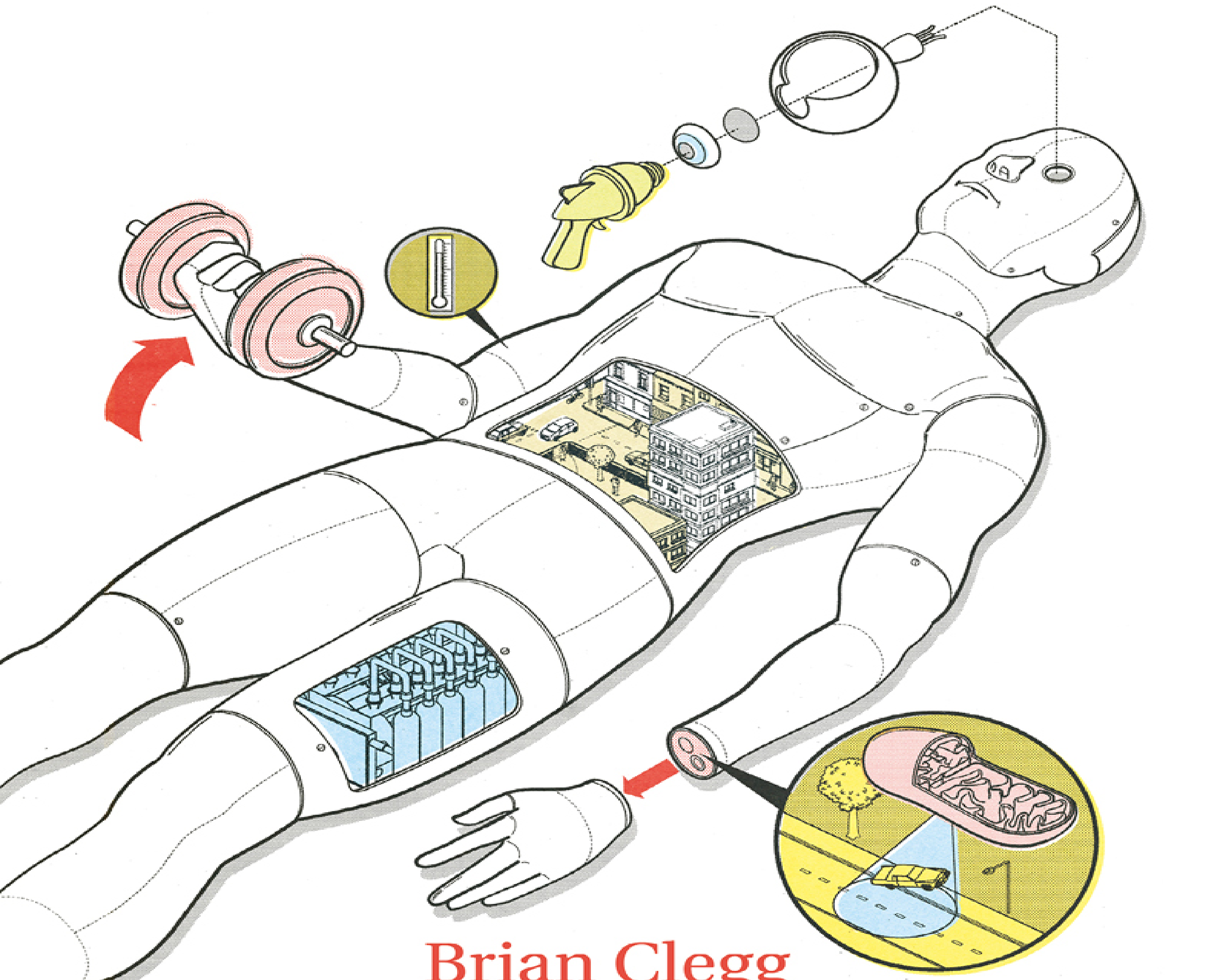
THE UNIVERSE INSIDE YOU

The Extreme Science of the Human Body From Quantum Theory to the Mysteries of the Brain



