EVOLUTION

A guide for the not-yet perplexed

If you think you understand it, you don't know nearly enough about it. **Michael Le Page** tackles some myths and misconceptions

IT WILL soon be 200 years since the birth of Charles Darwin and 150 years since the publication of *On the Origin of Species*, perhaps the most important book ever written. In it Darwin outlined an idea that many still find shocking: that all life on Earth, including us humans, evolved through natural selection.

Darwin presented compelling evidence for evolution in *On the Origin* and since his time the case has become utterly overwhelming. Countless fossil discoveries have allowed us to trace the evolution of today's organisms from earlier forms. DNA sequencing has confirmed beyond any doubt that all living creatures share a common origin. Innumerable examples of evolution in action can be seen all around us, from the famous pollution-matching pepper moth to the emergence of diseases such as AIDS and H5N1 bird flu. Evolution is as firmly established a scientific fact as the roundness of the Earth.

Yet despite the ever-growing mountain of evidence, most people around the world are not taught the truth about evolution, if they are taught about it at all. Even in the UK, the birthplace of Darwin, one recent poll suggests less than half the population accepts evolution.

For those who have never had the opportunity to learn much about biology or science in general, the claims about evolutionary theory made by those who believe in supernatural alternatives can appear convincing. Even among those who do accept the reality of evolution, misconceptions still abound.

Most of us are happy to admit that we do not understand, say, string theory in physics, yet we would baulk at saying the same about evolution. In fact, as biologists are discovering, evolution can be stranger than their predecessors ever imagined. So here is *New Scientist*'s guide to a few common myths and misconceptions about evolution. ▶

1 EVERYTHING IS AN ADAPTATION

Contrary to popular belief, not all characteristics of plants and animals are adaptations or the result of natural selection

Why do so many of us spend our evenings in front of the TV with a microwave meal? Could it be that television is the modern equivalent of a Neolithic fire, making TV dinners "the natural consequence of hundreds of thousands of years of human evolution", as one researcher recently concluded?

Stop laughing. It is very tempting to invent evolutionary "just so" stories to explain almost any aspect of our body or behaviour. We all tend to assume that everything has a purpose – but we are often wrong.

Take male nipples. Male mammals clearly do not need them. They have them because females do: it doesn't cost much to grow a nipple, so there has been no pressure for the sexes to evolve separate developmental pathways, to switch off nipple growth in males. Some researchers claim the female orgasm exists for the same reason, though this is far more controversial.

Or consider your sense of smell. Do you find the scent of roses overwhelming or

2 EVOLUTION CAN'T BE DISPROVED

There are all sorts of findings and experiments that could have falsified evolution, but in the century-and-a-half since Darwin published his theory, not a single one has

When asked what would disprove evolution, the biologist J. B. S. Haldane famously growled: "Fossil rabbits in the Precambrian." What he meant was that evolution predicts a progressive change over time in the millions of fossils unearthed around the world: multicellular organisms should come after unicellular ones; jawed fish should come after jawless ones, and so on. All it would take is one or two exceptions to challenge the theory. If the first fossil amphibians were older than the first fossil fish, for example, it would show that amphibians could not have evolved from fish. No such exceptions have ever been found anywhere.

The discovery of a mammal-bird hybrid, such as a feathered rabbit, could also disprove evolution. There are animals with a mixture of mammalian and reptilian features – such as the spiny anteater – and there are fossils with a mixture of bird and reptilian features, such as the toothy archaeopteryx. But no animals have a mixture of mammalian and bird features. This is exactly what you would expect if birds and mammals evolved from separate groups of reptiles, whereas there is no reason why a "designer" would not have mixed up these features, creating mammals with feathers and bird-like lungs, or furry, breastfeeding ostriches.

A young Earth would also be a problem for evolution, since evolution by natural selection requires vast stretches of time – "deep time" – as Darwin realised. Some thought evolution had been falsified in the 19th century when physicist William Thomson calculated that the Earth was just 30 million years old. In fact, several lines of evidence, such as lead isotopes, show the Earth is far older than even Darwin imagined – about 4.5 billion years old.

Suppose for a moment that life was designed rather than having evolved. In that case, organisms that appear similar might have very different internal workings, just as an LCD screen has a quite different mechanism to a plasma screen. The explosion of genomic research, however, has revealed that all living creatures work in essentially the same way: they store and translate information using the same genetic code, with only a few minor variations in the most primitive organisms. Huge chunks of this information are identical or differ only slightly even between species that appear very different.

What's more, the genomes of complex creatures reveal a lack of any intelligence or foresight. Your DNA consists largely of millions of defunct copies of parasitic DNA. The inescapable conclusion is that if life was designed, the designer was lazy, stupid and cruel.

Not only that, if organisms had been designed for particular roles, they might be unable to adapt to changing conditions. Instead, countless experiments, both planned and unplanned, show that organisms of all kinds evolve when their environment is altered, provided the changes are not too abrupt. In the laboratory, tweaking organisms' environments has enabled researchers to produce bacteria, plants and animals with all kinds of novel characteristics – even entirely new species. In the wild, human activity is reshaping many species: urban birds are diverging from their country cousins, some fish are getting smaller because fishermen keep only big fish, and trophy hunting is turning bighorn sheep into smallhorns, for instance.

