ISSUE FOUR

NewScientist
THE COLLECTION

THE HUMAN STORY

OUR DISTANT ORIGINS

HOW APE BECAME HUMAN

BRAINS, GENES AND LANGUAGE

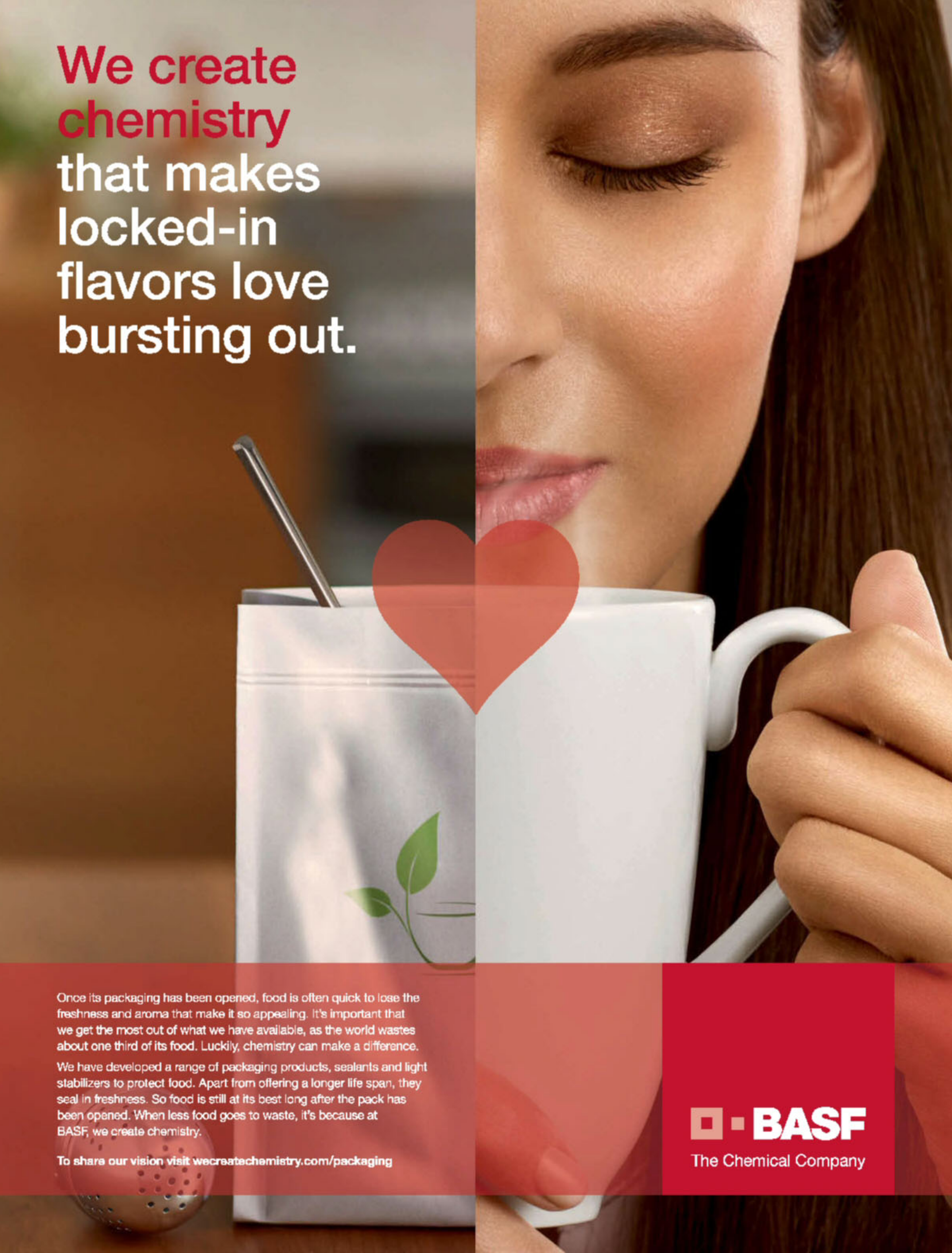
THE CONQUEST OF EARTH

OUR LONG-LOST COUSINS

CIVILISATION AND BEYOND

£9.99

04
9 772054 638003


We create chemistry that makes locked-in flavors love bursting out.
Once its packaging has been opened, food is often quick to lose the freshness and aroma that make it so appealing. It's important that we get the most out of what we have available, as the world wastes about one third of its food. Luckily, chemistry can make a difference.
We have developed a range of packaging products, sealants and light stabilizers to protect food. Apart from offering a longer life span, they seal in freshness. So food is still at its best long after the pack has been opened. When less food goes to waste, it's because at BASF, we create chemistry.
To share our vision visit wecreatechemistry.com/packaging
BASF
The Chemical Company

NewScientist
THE COLLECTION

ISSUE FOUR
THE HUMAN STORY

NEW SCIENTIST THE COLLECTION
110 High Holborn,
London WC1V 6EU
+44 (0)20 7611 1202
enquiries@newscientist.com

New Scientist The Collection is published four times per year by Reed Business Information Ltd
ISSN 2054-6386

Printed in England by Polestar (Bicester) and distributed by Marketforce UK Ltd
+44(0)20 3148 3333

The evolution of a genius ape

When Charles Darwin set out his theory of evolution in On The Origin of Species, he was all but silent on the origin of our own kind. The 1859 book contains only one brief mention of human evolution: "In the distant future… light will be thrown on the origin of man and his history".

Darwin was wise to be reticent. Although he was convinced that *Homo sapiens* evolved just like all other species, the world was not ready. The idea that we evolved from apes, rather than being the result of divine creation, was scandalous. As Darwin admitted in his autobiography: "It would have been useless and injurious to the success of the book to have paraded, without giving any evidence, my conviction with respect to his origin."

Darwin did not live to see the discovery of Java man, the first proposed "missing link" between apes and humans. Since then a stream of fossil and archaeological finds has illuminated our evolutionary past, and now genetics is telling us even more. We now know more than Darwin could have dreamed of.

From ape to human

This fourth issue of *New Scientist: The Collection* is dedicated to the human story. A compilation of classic articles from *New Scientist*, it explains how an ordinary ape evolved into the most remarkable species the Earth has ever known.

Chapter 1 lays out the bare bones of the tale, from our split with chimpanzees to our exit from Africa, and also sets out what we still don't know.

Chapter 2 takes the long view. It traces our evolution from the first primates to modern humans, and confronts the vexed question of whether our species interbred with others.

Chapter 3 traces the evolution of our most important organ. The human brain is the most complex object we know of, and is responsible for much of what of what sets us apart. How did it evolve its unique capabilities?

Chapter 4 zooms into the small print. If the genome is a species' blueprint, then ours must be pretty special. But the 3-billion-year story of our DNA contains many surprises.

Chapter 5 takes on another defining human characteristic. Language has been at least as important to our success as our brains and genes, but reconstructing its evolution poses a challenge. Where did it come from?

Chapter 6 charts our journey around the world. *Homo sapiens* was confined to Africa 140,000 years ago, but by 10,000 years ago we lived on every continent except for Antarctica. How did we do it? In particular, how did we reach the remote, inaccessible Americas?

Chapter 7 is the story of The Others. When modern humans arrived in Europe and Asia, they met people much like themselves. Who were the Neanderthals, and their recently discovered sister species the Denisovans? What were they like, and why did they die out?

Chapter 8 introduces an often-ignored factor in human evolution. Wherever you find humans, you find animals, and cave art is dominated by images of them, so they were clearly very important to our ancestors. What effect did this animal connection have on them, and us?