Brian Clegg

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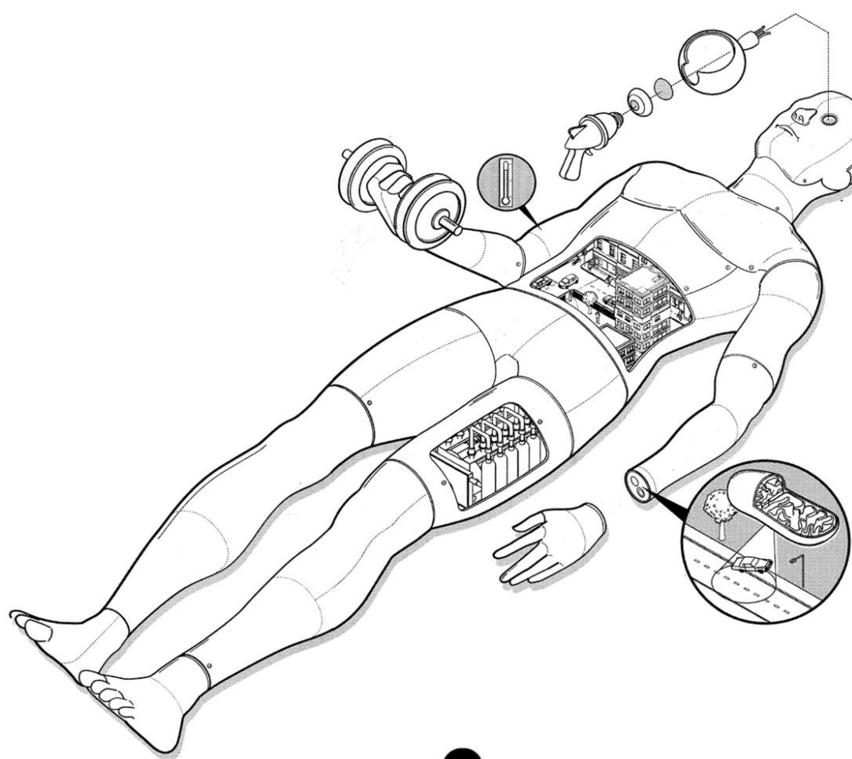

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Introduction

We are used to science being something remote, performed by experts in laboratories full of strange equipment or using vast and highly technical machinery like the Large Hadron Collider. But we all have our own laboratories in the form of our bodies – hugely complex structures that depend for their functioning on all of the many facets of science and nature.

In this book you will use the workings of your body as a tool to explore the science of the universe. Some of that exploration will be very close to home, while for some of it you will necessarily journey away from your body, to the heart of stars and beyond. These tangents always have a point, illustrating the fundamental science that underlies reality, and we will always, in the end, return to that most miraculous of constructs that is the human body.

Brian Clegg, 2012

1. In the mirror

Stand in front of a mirror, preferably full length, and take a good look at yourself. Not the usual glance – really take in what you see. You may become a little coy at this point. It's easy to start looking for imperfections, noticing those extra centimetres on the waistline, perhaps. But that's not the point. I want you to really look at a human being.

In this book you are going to use the human body, your body, to explore the most extreme aspects of science. It's all there. Everything from the chemistry of indigestion to the Big Bang and the most intractable mysteries of the universe is reflected in that single, compact structure. Your body will be your laboratory and your observatory.

You can look at the whole body, treating it as a single remarkable object. A living creature. But you can also plunge into the detail, exploring the ways your body interacts with the world around it, or how it makes use of the energy in food to get you moving. Zoom in further and you will find somewhere between ten and 100 trillion cells. Each cell is a sophisticated package of life, yet taken alone a single cell is certainly not *you*. Go further still and you will find complex chemistry abounding – you have a copy of the largest known molecule in most of your body's cells: the DNA in chromosome 1.

Continue to look in even greater detail and eventually you will reach the atoms that make up all matter. Here traditional numbers become clumsy; a typical adult is made up of around 7,000,000,000,000,000,000,000,000,000 atoms. It’s much easier to say 7×10^{27}, simply meaning 7 with 27 zeroes after it. That’s more than a billion atoms for every second the universe is thought to have existed.