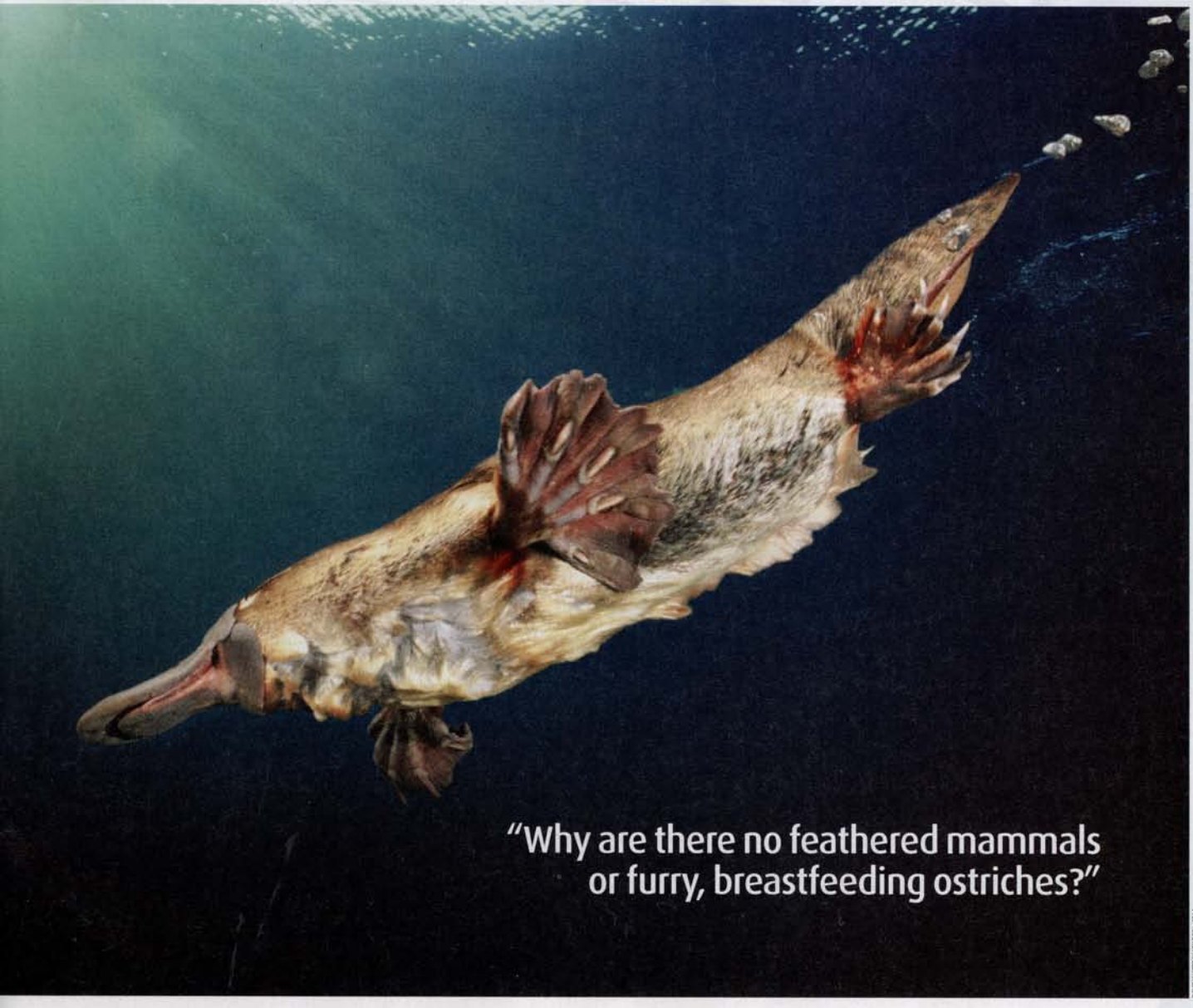
struggle to smell anything at all? Can you detect the distinctive odour that most people's urine acquires after eating asparagus? People vary greatly when it comes to smell, and this is probably less to do with natural selection than with chance mutations in the genes coding for the smell receptors.

Then there are features which do result from selection, but for another trait entirely. For instance, the short stature of pygmies might have no survival advantage in itself, but instead be a side effect of selection for early childbearing in populations where mortality is high. Similarly, since the same gene often has different roles at different times of development or in different parts of the body, selection for a variant that is beneficial in one way can have other, seemingly unrelated effects. Male homosexuality might be a side effect of genetic variants that boost female fertility. What's more, a mediocre or even poor gene variant can spread rapidly through a population if it happens to be located near a highly beneficial gene.

Other features of plants and animals, such as the wings of ostriches, are adaptations no longer needed for their original purpose. These vestigial traits can persist because they make no difference to an individual's chances of survival, or they have taken on another function, or because even though they have become disadvantageous, they occur in a population that is too small or has undergone too few generations for evolution to eliminate them.