Finally, chapter 9 takes us to the modern age. Around 10,000 years ago humans stopped hunting and gathering and built villages. Farming, cities, and technological progress followed, eventually leading us off the surface of the Earth. Why did it happen? And is it still driving our evolution today?

Graham Lawton, editor-in-chief

CONTENTS

NewScientist
THE COLLECTION

CONTRIBUTORS

Robert Adler
is a writer based in California and Mexico
Colin Barras
is a freelance writer based in Michigan
Michael Bawaya
is the editor of *American Archaeology* magazine based in Albuquerque, New Mexico
Catherine Brahic
is a news editor at *New Scientist*
Frederick L. Coolidge
is a professor of psychology at the University of Colorado in Colorado Springs
Kate Douglas
is a feature editor at *New Scientist*
Rob Dunn
is an evolutionary biologist at North Carolina State University in Raleigh
Alison George
is an opinion editor at *New Scientist*
Dan Jones
is a writer based in Brighton, UK
Michael Le Page
is a feature editor at *New Scientist*
David Lewis-Williams
is founder of the Rock Art Research Institute at the University of the Witwatersrand, Johannesburg
Michael Marshall
is deputy editor of BBC Earth
April Nowell
is an archaeologist at the University of Victoria in British Columbia, Canada
Mark Pagel
is an evolutionary biologist at the University of Reading, UK
David Pearce
is director of the Rock Art Research Institute at the University of the Witwatersrand, Johannesburg
Helen Pilcher
is a writer based in the UK
Sean Roberts, Dan Dediu and Scott Moisik
are language researchers at the Max Planck Institute for Psycholinguistics in Nijmegen, the Netherlands
David Robson
is a feature writer at BBC Future
Frank Ryan
is a writer, medical doctor and biologist based in Sheffield, UK
Pat Shipman
is a adjunct professor of biological anthropology at Pennsylvania State University in University Park
Laura Spinney
is a writer based in Lausanne, Switzerland
Clare Wilson
is a news reporter at *New Scientist*
Tim D. White
is director of the Human Evolution Research Center at the University of California, Berkeley
Thomas Wynn
is a professor of anthropology at the University of Colorado in Colorado Springs
Ed Yong
is a freelance writer based in London

Cover image
Tadaomi Shibuya

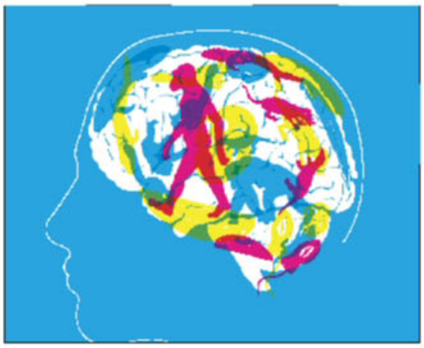
ISSUE FOUR
THE HUMAN STORY

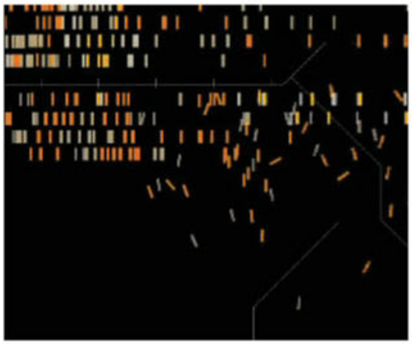
1
The big picture

The articles in this collection were first published in *New Scientist* between October 2007 and May 2014. They have been updated and revised

2
Distant origins

3
Brain evolution





4

Your ancient genome

5

Language origins

6

Around the world

7

Extinct cousins

8

The creature factor

9

Civilisation and beyond


STYLED BY SUBSTANCE.
THE NEW 4 SERIES COUPÉ.
What do you look for in a car? If it's style, you'll appreciate the arrow-like proportions, wide stance and low centre of gravity of the new BMW 4 Series.
If it's substance, see above.
Discover the new BMW 4 Series range and the Styled by Substance art collaborations at **bmw.co.uk/4series**


The new
BMW 4 Series
bmw.co.uk
0800 083 4389
The Ultimate
Driving Machine
LX14 LNG

The origin of our species

Where did we come from? Palaeoanthropologist Tim D. White lays out the latest thinking

FROM APES TO HUMANS

Twelve million years ago, Earth was a planet of the apes. Fossil evidence shows there were many ape species spread across Africa and Eurasia. About 7 million years ago, a species that would give rise to humans and our closest living relatives, the chimpanzees, lived in Africa. The fossils of this "last common ancestor" have yet to be found.

By 6 million years ago, the human lineage had evolved primitive bipedality. Some 2 million years later it had extended its range across Africa. After another million years, the genus *Australopithecus* came on to the scene. One species sparked a technological revolution based on stone tool manufacture that helped later hominids* to spread beyond Africa.

The first species of to do this, *Homo erectus*, rapidly spread from Africa into Eurasia by 1.8 million years ago, reaching Indonesia and Spain. Nearly a million years later, an African descendant of *Homo erectus* – one that would eventually vaingloriously name itself *Homo sapiens* – again ventured beyond the continent. It has now reached the moon, and perhaps soon, will stand on a neighbouring planet.

* Ever since Darwin, humans and our extinct relatives on our side of the split with chimps have been placed in the zoological family Hominidae, or hominids. The finding that humans and African apes are genetically very similar has led to calls for chimps and gorillas to be included in the family, with the human side classified at the subfamily level as "hominins". The distinction is somewhat arbitrary. I prefer the stability and clarity of continuing to use "hominid" in its original sense. Elsewhere in this volume we use "hominins".

Reconstruction of the skull of *Ardipithecus ramidus*

THE EARLIEST HOMINIDS

We still lack enough fossils to say much about the very earliest hominids. The key features of the fossils that have been found suggest that they walked on two legs. We also know their social system was different to that of any other living or extinct non-human ape, because the males' canines were much smaller and blunter, and so did not function as weapons.

Fossils of these earliest hominids from about 6 million years ago have been given different names: *Sahelanthropus tchadensis*, found in Chad; *Orrorin tugenensis* from Kenya; and *Ardipithecus kadabba* from Ethiopia. None resembles modern apes, and all share anatomical features with later *Australopithecus*.

Before these fossils were found, many researchers had predicted that we would keep finding *Australopithecus*-like hominids all the way back to the common ancestor of humans and chimpanzees. The discovery of a skeleton of *Ardipithecus ramidus* from Ethiopian deposits dated at 4.4 million years upset all of those expectations, because it is so different from even the most primitive *Australopithecus*.

The partial skeleton, nicknamed "Ardi", suggests that our last common ancestor with chimpanzees was not a halfway house between a chimpanzee and a human, but rather a creature that lacked many of the specialisations seen in our closest cousins, such as knuckle-walking, a fruit-based diet, male-male combat and climbing. Ardi was a mosaic organism: partly bipedal, omnivorous with small canines, relatively little difference between the sexes and a preference for woodland habitats. Ardi represents the first phase of hominid evolution.

ON TO THE SAVANNAH

Many modern palaeoanthropologists invoke climate change as the motor for our evolution. But they are hardly the first to recognise the impact of the environment. Long before relevant fossils were found, an early proponent of evolution, Jean-Baptiste Lamarck, saw grasslands as pivotal in the evolution of our ancestors from tree dwellers to bipeds. He was followed by Raymond Dart in the 1920s, who argued correctly that the fossil child he named *Australopithecus* was adapted to open environments.