There’s a whole lot going on inside that apparently simple form that you see standing in front of you in the mirror.

On reflection

In a moment we’ll plunge in to explore the miniature universe that is you, but let’s briefly stay on the outside, looking at your image in the mirror. Here’s a chance to explore a mystery that puzzled people for centuries.

Stand in front of a mirror. Raise your right hand. Which hand does your reflection raise?

As you’d expect from experience, your reflection raises its left hand.

Here’s the puzzle. The mirror swaps everything left and right – something we take for granted. Your left hand becomes your reflection’s right hand. If you close your right eye, your reflection closes its left. If your hair is parted on the left, your reflection’s hair is parted on the right. Yet the top of your head is reflected at the top of the mirror and your feet (if it’s a full-length mirror) are down at the bottom. Why does the mirror switch around left and right, but leave top and bottom the same? Why does it treat the two directions differently?

Here’s a chance to think scientifically. There are three things influencing how the mirror produces your image. The way light travels between you and the mirror, the way that you detect that light (with your eyes) and, finally, the way that your brain interprets the signals it receives. We will explore all of these aspects of your body in more detail later in the book, but one significant point may leap out immediately as you think about the process of seeing your reflection. Your eyes are arranged horizontally. You have a left and a right eye, not top and bottom eyes. Could this be why the switch only happens left and right?

Sadly, no. It's a pretty good hypothesis, but in this case it's wrong. That's not a bad thing; much of our understanding of science comes from discovering why ideas are wrong. Let's try a little experiment that will help clarify what is really happening.

Experiment – On reflection

Hold up a book (or magazine) in front of you, closed, with the front cover towards you. Look at the book in the mirror. What do you see? Be as precise as possible. List everything that you can say about the reflected book. Does this help explain why the mirror works the way it does?

Do try this yourself first, but here's what I see:

- The book in the mirror is printed in mirror writing, swapped left to right.
- The reflected book is as far behind the mirror as my book is in front of it.
- The book's colours are the same in the mirror as they are on my side.
- The front cover of the book in the mirror is the back cover of my book.

Just take a look at that last statement. If I simply consider the book in the mirror to be an ordinary book then, as I look at it, my book's back cover has become the mirror book's front cover. Lurking here is the explanation of the mirror's mystery. It doesn't swap left and right at all. It swaps back and front.

In effect, what the mirror does is turn an image inside out. The back of my book becomes the front of the book in the mirror. Put the book down and look at your own reflection again. Imagine that your skin is made of rubber and is detachable. Take off that imaginary skin, move it straight through the mirror and, *without turning it round*, turn it inside out. The point of your nose, which was pointing into the mirror is now pointing out of the mirror. The parts of you that are nearest the mirror are also nearest in the reflection. Your entire image has been turned inside out.

In reality there is no swapping of left and right, so you don't have to explain why the mirror handles this differently from top and bottom. The reason we have the illusion of a left-right switch is down to your brain. When you see your reflection in a mirror your brain tries to turn the reflection into you. It makes a fairly close match if it rotates you through 180 degrees and moves you back into the mirror. This half turn flips left and right. But the key thing to realise is that it's not the mirror that performs a swap of left and right, it is your brain, trying to interpret the signals it receives from the mirror.

Now, with the mirror’s mystery solved, let’s start our exploration of the universe by taking a look at a single, rather unusual part of your body. We are going to investigate a human hair.

2. A single hair

Take a firm hold of one of the hairs on your head and pull it out. No one said science was going to be entirely painless. If you want to make this less stressful, get a hair from a hairbrush. If you are bald, get hold of someone else's hair – but ask first! Now, examine what you've got. It's a long, very narrow cylinder, flexible yet surprisingly strong considering how thin it is.

Take as close a look at the hair as you can. If you can lay your hands on a microscope, use that, but otherwise use a magnifying glass.

That strand of hair is going to start us off on everything from philosophy to physics. Dubious about just how philosophical hair can be? Consider this: you are alive and that hair is an integral part of you (or at least it was until you pulled it out). Yet the hairs on your body are dead – they are not made up of living cells. The same is true of fingernails and toenails. So you are alive, but part of what goes to make 'you' is dead.