A prime example in humans is the appendix. While claims abound that it has this or that function, the evidence is clear: you are more likely to survive without an appendix than with one. Another example is wisdom teeth. Having a smaller, weaker jaw allowed our ancestors to grow larger brains, but left less room for molars. Yet many of us still grow teeth for which there is no room, and the consequences can be fatal.

Evolutionary psychology in particular is notorious for attempting to explain every aspect of human behaviour, from gardening to rape, as an adaptation that arose when our ancestors lived on the African savannah. Some behaviours may indeed be past adaptations, but in the absence of any proof, claims about TV dinners should be taken with a large pinch of salt.



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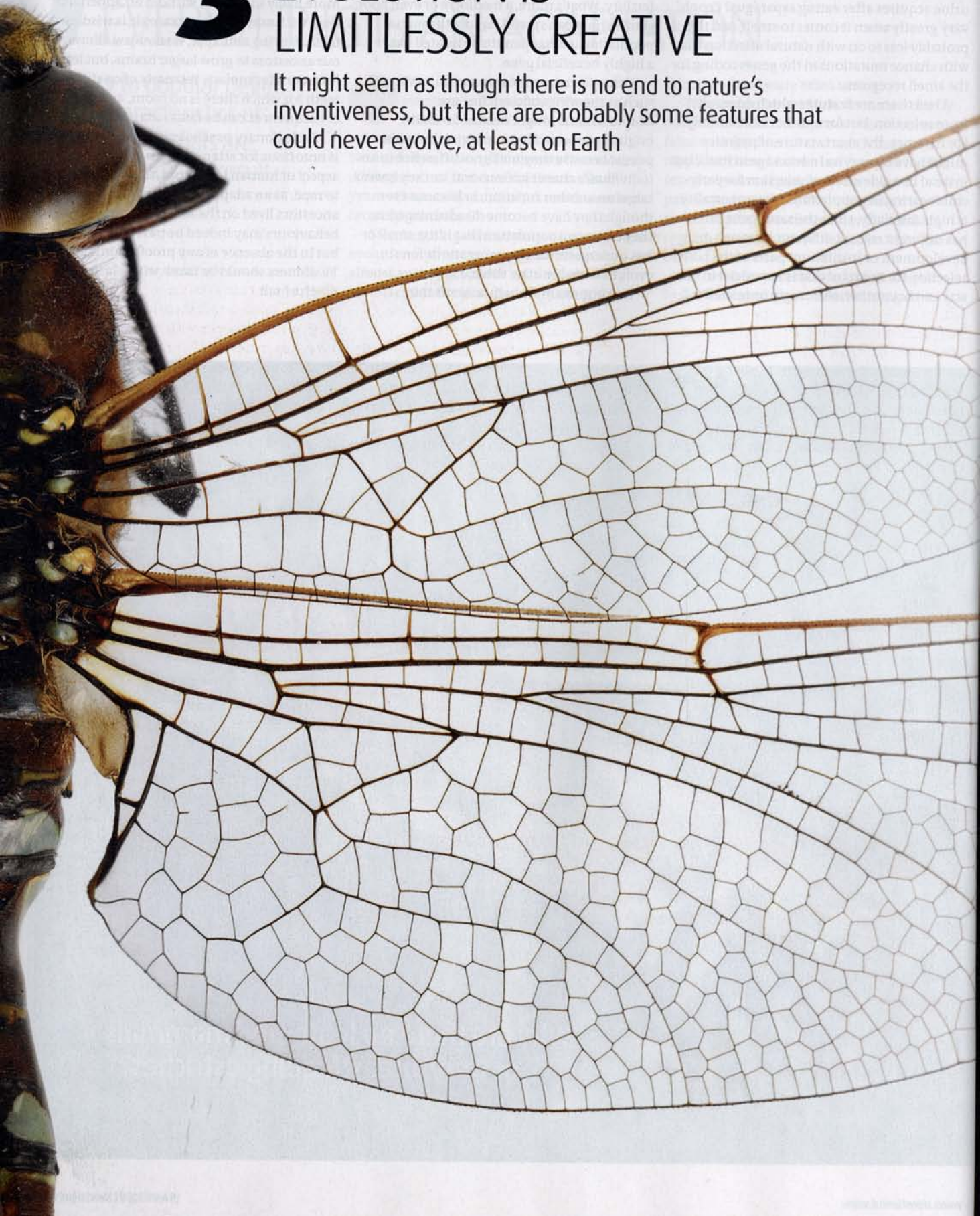
3 EVOLUTION IS LIMITLESSLY CREATIVE

It might seem as though there is no end to nature's inventiveness, but there are probably some features that could never evolve, at least on Earth



It often seems that nature invented pretty much everything that can be invented long before humans arrived on the scene, even a form of wheel. There is a salamander living in the Californian mountains that coils itself up and rolls downhill when threatened. The pearl moth caterpillar goes one better and can roll itself along a flat surface for four or five revolutions to escape predators.