But the popularity of the "savannah hypothesis" began to wane in the 1990s, when *Ardipithecus* fossils were found in contexts suggesting a woodland habitat (see above). Today, independent lines of evidence suggest that the earliest hominids were indeed woodland creatures: climbing adaptations; diet as deduced from the shape, wear and isotopic composition of teeth; and the thousands of plants, insects, snails, birds and mammals that also prefer such habitats and are abundant in the same localities. *Australopithecus*, though, does appear to have been associated with more open landscapes.

It has been known since the 1940s that the hip, knee and foot of *Australopithecus* were adapted to bipedality. However, it was the discovery of the "Lucy" fossils (see right) in Ethiopia, and fossilised footprints in Tanzania during the 1970s, that established this genus as representative of the evolutionary phase from which later hominids evolved. By 3 million years ago, *Australopithecus* species had spread from north to south across much of Africa.

To 20th-century scientists, *Australopithecus* seemed like an unstable transition between ape and human. Now, however, this genus is seen as a long-lasting phase of our evolution. As well as gaining the means for habitual two-footed walking, robust forms became adapted to heavy chewing (see "Robust *Australopithecus*", page 8). Some contemporary but less robust species of *Australopithecus* is likely to have given rise to the third phase of human evolution, the *Homo* genus.

"Lucy", the fossil of *Australopithecus afarensis*, is 3.2 million years old

DAVID L. BRILL MAIN IMAGE: TIM WHITE / A VENERABLE ORANGOUTANG, FROM 'THE HORNET' / PRIVATE COLLECTION / THE BRIDGEMAN ART LIBRARY / AGNES GARAUDEL

TECHNOLOGICAL PRIMATE

Stone tool from Gona, Ethiopia, made about 2.6 million years ago

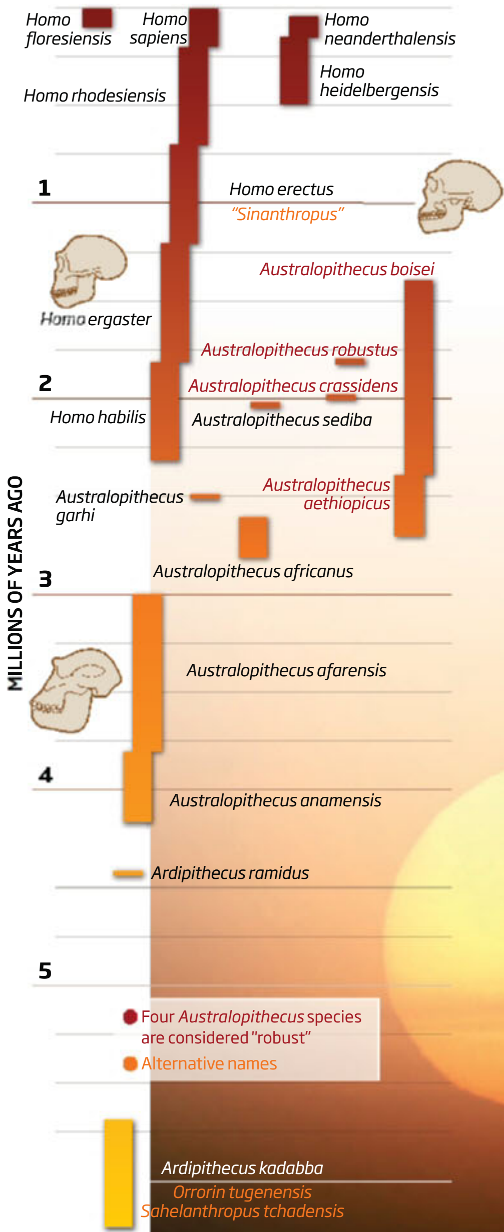
Hominids are frustratingly rare in the fossil record, but at some time around 2.6 million years ago they began to leave calling cards in the form of stone artefacts.

At the adjacent archaeological sites of the Gona and Middle Awash in Ethiopia, there is now abundant and unambiguous evidence of the earliest stone tools made by hominids, including fossilised bones of large mammals bearing definite traces of marks made by sharp instruments.

The production of sharp-edged stone flakes enabled hominids to eat large amounts of meat and marrow previously unavailable to primates. At the same time, the selective pressures associated with such activities – particularly for a bipedal primate operating cooperatively under the noses of abundant predators, from hyenas to sabre-toothed cats – would lead to dramatic anatomical change as the braincase enlarged in *Homo*.

Stone technology greatly widened our ancestors' ecological niche, as well as their geographic range, enabling *Homo erectus* to reach Europe and Indonesia more than 1.5 million years ago.

TIM WHITE



CACTUS OR BUSH?

The late American palaeontologist Steven Jay Gould wrote a classic essay in 1977 in which he predicted that the hominid family tree would prove to be "bushy". Today, it is common to see lists of more than 25 different hominid species, and Gould's prediction is often declared to be fulfilled.

Not so fast. Many of these species are "chronospecies", which evolve from one to the other, such as the earliest two species of *Australopithecus, A. afarensis* and *A. anamensis.* These names are merely arbitrary divisions of a single, evolving lineage.

A modern biologist addressing the question of species diversity counts the number of related species existing at any one time. When we do that across the hominid fossil record, what we get is not a bush but something like a saguaro cactus, with only a few species lineages. The greatest diversity appears to be at around 2 million years ago, when as many as four different hominid lineages coexisted in Africa, including the robust Australopithecines (see below).

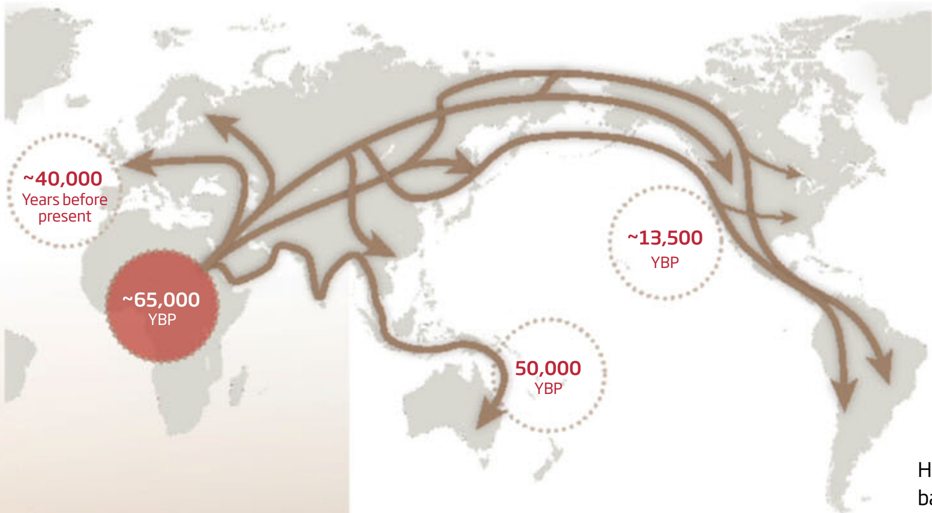
The key question turns out to be not how many species there were *per se*, but rather why species diversity has been so limited on our branch of the evolutionary tree compared with other mammals such as fruit bats or South American monkeys. The reason is probably that our ancestors' niche kept broadening, as a woodland omnivore 6 million years ago expanded ecologically into more open environments, and then again as technology further extended its capability and horizons.