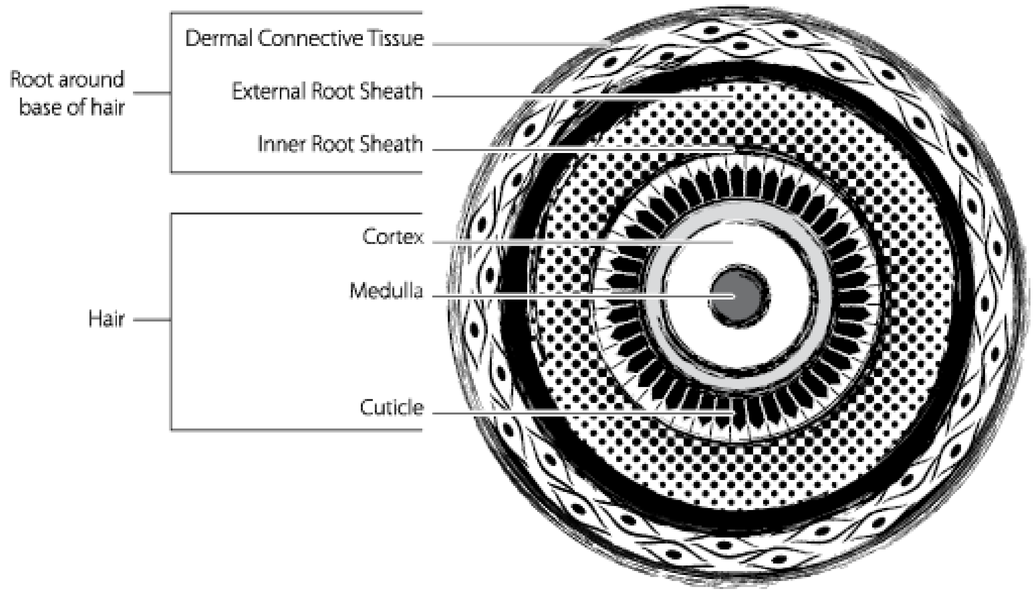
Remember that next time a TV advert is encouraging you to 'nourish' your hair. You can't feed hair. You can't make it healthy. It's dead. Deceased. It has fallen off its metaphorical perch. Worried that your hair is lifeless? Well, don't be. That's how it is supposed to be. It's quite amazing just how many hair products are advertised using the inherently meaningless concept of 'nourishing'.

We're talking about a single hair, but of course you have (probably) got many more than one on your head. A typical human head houses around 100,000 hairs, though those with blonde hair will usually have above the average, and those with red hair rather fewer. Looking at that individual hair, the colour that provides this distinction doesn’t stand out the same way it does on a full head of hair, but it’s still there.

The colours of nature

The colour in hair comes from two variants of a pigment called melanin. One, pheomelanin, produces red colours. Blonde and brown hair colourings are due to the presence of more or less of the other variant of the pigment, eumelanin. This is the original form of hair pigment – red hair is the result of a mutation at some point in the history of human development.

As we become older, the amount of pigment in our hair decreases, eventually disappearing altogether. Grey and white hairs don’t have any melanin-based pigment inside. In effect they are colourless, but the shape of the hair and its inner structure has an effect on the way that the light passes through it, producing grey and white tones.



Cross-section of a human hair

The inner structure of hair isn’t particularly obvious when you hold a single strand in your hand and look at it with the naked eye, but under a microscope it becomes clear that there is more going on than just a simple filament of uniform material. In effect your hairs have three layers: an inner one that is mostly empty, a middle one (the cortex) that has a complex structure that holds the pigments and can take in water to swell up, and an outer layer called the cuticle which looks scaly under considerable magnification, and which has a water-resistant skin.

On the end of the hair, where you have pulled it out of your scalp, there may be parts of the follicle, the section of the hair usually buried under your skin. The follicle is responsible for producing the rest of the structure and is the only part of the hair that is alive.