Even so, there are structures that would clearly be useful but have never evolved: lions would steer clear of zebras with built-in machine guns, for example. Why can evolution invent some things but not others?

It's a very tricky question. One way to answer it is to start with a question used by deniers of evolution to suggest that many of nature's inventions – the eye, the bacterial flagellum – are too complex to have evolved. What use is half a wing, they ask?

Very useful, is the answer. The wings of insects might have evolved from flapping gills that came to be used for rowing on the surface of water. This is an example of exaptation – structures and behaviours that evolved for one purpose taking on wholly new functions, while remaining useful at every intermediate stage.

Turn this argument around, however, and it does suggest that some features cannot evolve because half of them really would be no good. For example, two-way radio would be useful for animals – for making silent alarm calls, perhaps, or tracking down their companions – so why hasn't it evolved? The recent invention of nanoscale radio receivers suggests it is not physically impossible.

The answer might be that half a radio really is useless. Detecting natural radio waves – from lightning, for instance – doesn't tell animals anything useful about their environment. That means there will be no selection for mutations that allow organisms to detect radio waves. Equally, without any means of detecting radio waves, emitting them serves no useful purpose either.

The contrast with visible light could hardly be greater. Simply detecting the presence or absence of light is a big advantage in many environments, a very blurry picture is better than no resolution at all, and so on.

Emitting visible light can be helpful too, even for creatures that cannot detect it themselves. For the bioluminescent phytoplankton that light up ocean waves, for instance, it is a way of summoning predators that eat the phytoplankton's own enemies. A similar argument applies to sound: it is not hard to see how forms of echolocation evolved independently in groups such as bats, cave swiftlets and whales.

Another impossibility seems to be plants that float in the sky like balloons. The idea doesn't seem too far-fetched at first glance: many seaweeds have floats called pneumatocysts, filled with oxygen or carbon dioxide. Other algae can produce hydrogen. Fill a large, thin pneumatocyst with hydrogen and perhaps a seaweed could fly. Flying plants would beat water and land plants to the light, so why aren't our skies green?

The trouble is that there is no pressure for large pneumatocysts with thin membranes to evolve, as these would be more vulnerable to predators and wave damage. What's more, algae produce hydrogen only when there's a lack of sulphur, and hydrogen would leak out of any pneumatocyst. Half a hydrogen balloon doesn't look very good for anything. Evolution almost certainly has its limits.

4 NATURAL SELECTION LEADS TO EVER GREATER COMPLEXITY

Actually natural selection can lead to ever greater simplicity, and complexity may initially arise when selection is weak or absent

Use it or lose it. That old adage applies to evolution as well as everyday life, and explains why cave fish are eyeless and parasitic tapeworms gutless.

Until recently, such examples were considered the exception, but it seems we may have seriously underestimated the extent to which evolution likes to simplify matters. There are entire groups of apparently primitive creatures that are turning out to be the descendants of more complex organisms. For instance, the ancestor of brainless starfish and sea urchins had a brain; why their descendants dispensed with a brain is still unclear.

Despite this, there is no doubt that evolution has produced ever more complex life forms over the past four billion years. This is usually assumed to be the result of natural selection, but recently some biologists studying our bizarre and bloated genomes have turned this idea on its head. They propose that, initially at least, complexity arises when selection pressure is weak or absent. How could this be?

Suppose an animal has a gene with two different functions. As a result of mutation some offspring may get two copies of this gene. In a large population where competition is fierce and selection pressure strong, such mutations are likely to be eliminated because they do not increase an individual's fitness and are probably slightly disadvantageous.

In smaller populations where selection pressure is weak, however, these mutations have a small chance of surviving and spreading as a result of random genetic drift (see page 33). If this happens, the duplicate genes will start to acquire mutations of their own. A mutation in one copy might destroy its ability to carry out the first of the original gene's two functions, while the other copy might lose the ability to perform the second function. Again these changes don't confer any advantage – such animals would still look and behave exactly the same – but these mutations might also spread by genetic drift. So the population would have gone from having one gene with two functions to two genes with one function each.