JAMES HAGER/ROBERT HARDING/GETTY-INSET SKULL JAVIER TRUEBA/MSF/SPL

ROBUST *AUSTRALOPITHECUS*

When palaeontologist Robert Broom discovered this hominid skull in South Africa in 1938, he was struck by its unusual appearance. It has oversized molars, tiny canines and incisors, a massive lower jaw, a dished face, a small brain and a bony crest atop its skull. Broom named it *Paranthropus robustus.* It probably evolved from an *Australopithecus* species and is also known as "robust" *Australopithecus.*

It appears in the fossil record more than 2.5 million years ago, in eastern Africa, with its last members some 1.2 million years ago. By that date, our genus, *Homo*, had been on the scene for more than a million years. There are many mysteries about robust *Australopithecus* still to be solved, but one thing is clear: for at least 1.3 million years, ours was not the only hominid lineage in Africa.



Human migration routes based on analysis of mitochondrial DNA

OUT OF AFRICA, TWICE

The first hominid expansion from Africa came about 2 million years ago, as revealed by stone tools and an outstanding collection of hominid fossils at the site of Dmanisi in Georgia. This expansion has sometimes been called "Out of Africa, Part 1", but the implication that hominids deserted Africa is manifestly incorrect. This continent continued to be the crucible of our evolution. Even the emigrant *Homo erectus* and its hand-axe technology are ubiquitous in Africa, with evidence of the species' occupation from the Cape to near Cairo.

Darwin predicted that Africa would one day yield fossils to illuminate human evolution. Today, he would be delighted to learn we have found fossils not only from the first two phases of human evolution – Ardi and the Australopithecines – but also within our own genus, *Homo*. The earliest is *Homo habilis*, makers of stone flakes and cores that dominated technology for almost a million years. Next came *Homo erectus*. What is clear is that our ancestors continued to evolve in Africa as more northerly latitudes were repeatedly buried in thick ice.

By 160,000 years ago, African hominids were nearly anatomically modern, with faces a little taller than ours, and skulls a little more robust. Their brain sizes were fully modern. In Ethiopia, at a locality called Herto by the local Afar people, the crania of two adults and a child represent some of the best evidence of the anatomy of these early people, who lived by a lake. Among their activities was the butchery of hippopotamus carcasses with their sophisticated stone toolkits.

Herto humans were also doing things that we would recognise as distinctively human: they were practising mortuary rituals. Fine cut-marks and polishing on a child's cranium show that it was defleshed when fresh, and then repeatedly handled.

Examination of the DNA of people today shows we all carry inside us a kind of "living fossil" that opens a window on our past. Whether modern human DNA samples are taken in the Congo or the Arctic, our DNA is remarkably similar to each other's, especially when compared with the variation seen in most other mammals. And the variation observed is greatest among African populations.

What this means is that we are a recent species, and that the ancestors of all modern people were Africans.

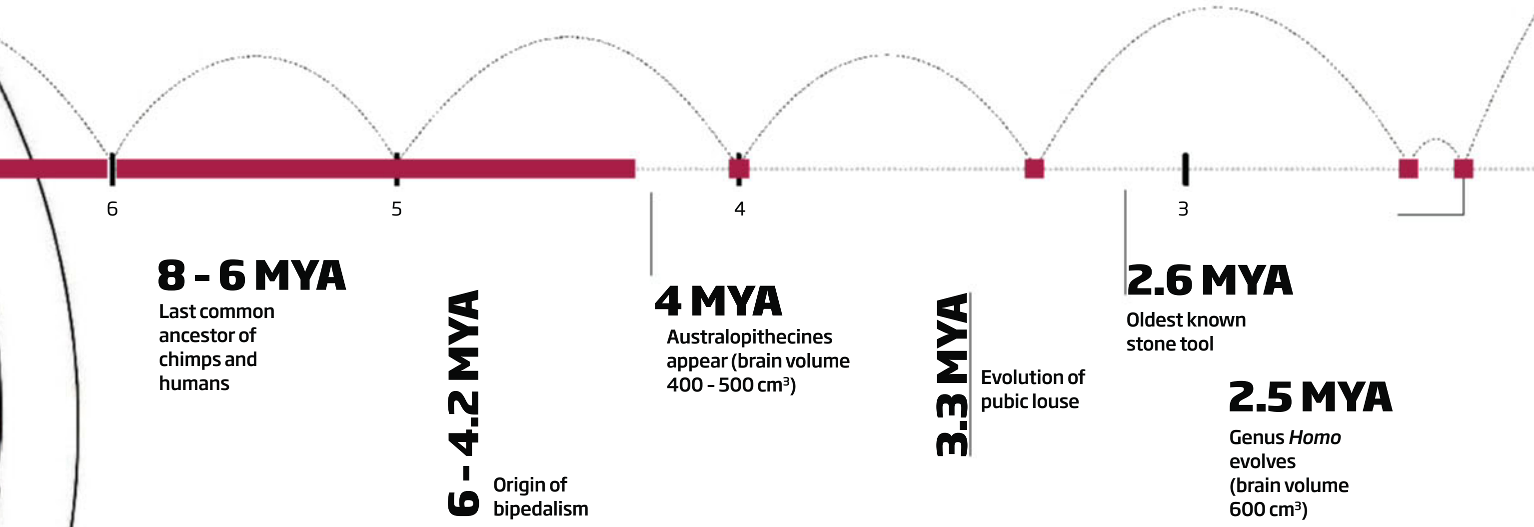
"Around 2 million years ago as many as four hominid lineages coexisted in Africa"

Skull of *Paranthropus robustus*


8 million years ago

MYSTERIES OF OUR PAST

The big picture of human evolution is becoming clear, but there's still a lot we don't know



Why are we so different from chimps?

NOBODY would mistake a human for a chimpanzee, yet we share more DNA than mice and rats do. How can that be? Advances in genomics are starting to unravel the mystery.

Line up the genomes of humans and chimps side by side and they differ by little more than a few per cent. That may not seem like much, but it equates to more than 30 million point mutations. Around 80 per cent of our 30,000 genes are affected, and although most have just one or two changes, the effects can be dramatic.

For example, the protein made by the human gene *FOXP2*, which helps us to speak, differs from its chimp counterpart by just two amino acids. And small changes in the *microcephalin* and *ASPM* genes may underlie big differences in brain size between humans and chimps.

But protein evolution is only part of what makes us human. Also critical are changes in gene regulation – when and where genes are expressed during development - says James Noonan of Yale University. Mutations in key developmental genes are likely to be fatal. But, he says, "altering the expression of a gene in a single tissue or at a single time can more easily lead to an innovation that is not lethal." Noonan's lab is one of many investigating the genetic origins of human uniqueness.

Then there's gene duplication. This can give rise to families of genes that diversify and take on new functions, says Evan Eichler at the University of Washington in Seattle. His lab has identified uniquely human gene families that affect many aspects of our biology, from the immune system to brain development. He suspects that gene duplication has contributed to the evolution of novel cognitive capacities in humans, but at a cost: it has made us more susceptible to neurological disorders.

Copying errors mean whole chunks of DNA have been accidentally deleted. Other chunks find themselves in new locations when mobile genetic elements jump around the genome or viruses integrate themselves into our DNA. The human genome contains more than 26,000 of these so-called indels (insertions or deletions), many linked with differences in gene expression between humans and chimps.

Even a complete catalogue of genetic differences will not solve the mystery. Much of what makes us human is cultural, passed from generation to generation by learning, says Ajit Varki at the University of California, San Diego. What's more, he says, the co-evolution of genes and culture is a major force in human evolution, famously leaving the descendants of dairy farmers able to continue to digest the milk sugar lactose in adulthood, for example.

To crack the mystery of human uniqueness we need to know how genomes build bodies and brains, how brains create culture, and how culture eventually feeds back to alter the genome. It remains a distant goal. Dan Jones

TIM WATKINS

Why did we become bipedal?