Dyeing to be attractive

The idea that the colouring of your hair is produced by melanins assumes it has its natural hue, but many of us have changed our hair colour using dyes at one time or another. Dyes use a surprisingly complex mechanism to carry out the superficially simple task of changing a colour. It's not like slapping on a coat of paint – the process of dyeing hair owes more to the chemist's lab than the beauty salon.

In a typical permanent dyeing process, a substance like ammonia is used to open up the hair shaft to gain access to the cortex. Then a bleach, which is essentially a mechanism for adding oxygen, is used to take out the natural colour. Any new colouration is then added to bond onto the exposed cortex. Temporary dyes never get past the cuticle; they sit on the outside of the hair and so are easily washed off.

Worrying about hair loss

Almost every human being has hairs, but compared with most mammals we are very scantily provided. Not strictly in number – we have roughly the same number of hairs as an equivalent-sized chimpanzee – but the vast majority of these hairs are so small as to be practically useless.

Next time you are cold or get a sudden sense of fear, take a look at the skin on your arms. You should be able to see goose bumps or goose pimples. This hair-related (indeed, hair-raising) phenomenon links to the fact that our ancestors once were covered in a thick coat of fur like most other mammals.

When you get goose bumps, tiny muscles around the base of each hair tense, pulling the hair more erect. If you had a decent covering of fur this would fluff up your coat, getting more air into it, and making it a better insulator. That’s a good thing when you are cold, at least if you have fur – now that we’ve lost most of our body hair, it just makes your skin look strange without any warming benefits.

Similarly, we get the bristling feeling of our hair standing on end when we’re scared. Once more it’s a now-useless ancient reaction. Many mammals fluff up their fur when threatened to make themselves look bigger and so more dangerous. (Take a dog near to a cat to see the feline version of this effect in all its glory. The cat will also arch its back to try to look even bigger.) Apparently we used to perform a similar defensive fluffing-up, but once again the effect is now ruined by our relatively hairlessness. We still feel the sensation of having our hair stand on end, but get no benefit in added bulk.

Our lack of natural hairy protection struck me painfully when out walking my dog recently. It was a cold day and I was under-dressed for the weather in a short sleeved shirt. I was shivering and my trainers were soaked from the wet grass, so that I squelched as I walked. When passing through the fence from one field to the next, I managed to brush against a rampant clump of nettles, stinging both my arms.

But the dog, with her thick fur coat and hard padded feet, was impervious to both the weather and the vegetation.

She seemed much better prepared to survive what nature could throw at her than I was.

I wondered why human beings are so badly equipped to cope with the discomforts and dangers of the natural world. We know that our distant ancestors had good, thick coats of protective fur, just as the apes still do today. (Present-day apes like chimpanzees and gorillas aren't our ancestors, but it's a mistake that's still often made in describing them.) It seems counter-intuitive that the early humans should have lost that helpful fur.

Of course, it's a misunderstanding to think that evolution has our best interests in mind. Evolution doesn't *have* a mind, or any concept of what is good or bad for us. Evolution usually works by gradual selection of subtle variants that enhance the survival and reproduction capabilities of individual members of species. It doesn't take an overview and think 'That's good, I'll keep that'. Even so, it seemed unlikely that there was any evolutionary benefit in losing the warmth and protection of that natural fur coat.

Just because evolution deals us a set of cards it doesn't mean that everything we receive in our genetic hand is beneficial. There doesn't have to be an obvious evolutionary advantage just because we have developed a certain trait. It's just as likely to be a side effect of another evolutionary development. For example, many birds have wings that are easily snapped, because the bones are thin and hollow. Having weak bones isn't a good thing in itself – on the contrary, it's bad for survival. However, it is necessary to reduce the bird's weight enough for it to be able to fly.

There are various possibilities as to why it made evolutionary sense to lose the majority of our hair. It might have been due to the need to sweat more as our ancestors moved from the forest to the savannah – it's easier to sweat with less hair, exposing more skin for sweat to evaporate. Equally it could have been a response to the increase in parasites (though all the great apes are afflicted with these). Most exotically it has been suggested that early humans were partly aquatic, and less body hair made for a sleeker swimmer (though many semi-aquatic mammals are hairy). But the explanation that works best for me is that the loss was an accidental side effect, like those precariously thin bird bones.