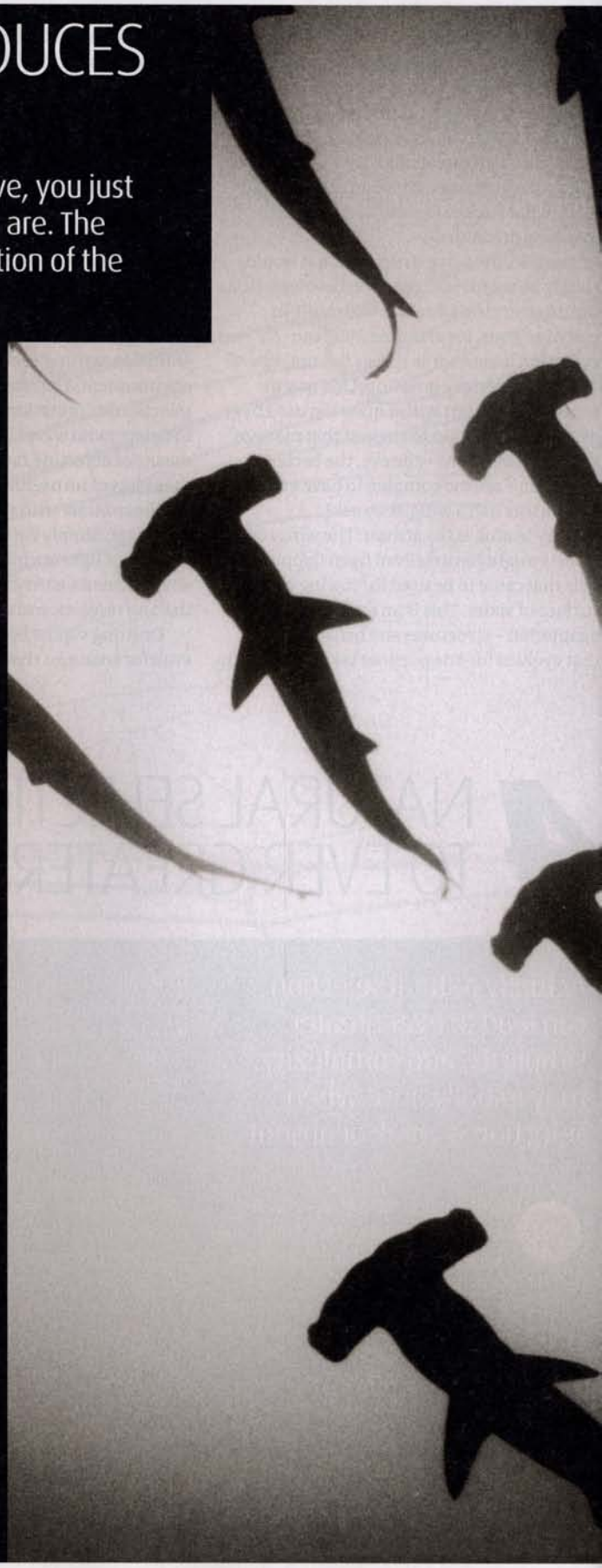
This increase in genomic complexity would have occurred not because of selection pressure but despite it. Yet it can be the foundation of greater physical or behavioural complexity because each gene can now evolve independently. For example, either can be switched on or off at different times or in different tissues. And as soon as any beneficial mutations arise, natural selection will kick in.

It seems there are opposing pressures at the heart of evolution: while complex structures and behaviours, such as eyes and language, are undoubtedly the product of natural selection, strong selection – as in large populations – blocks the random genomic changes that can throw up greater complexity in the first place.

POLKA DOT/JUPITER

5 EVOLUTION PRODUCES PERFECTION

You don't have to be perfectly adapted to survive, you just have to be as well adapted as your competitors are. The apparent perfection of animals is more a reflection of the poverty of our imaginations than of reality



It's a theme endlessly repeated in wildlife documentaries. Again and again we are told how perfectly animals are adapted to their environment. It is, however, seldom true.

Take the red squirrel, which appeared to be perfectly adapted to its environment until the grey squirrel turned up in the UK and demonstrated that it is in fact rather better adapted to broadleaf forests.

There are many reasons why evolution does not produce perfect "designs". Natural selection only requires something to work, not to work as well as it could. Botched jobs are common. The classic example is the panda's "thumb", a modified wrist bone that the animal uses like an opposable thumb to grasp bamboo. It's far from the ideal tool for the job, but since the panda's true thumb is fused into its paw, the panda had to settle for a clumsier alternative.

Evolution is far more likely to reshape existing structures than throw up novel ones. The lobed fins of early fish have turned into structures as diverse as wings, hoofs and hands. What this means is that we have five fingers because amphibians had five digits, not because five fingers is necessarily the optimal number for the human hand.

Many groups haven't evolved features that would make them better adapted. Sharks lack the gas bladder that allows bony fish to precisely control their buoyancy, and instead have to rely on swimming, buoyant fatty livers and, occasionally, gulping air. Mammals' two-way lungs are far less efficient than those of birds, in which the air flows in one direction.

Continual mutation also means that potentially useful features can get lost. Many primates cannot make vitamin C, an ability that wasn't missed in animals that get lots of vitamin C in their diet. However, such losses can be limiting if the environment changes, as one primate discovered on long sea voyages.

Evolution's lack of foresight also leads to inherently flawed designs. The vertebrate eye, with its blind spot where the wiring goes through the retina, is one example. Once natural selection fixes upon a bad – but workable – design, a species' descendants are usually stuck with it.

Environments also change. In the arms race between predator and prey, parasite and host, species have to keep evolving just to maintain their current level of fitness, let alone get even fitter. As the Red Queen says in *Through the Looking Glass*: "It takes all the running you can do, to keep in the same place."

Humans aren't running fast enough. Evolving and adapting is a numbers game: the larger a population and the more generations there are, the more mutations will appear and the more chances there will be for natural selection to favour the beneficial and eliminate the harmful. Around 10 billion new viral particles can be produced every day in the body of a person infected with HIV; the total human population on Earth was no more than a few million until fairly recently. A bacterium can produce 100,000 generations in a decade, but there have probably been fewer than 25,000 generations since the human lineage split from that of chimpanzees. So it's hardly surprising that in less than a human lifespan, we've seen the evolution of new viruses, such as HIV.