CHARLES DARWIN suggested that our ancestors first stood upright to free their hands for tool-making. We now know that cannot be right, since the oldest tools yet discovered are a mere 2.6 million years old, whereas the anatomy of hominin fossils reveals that bipedalism emerged at least 4.2 million – and possibly even 6 million – years ago.

The trouble with bipedalism, says Chris Stringer at the Natural History Museum in London, is that although proficient walking has many advantages, acquiring the skill requires anatomical changes, and in the meantime you will be slow, clumsy and unstable. "It could have begun in the trees," he suggests, pointing out that orang-utans and other primates walk upright along branches when feeding. This fits with what we know about the lifestyle of the first bipeds but does not explain why they evolved specialist anatomy. By 4 million years ago, for instance, the tibia in the lower leg was held upright to the foot, whereas it is angled to the outside in apes living now, even those that spend the most time on two legs.

In a more compelling evolutionary explanation bipedalism would substantially boost survival, which is why some people believe it evolved to allow males to access more food so that they could help feed their partners and offspring. But this idea presupposes a very early origin of monogamy, which the evidence doesn't support, says Donald Johanson, director of the Institute of Human Origins at Arizona State University in Tempe, who in 1974 discovered Lucy, a 3.2-million-year-old, upright Australopithecine. He points out that among early hominins, males were much larger than females, which in primates is a sign that there is competition rather than cooperation between the sexes.

"The real question is what were the benefits," says Johanson. One possibility is that individuals who could wander further than others had access to a wider variety of food sources, allowing them to live longer and produce more surviving offspring. In addition, bipedalism would have left their hands free to carry things and, being taller, they may have been better at spotting predators. "There might have been a whole package of advantages," he says, adding that bipedalism may have emerged more than once.

All of which would have set the stage for a second phase of evolution around 1.7 million years ago, when our ancestors left the forests for the savannah. This is when the greatest anatomical changes took place, with shoulders pulled back, legs

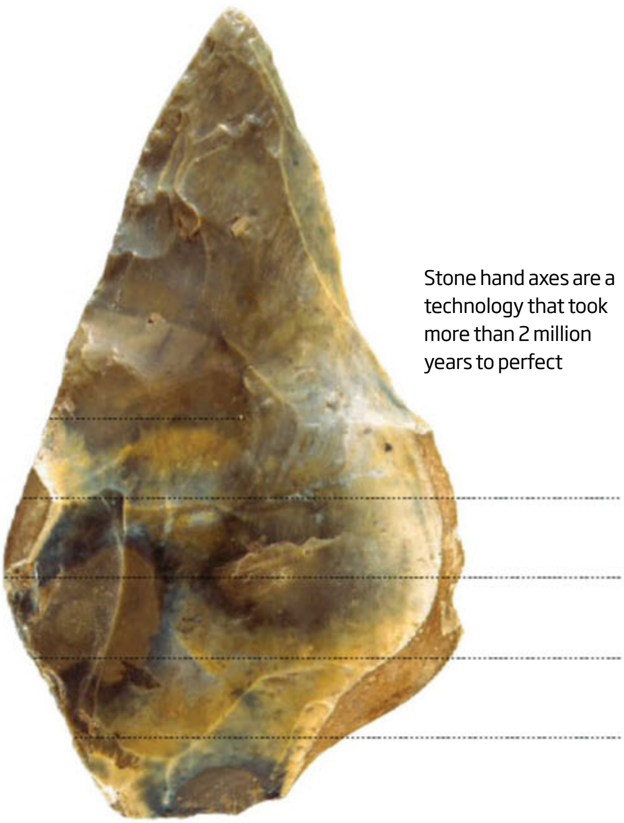
2 — 1 million

2 MYA *Homo erectus* evolves (brain volume 850 cm^3)

1.8 MYA *Homo erectus* leaves Africa for Asia (brain volume 1000 cm^3)

1.7 MYA Savannah living established

1.6 MYA Pleistocene ice age begins



Stone hand axes are a technology that took more than 2 million years to perfect

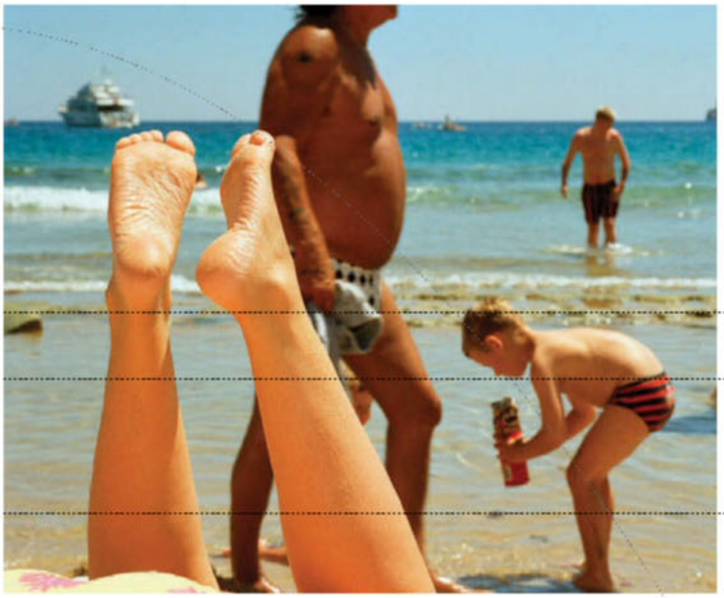
THE NATURAL HISTORY MUSEUM/ALAMY

Why was technological development so slow?

SHARP stone flakes found two decades ago in a parched riverbed in the Afar region of Ethiopia are the oldest tools yet discovered. They date from 2.6 million years ago. It would be another million years before our ancestors made their next technological breakthrough. Then, instead of using the chips off a river cobble as blades and scrapers, someone realised that the cobble itself could be worked into a tool.

"It is recognisable as a hand axe, but very rough," says Dietrich Stout of Emory University, Atlanta. Another million years passed before early modern humans perfected this type of tool. What took them so long?

Intelligence must have played a part. In the 2 million years after the appearance of the first tools, hominin brain size more than doubled, to around 900 cubic centimetres. Tool-making undoubtedly requires smarts, and Stout has used MRI scans of people knapping stones to find out which brain areas are involved. The studies suggest that early technological innovations depended on novel perceptual-motor capabilities – such as the ability to control joint stiffness – while later developments were underpinned by growing cognitive complexity, including the sort of recursive thinking required for language. So, although tools appear not to develop much, their production is underpinned by great cognitive advance, leading Stout to conclude that there was more progress during this period than we tend to think. What's more, he says, people may have made other tools from



MARTIN PARR/MAGNUM

Walking upright boosts mobility and decreases exposure to the sun

lengthened and a pelvis adapted to life on two legs.

There are many possible reasons why bipedalism took off at this point. Walking upright might have helped individuals deal with the scorching heat of the open grassland, allowing air to circulate around the body while minimising direct exposure to the sun. It would also have increased mobility.

"I think the argument comes down to travel efficiency and travel distance," says Robin Dunbar, an evolutionary psychologist at the University of Oxford. Bipedalism allowed our ancestors to walk long distances, enabling them to track down prey on the savannah. One study even suggests that we become adapted for endurance running, although modern couch potatoes may consider this idea a step too far. **Kate Douglas**

900,000 | 800,000 | 700,000 | 600,000 | 500,000 | 400,000

600,000 YA

Homo heidelbergensis **capable of speech (brain volume 1200 cm³)**

500,000 YA

Sophisticated hand axes

materials such as wood and bone that perished long ago.