To make allies, lose your hair

Around 100,000 years ago our distant ancestors went through the final changes that made them into modern humans. That was the end of our evolution to date. We are the same biological species now as they were back then. There have been plenty of tiny changes at the genetic level, but as a species we are essentially the same. We have the same potential for physical strength, for longevity, for attracting the opposite sex, for thinking and more.

Those many thousands of years ago, our predecessors had undergone huge evolutionary changes from the common ancestor they shared with chimpanzees and the other great apes. The pre-humans had lost most of their hair, leaving a delicate, thin skin exposed. They had shifted from a fourlegged gait to walking upright. Their brains had grown out of all proportion with their bodies, leaving them bulgy-headed and top heavy (quite possibly unattractive features at the time). Their mouths had become smaller, making their teeth less effective as a biting weapon. The big toe had ceased to be an opposing digit that could be used to grip a tree branch.

Taken together, these alterations made the pre-humans more vulnerable to attack by predators. Their naked, unprotected skin was pathetically easy for claws and teeth to rip through. Compared with the smooth, four-footed pace of other apes, their tottering movements on two legs were painfully clumsy – a rabbit could easily outrun this strange unstable creature. The adaptations that came through in pre-humans don't seem to make any sense except as side effects. Put them alongside the change of behaviour that may have triggered them, and they were an acceptable price to pay.

These physical modifications of pre-humans are likely to have been an indirect result of an environmental upheaval. As the global climate underwent violent change, our ancestors were pushed out of the protective forests into the exposed world of the savannah. Facing up to starkly efficient predators, they were forced to change behaviour or become extinct. Back then, most pre-humans could not function well in large groups. This is still the case with most of our close relatives. The chimpanzee, for example, is incapable of forming large, cooperative bands. Get more than a handful of males together and the outcome is bloody carnage as battles for supremacy break out.

The pre-humans who first straggled onto the savannah around five million years ago were probably much the same. But the fast, killing-machine predators of the day – from the terrifying sabre-toothed dinofelis and the lion-sized machairodus to the more familiar hyena – made sure that things changed. The most likely pre-humans to survive were those with a natural tendency to cooperate. Our ancestors began to live in larger groups, giving them the ability to take on a predator and win, where a small band would be torn to pieces. And this change of behaviour may well have brought with it as side effects all the physical oddities that we observe in modern man.

The characteristics that repressed aggression and enhanced the ability to cooperate are typical of juvenile apes. Our primate cousins' inability to function in large groups only appears with maturity. The individuals amongst our predecessors who were more likely to survive on the savannah, those with the immature ability to get on with their fellows rather than tear them to pieces, were also the least physically developed. The eventual outcome was lack of hair on most of the body, a large head, a small mouth and even the upright stance – all features of the early part of the primate lifecycle that have normally disappeared by the time an individual matures.

As an aside, this mechanism of selecting for cooperative behaviour and getting an infant-like version of the animal is something humanity has since managed to produce repeatedly in its domestic animals. The dog, for example, has much more in common with a wolf cub than with the mature wolf that it was bred from. This is not just a matter of theory. In a fascinating long-term experiment between the 1950s and the 1990s, Russian geneticist Dmitri Belyaev selectively bred Russian silver foxes for docile behaviour and showed just how early man managed to turn the wolf into a dog.

Over 40 years – an immensely long experiment, but no time in evolutionary terms – the fox descendants began to resemble domesticated dogs. Their faces changed shape, becoming more rounded. Their ears no longer stood upright, but drooped down. Their tails became more floppy. Their coats ceased to be uniform in appearance, developing colour variations and patterns. They spent more time playing, and constantly looked for leadership from an adult. As they became more cooperative, they took on the physical appearance and the behaviour patterns of overgrown fox cubs.

To get back to humans, in the process of becoming more cooperative, and so more infantile (neotenous in the scientific jargon), the pre-humans lost the majority of their hair, leaving us with the largely hairless appearance we have today. Except, of course, on our heads. Head hair can be lush in the extreme, and unlike the rest of our body hair (and that of other mammals) it just keeps on growing.