Our evolution has accelerated in the last 10,000 years, but we are changing our environment ever faster, leading to problems ranging from obesity and allergies to addictions and short-sightedness. Viruses and bacteria might approach perfection: we humans are at best a very rough first draft.

AMOS NACHOUM/CORBIS

6 IT DOESN'T MATTER IF PEOPLE DON'T GRASP EVOLUTION

At an individual level, it might not matter very much. However, any modern society which bases major decisions on superstition rather than reality is heading for disaster

So your brother or mother is a creationist. Let them believe what they want, you might think. After all, that makes family get-togethers a lot easier and it make no difference to anyone else.

Or does it? Imagine if Mike Huckabee ends up as vice-president of the US – a mere heart attack away from the top job. Would you feel comfortable if the world's biggest superpower was run by a man who rejects evolution, thanks to the support of the tens of millions of people in the US who also cannot accept reality? It is dangerous when leaders prefer dogma to biological reality: Stalin's support for the pseudoscience of Trofim Lysenko was a disaster for Soviet agriculture.

The success of western civilisation is based on science and technology, on understanding and manipulating the world. Its continued success depends on it, perhaps now more than ever as sources of cheap, easily available energy start to dry up and climate change kicks in. Any leader who thinks evolution is a matter of belief is arguably unfit for office. How can a leader capable of ignoring the staggering amount of evidence for evolution assembled by researchers in myriad fields possibly judge the more subtle scientific evidence for, say, climate change?

What's more, evolution is directly relevant to many policy decisions. Infectious diseases from tuberculosis to wheat rust are making a comeback as they evolve resistance to our defences. Antibiotic-resistant superbugs like MRSA are a growing problem. A deadly virus such as H5N1 bird flu or Ebola might evolve the ability to spread from human to human at any time, leading to a devastating pandemic. It is not possible to grasp how serious the threat is and plan for it unless you understand the power of evolution.

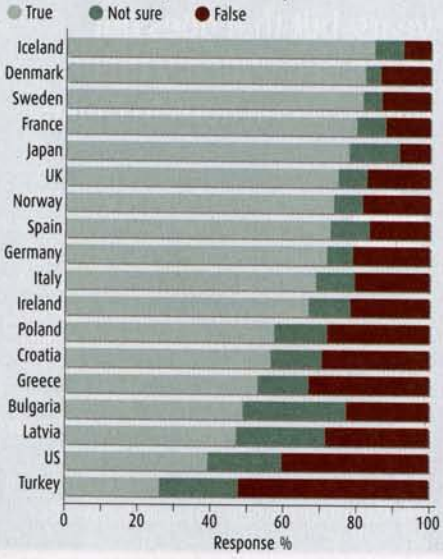
There are many more subtle areas where understanding evolution matters too. For instance, fishing policies that allow fishermen to keep only large fish are leading to the evolution of smaller fish. The tremendous changes we are making to the environment are altering many species, from rats becoming resistant to poisons to urban birds that are changing their songs to counter noise pollution (*New Scientist*, 29 March, p 33).

There is our future, too. Modern biology is on the brink of giving us previously unimaginable power over the human body, from reshaping embryos to rewriting the genetic code to delaying the effects of ageing. Societies' views on if and how these powers should be used will inevitably be shaped by people's understanding of their evolutionary origins. Things look rather different depending whether you think we are a perfect, finished product or a crude early prototype thrown up by a desperately cruel process from whose clutches we now have the opportunity to start to free ourselves.