"Even allowing for that, stone-tool progress looks painfully slow," says Chris Stringer of the Natural History Museum in London. In his book *The Origin of Our Species* he identifies another reason – demography. "It's not what you know, it's who you know," he says. Modern humans have large populations with lots of people copying each other's behaviour, and many ways to pass on information. Our long lives also permit transfer of ideas down the generations, whereas *Homo erectus* and *Homo heidelbergensis* probably had a maximum lifespan of around 30 years, and Neanderthals maybe 40. "They're having to grow up very fast and there's much less networking between groups," Stringer says.

Furthermore, our ancestors may have shunned change since life would have been challenging enough without risky experimentation. "It's dangerous to go around innovating and inventing," says Stringer. Mark Pagel at the University of Reading, UK, doubts that hominins before *Homo sapiens* had what it takes to innovate and exchange ideas, even if they wanted to. He draws a comparison with chimps, which can make crude stone tools but lack technological progress. They mostly learn by trial and error, he says, whereas we learn by watching each other, and we know when something is worth copying. If Pagel is correct, then social learning is the spark that ignited a technological revolution . "With the arrival of modern humans the game changed," he says. **Kate Douglas**

98.5%

DNA shared by chimps and humans

When did language evolve?

15W

Energy consumption of a human brain

WITHOUT language we would struggle to exchange ideas or influence other people's behaviour. Human society as we know it could not exist. The origin of this singular skill was a turning point in our history, yet the timing is extremely difficult to pin down.

We do know that *Homo sapiens* was not the only hominin with linguistic abilities. Neanderthals, who evolved some 230,000 years ago, had the neural connections to the tongue, diaphragm and chest muscles necessary to articulate intricate sounds and control breathing for speech. Evidence comes from the size of holes in the skull and vertebrae through which the nerves serving these areas pass. What's more, Neanderthals shared the human variant of the *FOXP2* gene, crucial for forming the complex motor memories involved in speech. Assuming this variant arose just once, speech predates the divergence of the human and Neanderthal lineages at least 550,000 years ago.

Indeed, it appears that *Homo heidelbergensis* already had the gift of the gab 600,000 years ago when they first appeared in Europe. Fossilised remains show they had lost a balloon-like organ connected to the voice box that allows other primates to produce loud, booming noises to impress their opponents. "That's a big disadvantage – we can't have lost them for nothing," says Bart de Boer at the University of Amsterdam in the Netherlands. His models suggest that air sacs would blur differences between vowels, making it difficult to form distinct words.

For older ancestors, the fossil record does not speak so eloquently. However, Robin Dunbar at the University of Oxford notes that the most recent

400,000 | 300,000 | 200,000

230,000 YA
Neanderthals evolve (brain volume 1300 cm³)

200,000 YA
Homo sapiens evolves (brain volume 1300 cm³)

CHEV WILKINSON/GETTY

Hand gestures may have led naturally to language

hominin to show evidence of apelike neural connections in the diaphragm and chest is 1.6 million years old, suggesting speech evolved sometime between then and 600,000 years ago. To complicate matters further, language may have started with hand gestures, before eventually becoming vocal. If so, hominins could have been conversing in sign language long before adaptations for speech left their mark in the fossil record.

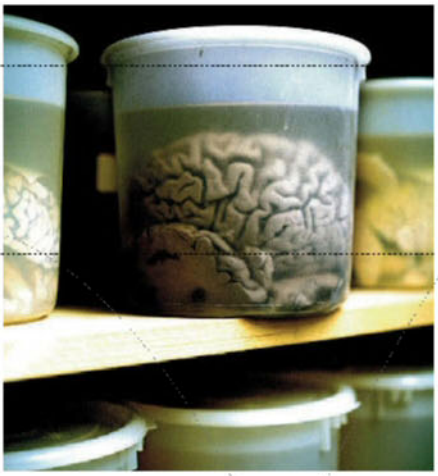
Even interpreting the available evidence is problematic because a hominin capable of speech cannot necessarily hold a meaningful conversation. Dunbar suggests that voices might have evolved to sing by the campfire. Like birdsong, they would not have carried much information, but the activity would have been important for group bonding.

Stringer, however, points out that *Homo heidelbergensis* and Neanderthals built complex tools and hunted dangerous animals – activities that would have been very difficult to coordinate without at least some primitive kind of language.

Indisputable evidence of speech conveying complex ideas comes only with the cultural sophistication and symbolism that is associated with *Homo sapiens*. But the first words, whenever they were spoken, started a chain of events that changed our relationships, society and technology, and even the way we think. David Robson

For more on this see chapter 5, "Language origins"

Our brain is twice as heavy as it should be for an ape of our size



STEEVE IUNCKER/AGENCE VU/CAMERAPRESS

Why are our brains so big?

A SINGLE mutation may have cleared the way for rapid brain evolution. Other primates have strong jaw muscles that exert a force across the whole skull, constraining its growth. But around 2 million years ago a mutation weakened this grip in the human line. A brain growth spurt began soon after.

What drove this spurt? The environment probably presented mental challenges. Social developments would have played a part, too. To test the relative importance of these pressures, David Geary at the University of Missouri in Columbia compared the skull size of various hominins against environmental conditions each lived in, such as the estimated variation in annual temperatures, and against proxies for social pressure, such as group size. Both were associated with bigger brains, but the difficulties of navigating a larger social network had the greatest impact.

A big brain is incredibly hungry, so early humans needed to change their diet. The transition to eating meat would have helped. So would the addition of seafood about 2 million years ago, providing the omega-3 fatty acids that we now know are vital for brain building. Cooking might have helped too, by easing digestion. This would have allowed ancestral humans to evolve smaller guts and devote the spare resources to brain building.

Big brains come at a price, however, including the dangers of giving birth. By the time the benefits no longer outweighed the costs, we had a 1.3 kilogram lump of tissue smart enough to question its own existence.

David Robson

For more on this see chapter 3, "Brain evolution"

100,000 90,000 80,000 70,000 60,000

125,000 YA

Humans leave Africa for Near East

70,000 YA

Last ice age begins

Why did we lose our fur?

MAMMALS expend huge amounts of energy just keeping warm, and fur coats are their insulation. When and why did humans forgo that benefit?

The most imaginative explanation is that our ancestors went through an aquatic phase millions of years ago and jettisoned their fur, which is a poor insulator in water, just as cetaceans did. Critics, though, say that if you want to keep warm in water you need to be round and lardy, not long and limby. Worse, the "aquatic ape" theory lacks fossil evidence to back it up.

More credible is the idea that we lost our fur when overheating, not cooling, became the biggest risk. "We don't pant or have large ears like elephants," says Chris Stringer of London's Natural History Museum. "Our only way to cool down is to sweat, and with thick fur that's inefficient." This wouldn't have been a problem in the shady forest, but when our ancestors moved to more open ground, natural selection would have favoured individuals with very fine hair to help air circulate around their sweaty bodies.

But sweating requires a large fluid intake, which means living near rivers or steams, whose banks tend to be wooded and shady – thus reducing the need to sweat. What's more, an ice age set in around 1.6 million years ago and even in Africa the nights would have been chilly.

One advantage of exposed skin is that it advertises good health

PIPER MACKAY/GETTY

Mark Pagel at the University of Reading, UK, points out that other animals on the savannah have hung on to their fur. He argues that we did not shed ours until we were smart enough to deal with the consequences, which was probably after modern humans evolved, about 200,000 years ago. "We can make things to compensate for fur loss such as clothing, shelter and fire," he says. Then, Pagel contends, natural selection favoured less hairy individuals because fur harbours parasites that spread disease. Later, sexual selection lent a hand, as people with clear, unblemished skin advertising their good health became the most desirable partners and passed on more genes.

