speeding up only relatively recently. Nobody has the slightest idea why. And, since they do not know why, it follows that nobody has any idea whether the expansion will continue speeding up for ever or whether it will one day run out of steam.

All Possible Histories and the Many Worlds

Since each possible universe evolved to its present state from a different choppy state of the quantum vacuum, saying that all possible universes exist somewhere in the bubble-universe is entirely equivalent to saying that all possible histories, from the Big Bang to the present day, are played out somewhere.

In the huge majority of universes, neither the Sun nor the Earth ever arose. However, there must be other universes containing Earths. And, among those, there must be Earths which were not devastated by a comet impact 65 million years ago and on which the dinosaurs evolved into intelligent beings. There must be universes with Earths where Rome was defeated by Carthage, where Einstein became a violin teacher and not a physicist, and where the Nazis prevailed in the Second World War. There must be a universe where Elvis is alive and well. In fact, Elvis must be alive in an infinite number of other space domains!

Those who are familiar with quantum theory may have noticed a certain similarity here with the so-called Many Worlds interpretation. Like all such 'interpretations', this is an attempt to explain why quantum theory predicts atoms can be in many places at once whereas such a thing is never observed. According to the Many Worlds, however, atoms can be in different places at once – but in different realities, or parallel universes. The Universe keeps bifurcating. If a quantum event can happen one way or another way – say, an atom can disintegrate or not – the Universe splits into copies, one in which the first outcome is played out and another in which the second outcome occurs. Because so much of what happens in the world hinges on quantum events – for instance, the random event that causes cancer through a mutation in DNA – all possible histories of the Universe are played out.

The Many Worlds seems to be very wasteful of universes. However, it faithfully predicts the outcome of all known experiments. Nevertheless, the location of the other universes of the Many Worlds interpretation is never specified. Nobody has the slightest clue where they might be.

In marked contrast, the other universes of the standard theory of cosmology are utterly concrete. We know exactly where they are. So many metres in that direction. If you believe the standard picture, you have to believe in them.

Their existence provides a major philosophical and moral headache. After all, if all possibilities happen somewhere, what's the point of fighting for a better world? No matter how successful you are, there will always be other Earths – in fact, an overwhelming number of them – where copies of you fail.

The science fiction writer Larry Niven explored this idea in his story 'All the Myriad Ways'.[*] In Niven's world, the Crosstime Corporation has made billions by importing and patenting scores of inventions from alternative time tracks. But the company's founder has jumped from the balcony of a thirty-sixth-floor luxury apartment, the latest in a series of inexplicable suicides which began only a month after Crosstime started. A detective embarks on an investigation and gradually realises the truth. People have committed suicide because of the knowledge of the other versions of themselves, the might-have-beens that lived lives that were less lonely or more fulfilled. They have committed suicide because of the knowledge that, if all possibilities happen, nothing you do ever matters; whatever decision you make, the opposite decision will also be made in some other reality. They have committed suicide out of despair.

If the existence of all the other yous seems extremely difficult to take, remember that it is an unavoidable consequence of the standard theory of our Universe, which is embraced by just about anybody who is

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[*] See my book *The Universe Next Door* (Headline, 2002).

anybody in science. The standard picture incorporates both quantum theory and inflation. So, if it is not true, then either quantum theory or inflation is incorrect. It would be nigh on impossible to find a physicist who believes quantum theory is fundamentally wrong or a cosmologist willing to discard inflation. But there it is. Either you throw away quantum theory or bin inflation. Or you are not the only version of you reading this – and Elvis is still alive and well in another space domain.