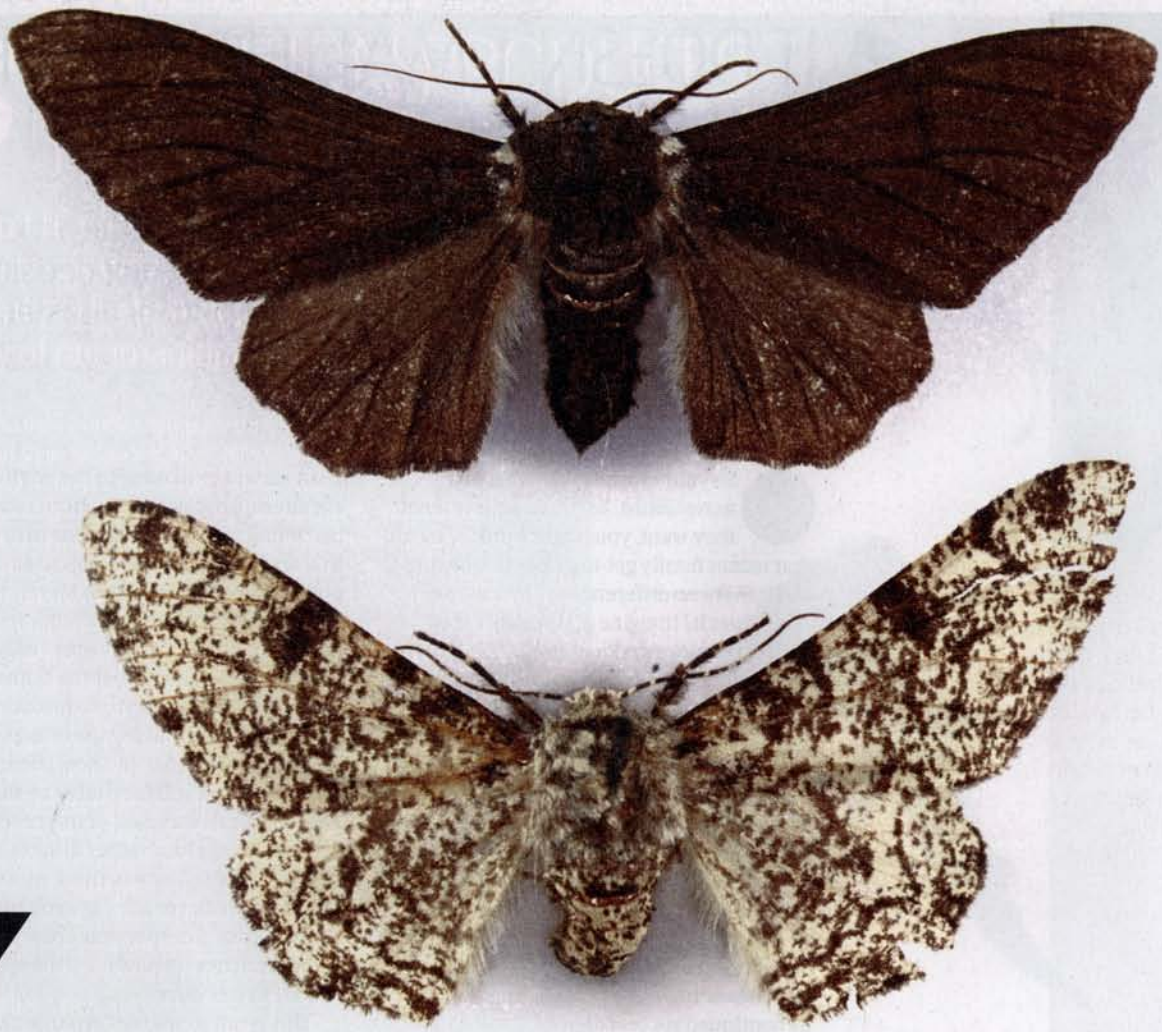
This is not to say that evolutionary theory tells us how to run societies or make ethical decisions. It doesn't. It is a descriptive science, not a prescriptive one. It does, however, help us to make informed decisions.

ACCEPTANCE OF REALITY

Adults were asked about this statement: "Human beings, as we know them, developed from earlier species of animals"



SOURCE: SCIENCE, 2006



7

EVOLUTIONARY SCIENCE IS NOT PREDICTIVE

We cannot say exactly what life will look like in a billion years, but that does not mean evolutionary theory has no predictions to make

Cosmologists make precise predictions about what will happen to the universe in 20 billion years time. Biologists struggle to predict how a few bacteria in a dish might evolve over 20 hours. Some claim that this lack of precise predictive power means evolution is not scientific.

However, what matters in science is not how much you can predict on the basis of a theory or how precise those predictions are, but whether you can make predictions that turn out to be right. Meteorologists don't reject chaos theory because it tells them it is impossible to predict the weather 100 per cent accurately – on the contrary, they accept it because weather follows the broad patterns predicted by chaos theory.

The difficulty in predicting the path of evolution partly springs from organisms' freedom to evolve in quite different directions. If we could wind the clock back 4 billion years and let life evolve all over again, its course might well be different. Life on this planet has also been shaped by chance events. If an asteroid had not wiped out the dinosaurs, intelligent life might have been very different, if it evolved at all.

Nevertheless, although evolution's predictive power might appear limited, the theory can and is used to make all sorts of predictions. For a start, Darwin predicted that transitional fossils would be discovered, and millions – trillions if you count microfossils – have been uncovered. What's more, researchers have predicted in which kinds of rocks and from what eras certain transitional fossils should turn up in, then gone out and found them, as with the half-fish, half-amphibian *Tiktaalik*.

Or take the famous peppered moth, which evolved black colouring to adapt to pollution-stained trees when industrialisation took place. Remove the pollution and, evolutionary theory predicts, the light strain should once again predominate – which is just what is happening.

This predictive power can also be put to much more practical use. For instance, evolutionary theory predicts that if you genetically engineer crops to produce a pesticide, this will lead to the evolution of insect strains which resist that pesticide, but it also predicts that you can slow the spread of resistance genes by growing regular plants alongside the GM ones. That has proved to be the case. Now, many researchers developing treatments for infectious diseases try to predict how resistance might evolve and to find ways to prevent this from happening, such as prescribing certain drugs in combination. This slows the evolution of resistance because pathogens have to acquire several different mutations to survive the treatment.