To confuse things still further, circumstantial evidence points to a very early loss of fur. The pubic louse evolved around 3.3 million years ago, says Mark Stoneking at the Max Plank Institute for Evolutionary Anthropology in Leipzig, Germany, and it could not have done so until ancestral humans lost their body fur, creating its niche. What's more, he has dated the evolution of body lice, which live in clothing, to around 70,000 years ago. So it looks like our ancestors wandered around stark naked for a very long time. **Kate Douglas**

For more on this see "Of lice and men", page 110

Why did we go global?

OUR ancestors achieved some epic migrations. *Homo erectus* made the first great trek out of Africa into east Asia 1.8 million years ago. Around a million years later, the predecessors of Neanderthals turned up in Europe. And 125,000 years ago, *Homo sapiens* made an early foray into the Middle East. None of these populations lasted. But some 65,000 years ago, one group of modern humans left Africa and conquered the world – an extraordinary achievement for any species, let alone a puny, furless ape. What possessed them to spread so far and wide?

It may have begun with a big squeeze. All humans belong to one of four mitochondrial lineages (L0, L1, L2 and L3) corresponding to four ancestral mothers, but only L3 is found outside Africa. Quentin Atkinson at the University of Auckland, New Zealand, has found that this lineage experienced a population explosion in the 10,000 years leading up to the exodus. So overcrowding in the Horn of Africa may have pushed the group to cross the Red Sea and move along the southern coast of Asia.

That still leaves the question of why numbers increased. Atkinson notes that for 100,000 years the African climate had oscillated between drought and floods before becoming stable around 70,000 years ago. Perhaps the environmental instability had forced early humans to become more inventive, with adaptations that helped population expansion once conditions improved.

Paul Mellars at the University of Cambridge has argued that the explosion in numbers was driven by a major increase in the complexity of technological, economic, social and cognitive behaviour. The ability to control fire came much earlier, as, probably, did language. But the period did see a blossoming of innovation such as the manufacture of complex tools, efficient exploitation of food sources, artistic expression and symbolic ornamentation. These cultural advances would have been crucial, says Mark Pagel at the University of

4%
Maximum Neanderthal genes in modern humans

60,000 | 50,000 | 40,000 | 30,000

50,000 YA
"Great leap forward", a human cultural revolution

45,000 YA
Colonisation of Australia

40,000 YA
Denisovans in Siberia

24,000 YA
Neanderthals become extinct

FRANK FRANKLIN/ASSOCIATED PRESS

The ancestors of Neanderthals made it to Europe about 800,000 years ago

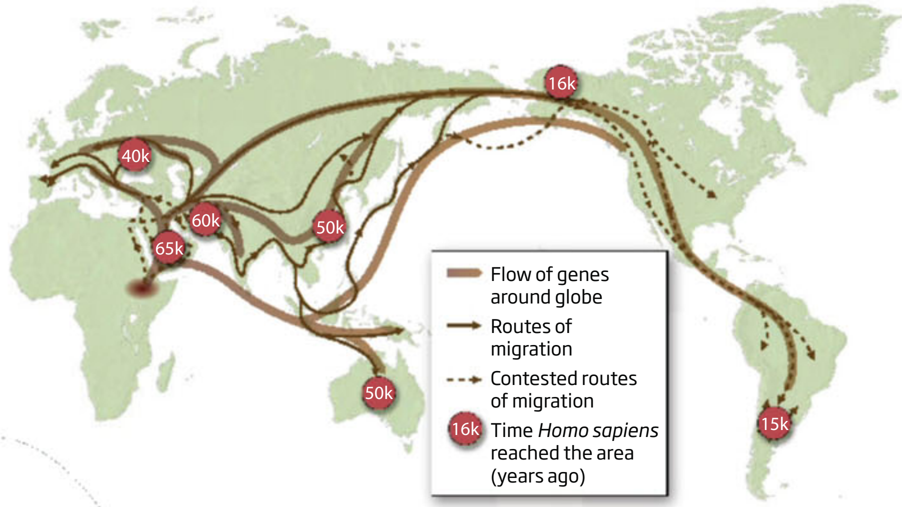
Reading, UK. "Not only can we walk, we can change the world when we get there," he says. This flexibility would have propelled migrants ever onward as populations quickly reached carrying capacity and individuals moved into new territory to avoid competition.

"Some of it would have been accidental," says Chris Stringer of London's Natural History Museum: the peopling of Australia may have come about when seafarers travelling between islands were blown further afield. Genetic mutations could also have made us more adventurous. For example, the so-called novelty-seeking gene *DRD4-7R* is more common in populations that migrated fastest and furthest from Africa. "Of course there is the human spirit - to climb the unclimbed mountain," says Stringer. Kate Douglas

For more on the human conquest of Earth see "Going global", page 80

To boldly go

After *Homo sapiens* left Africa 65,000 years ago they spread out across the globe



20,000

10,000

18,000 YA

Indonesian *Homo floresiensis* ("hobbit") becomes extinct

15,000 YA

Colonisation of the Americas

If "hobbits" existed, what else might be out there?

JEAN PAUL GUILLOTEAU/EXPRESS-REA

Are there any other hominins left?

LEGENDS of human-like creatures, such as Bigfoot, the Yeti and the Yowie have entranced people for centuries. They make for good stories, but could there be any truth in them?

It seems unlikely. Recently, Jeff Lozier at the University of Alabama in Tuscaloosa examined the location of all Bigfoot, or Sasquatch, sightings. He found that these "haunts" are identical to those of the black bear, suggesting it could simply be a case of mistaken identity. "I've never seen anything that has convinced me," adds David Coltman at the University of Alberta in Edmonton, Canada, who recently analysed a tuft of hair from a supposed Bigfoot to find that it came from a bison. Coltman concedes that new species of primate are occasionally found in remote regions, so there is a slim chance that there may be something out there. "But it's very unlikely that they could fly under the radar for so long."

Nevertheless, a few scientists are willing to contemplate the idea that *Homo sapiens* is not alone. Jeffrey Meldrum at Idaho State University in Pocatello, points out that other hominin species coexisted alongside our ancestors for most of human history. That's not all. Our family tree can still surprise us, as happened with the discovery of *Homo floresiensis*, aka the "hobbit" in 2003 (the left-hand skull in the picture, above left). This pint-sized hominin lived on the Indonesian island of Flores until 18,000 years ago. Just two years ago came another surprise when genetic analysis revealed a previously unknown species, the Denisovans, living in Siberia around 40,000 years ago (for more on this see chapter 7, "Our extinct cousins").

Meldrum finds it easy to imagine that small groups of our cousins could be clinging on in remote areas such as the Himalayas and the Caucasus.

They could even be a bit closer to home. In 1996, he heard reports of 38-centimetre-long, apelike tracks in the Blue mountain forests of Oregon. He arrived expecting to see a poor hoax, but the prints showed an extraordinary level of anatomical detail. The toes were flexed at certain locations but more relaxed at others, for instance, as if the animal had been running for some stretches of its journey. Such details would be very difficult to fabricate, Meldrum says. "I'm not trying to convince people of the existence of the Sasquatch, but we shouldn't turn our back on the possibility."

David Robson

Flower child

DIETER SCHAEFER/FLICKR/GETTY

What made the first primate evolve the special features that paved the way for human evolution? There's a surprising answer, says Helen Pilcher

BRING me his head. That was the job given to graduate student Jonathan Bloch two decades ago. His supervisor, Philip Gingerich, had collected some large fossil-rich limestone blocks from the Bighorn basin in Wyoming and brought them back to the museum at the University of Michigan.