As with our general lack of hair, there are several possible explanations for this. It's quite possible that originally all our hair stayed at a roughly fixed length, but over time natural selection moved us towards head hair that continued to grow. This could be because those with a mutation causing head hair to keep growing had better protected brains. Or it could have been a side effect of wearing clothes, leaving the head most in need of furry protection. Or it could have provided a shield against the full impact of the noonday Sun, which can be formidable (as anyone with a bald patch can testify). Or there might be another, quite different explanation.

Tracing back the ‘reason’ for an evolutionary trait like this is notoriously difficult because we can’t directly observe what happened or do an experiment to test a particular theory. It’s a bit like news analysis saying that the stock market fell ‘because of lack of confidence in the government’, or for some other reason. No one really knows for certain why the market reacted this way, and similarly no one can prove why humans developed a particular trait. It is inevitably a matter of conjecture.

Lost in space

But given that we are now largely hairless, in some circumstances, clothing is a survival essential. Whether you are venturing under the sea or to the North Pole, your clothing is part of your equipment. And perhaps the greatest example of clothes-as-protection is when someone is out in space. Your body was never intended to be exposed to the extremes of space. The temperature is impossibly cold, as low as –270°C. There is no atmosphere. It’s literally like nothing on Earth. Yet astronauts regularly make spacewalks protected only by specialist clothing.

It is possible to survive in space briefly without the right protection. Hollywood loves showing what would happen to a human being exposed unprotected, and can get it wonderfully wrong. The most ludicrous example is in the 1990 Arnold Schwarzenegger movie *Total Recall*, based on a Philip K. Dick story, where, expelled from the protected environment of a city on Mars, human beings inflate grossly before their heads explode messily.

Mars actually has a slight atmosphere (around one per cent of Earth’s atmospheric pressure), and even in space this sort of inflation and explosion caused by low pressure isn’t going to happen. There would be some discomfort as gas escaped from body cavities, but there is no danger that your head would inflate like a balloon.

It is true, though, that you would experience some liquids boiling. The lower the pressure, the lower the boiling point of anything, and in space – with no pressure to speak of – you will get an unpleasant drying up of the eyes as water boils away. Some fiction assumes your blood will boil in your veins, too – a horrible way to go – but according to NASA the pressure of your skin and circulatory system is enough to stop this happening.

Another worry is that you would freeze instantly in the very low temperatures of space. But bear in mind how a vacuum flask keeps its contents piping hot. Heat can only travel through a vacuum as light. We get our heat from the Sun in the form of light, which can happily cross empty space. Admittedly our bodies do glow with infrared – they do give off a degree of (invisible) light. But most of the heat we usually lose is passed on by conduction. The heat in our skin – atoms jiggling around with thermal energy – is passed on to the atmosphere, so our atoms jiggle a bit less, and the atmospheric atoms jiggle a bit more. That can't happen in a vacuum.

You would lose heat, but not very quickly. In practice, the thing that is going to kill you in space is simply the lack of air to breathe, and this will take a number of seconds. NASA has even experienced what would happen, when in 1965 a test subject's suit sprang a leak in a vacuum chamber. The victim (who survived) stayed conscious for around fourteen seconds in the airless chamber. According to NASA, the exact survival limit isn't known, but would probably be one to two minutes.

There's no doubt, then, that clothes can be important survival aids. Yet most of us, in everyday life, only have to cope with environments where plenty of other animals manage perfectly well with a bit of fur and some hardened skin on the feet. As naturists demonstrate, wearing clothes is often a social decision rather than an essential protection, and it's a decision we've been making for a long time. Woven cloth dates back at least 27,000 years – we know this because clay has been found at an ancient settlement at Pavlov in the Czech Republic with the imprint of woven cloth on its surface.

This isn't the oldest evidence for clothes we have, though. Bone needles have been found at Kostenki, a village in Russia, dating back around 40,000 years. These seem to have been used to stitch together animal skins to provide