8 NATURAL SELECTION IS THE ONLY MEANS OF EVOLUTION

Much change is due to random genetic drift rather than positive selection. It could be called the survival of the luckiest

Take a look in the mirror. The face you see is rather different from that of a Neanderthal. Why? The answer could be genetic drift. With features such as the shape of your skull, which can vary in form with little change in function, chance might play a bigger role in evolution than natural selection.

DNA is under constant attack from chemicals and radiation, and errors are made when it is copied. As a result, each human embryo contains 100 or more new mutations. Natural selection will eliminate the most harmful – those that kill the embryo, for instance. Most mutations make no difference because they occur in junk DNA, which makes up the vast majority of our genome. A few cause minor changes that are neither particularly harmful nor beneficial.

While most new neutral mutations die out, a few spread through later generations purely by chance. The odds of this happening are tiny, but the sheer number of mutations that arise make genetic drift a significant force. The smaller a population, the more powerful it is.

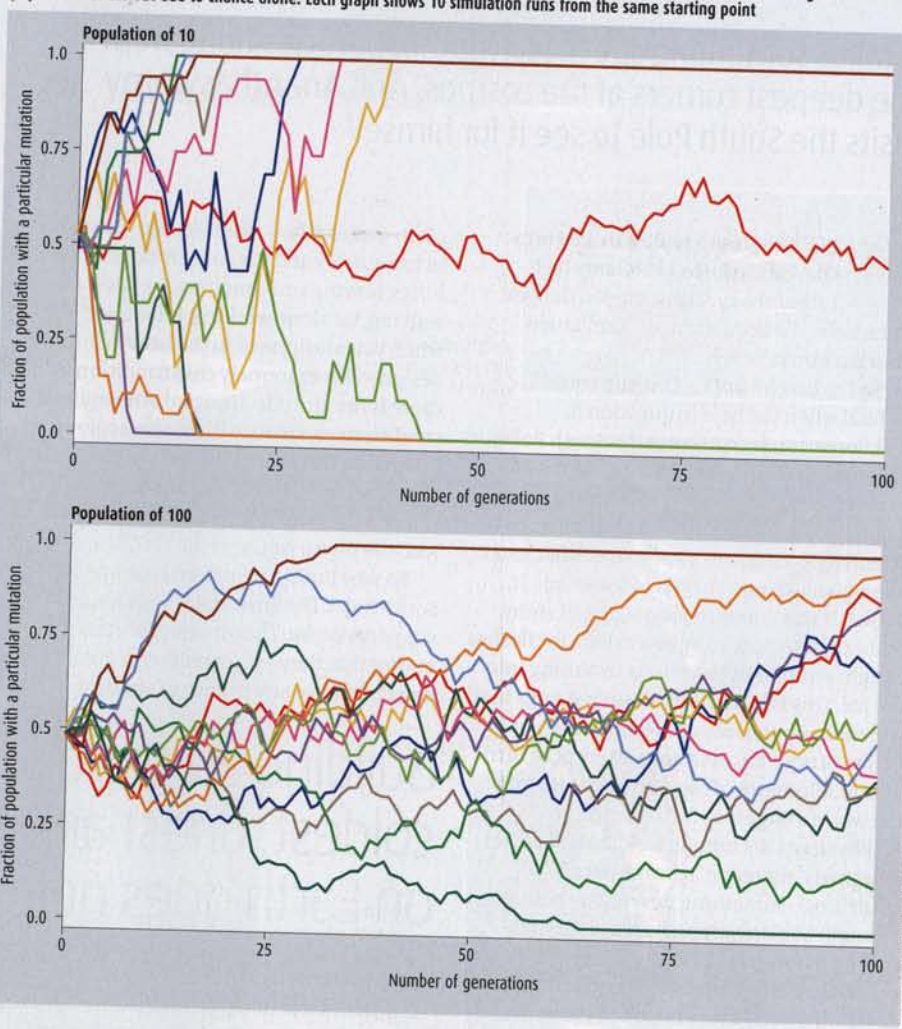
Population bottlenecks have the same effect. Imagine an island where most mice are plain but a few have stripes. If a volcanic eruption wipes out all the plain mice, striped mice will repopulate the island. It's survival of the luckiest, not the fittest.

These processes have almost certainly played a big role in human evolution. Human populations were tiny until around 10,000 years ago, and genetic evidence suggests that we went through a major bottleneck around 2 million years ago.

Most of the genetic differences between humans and other apes – and between different human populations – are due to genetic drift rather than selection, but as most of these mutations are in the nine-tenths of our genome that is junk, they do not make any difference. Of those that do affect our bodies or behaviour, it is likely that at least a few have spread because of drift rather than selection. ●

GENETIC DRIFT

Natural selection is not the only force in evolution. Mutations that have little or no effect on fitness can spread throughout a population or die out due to chance alone. Each graph shows 10 simulation runs from the same starting point



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COLLECTION MOUGEOTTY

- 'Survival of the fittest' justifies selfishness
- Religion and evolution are incompatible
- Evolution always increases fitness
- Accepting evolution undermines morality
- Mutations can only destroy information

and many more