"The rocks had bone in them, but what exactly was a mystery. It was my task to reduce the rock using acid to see what I could find," says Bloch. "When I asked Philip what I should be looking for, he said something like, 'how about a skull?'" Bloch said OK and set to work. At the time, he didn't realise how incredibly rare it is to find mammal skulls from the time after the death of the dinosaurs 66 million years ago, when the limestone had formed. "Within the first few days of work out popped the skull. I thought, well that is good, I found what I was supposed to. Philip was very surprised. He had the experience to recognise how big of a deal it was," Bloch recalls.

The skull was not just that of any old mammal, but of a much sought-after "missing link" in the primate fossil record. Fierce debate still rages over its significance, but many see it as a crucial piece of evidence in the story of how humans came to be – one that suggests flowers played a key role in our evolution.

Take a look at your hands and you'll see they have evolved for grasping things, with opposable digits and flat nails instead of claws. We also have forward-facing eyes, and bigger brains than most other mammals. We tend to think of these traits as human, but almost all primates share them too. So what made the ancestors of primates evolve them in the first place, paving the way for our evolution?

We know roughly when it happened. The first steps in primate evolution were probably taken around 60 million years ago, when the ancestor of all primates – thought to be a small creature, possibly nocturnal – took to the trees. The big question is why its descendants evolved in the way they did.

The explanation might seem obvious: when you take to the trees, you need grasping hands for clinging to branches and forward-facing eyes for judging distance. But in the 1970s, anthropologist Matt Cartmill pointed out that it can't be that simple. Many mammals have opted for a life in trees and thrived without ever evolving these features. Squirrels have sideways-facing eyes and claws instead of nails, for instance, but they're perfectly at home leaping from branch to branch. So there must be more to our eyes and hands than that.

The extra factor, Cartmill suggested, was catching insects. He pointed out that in living tree-dwellers, grasping hands and feet are usually found in animals that forage on young branches too thin for claws to get a grip. Forward-facing eyes, meanwhile, are common in predators, such as cats and owls, that rely on vision to catch their prey. In particular, he argued, the big overlap in the fields of vision of primate eyes is best for judging short distances – whether an insect is within arm's length rather than whether a branch is within leaping range.

"In these forests, there would have been a treasure trove of flowers and fruits at the end of thin branches"

So the key traits of our early primate ancestors evolved, Cartmill proposed, because they were hunting insects on fine branches. "It's a logical argument," says Robert Sussman, who studies primate evolution at Washington University in St Louis, Missouri. But, he adds, it depends largely on comparisons with living animals rather than the fossil record.

Fossil teeth suggest that insects were not the only food of early primates. Their flat, round molars were better suited to grinding fruit and plant material than they were to eating bugs, Sussman argues. And if the ancestors of primates were adapted to eating insects, wouldn't they have lots of insect-eating descendants? In fact, the vast majority of living primates eat a mixed diet including insects and plants. The few specialist insect-eaters that do exist, like the tarsier, tend to use sound rather than vision to catch their prey.

So Sussman came up with another idea. Inspired by his studies of modern Madagascan lemurs that regularly tap nectar-rich flowers for food, Sussman and palaeobotanist Peter Raven proposed that primates evolved in tandem with flowering plants.

The first flowering plants, angiosperms, which appeared around 135 million years ago, were small insect-pollinated shrubs and herbs. But by around 55 million years ago, when the first true primates turn up, flowering plants had evolved into many families of trees, and dominated the forests that covered much of the world. In these forests, there would have been a treasure trove of leaf buds, flowers, fruits and insects at the end of slender new branches – a whole new feeding niche, and a powerful draw for animals like primates, bats and birds, which evolved rapidly at this time.

The plants evolved nectar-rich flowers and bigger, fleshier fruit that attracted animals like primates, and these animals in turn pollinated their flowers, ate the fruits and spread the seeds. The primates evolved grabbing hands and feet, and digits with nails and sensitive pads that helped them to move around these fine branches and manipulate the food there.

This angiosperm evolution hypothesis not only explains why primates evolved some of their key traits, but also the timing. "The timing is one of the best bits of supporting evidence we have for this theory," says Magdalena Muchlinski, who studies primate evolution at the University of Kentucky in Lexington.

Another piece of supporting evidence comes from a 2012 study comparing the diets and ecology of hundreds of living and extinct primates. José Gómez of the University of Granada, Spain, and Miguel Verdú of the Desertification Research Centre in Valencia found that helping flowering plants was a recipe for success. Fruit-eating primates that spread the seeds of the plants they fed on were less likely to go extinct, had larger ranges and gave rise to more new species. "It suggests that fruit eating and seed dispersal helped fuel primate evolution and diversification," says Gómez. ›

FRANS LANTING/CORBIS

Key primate traits could have evolved for hunting insects or reaching flowers

All this evidence is circumstantial, though. It doesn't prove that flowers rather than insects drove early primate evolution. On paper, both theories have their merits.

What was needed was hard evidence, but there were hardly any fossils from the period in question. The primate fossils that had been found all dated from 55 million years onwards. These early primates looked a bit like modern-day lorises or tarsiers. From the size of a mouse to the size of a cat, they fed on insects and fruit. Crucially, though, they all already possessed key primate traits such as forward-facing eyes, dextrous nailed fingers and grasping hands.

This means these key characteristics evolved earlier, probably in the time between the dinosaurs' demise 66 million years ago and the appearance of the first true primates around 55 million years ago. Unfortunately, the fossil record from this time is patchy, scarce and equivocal, made up largely of jaws and teeth. So when Gingerich asked Bloch to find a skull in a block of 56-million-old limestone, he was really hoping to find one of the "missing links" in the primate record – a transitional fossil with a mix of primitive and modern features. And that may be exactly what Bloch found.

Etching the rock away from fossils is a slow process. It was several years after the discovery of the skull before Bloch, working with Doug Boyer of Duke University in Durham, North Carolina, found that much of the animal's skeleton was hiding within. "It was remarkable in many ways," says Bloch, now a palaeontologist at the Florida Museum of Natural History in Gainesville.

Arboreal acrobat

The fossil belonged to a species that was new to science, *Carpolestes simpsoni*. In life it was rat-sized, with a long tail. It had huge serrated premolars, probably used to saw open fibre-rich fruits and nuts. It may have eaten the odd insect, but its eyes were sideways-facing. What it did have, though, was grasping hands and feet, with nails on its big toes only. With claws on its other digits, *Carpolestes* would have easily scrabbled up and down bigger branches, much like a squirrel. The details of the fossil were published in 2003 in the journal *Science*.

"It was an extraordinary specimen," says primatologist Mary Silcox of the University of Toronto, Scarborough. "It was very influential in people's thinking." And the fossil doesn't fit with Cartmill's visual predation theory as it was originally proposed, according to which grasping hands and forward-facing eyes should have evolved at the same time.

Instead, *Carpolestes* points to a scenario first proposed by anthropologist Tab Rasmussen of Washington University back in 1990, after he spent many nights studying the woolly opossum. This arboreal acrobat, found in the rainforests of Costa Rica, is not related to the primates but has evolved similar characteristics, including forward-facing eyes and the ability to grasp. Rasmussen thought the marsupial evolved these traits because it behaves like the early primates. It picks fruit on thin branches, clinging with its hands and feet as the branches shake and pitch violently under its weight. But the woolly opossum is an adept visual predator too, snatching moths and other insects.

"An ancestral primate may have evolved forward-facing eyes to give it 'X-ray vision' in forests"

Rasmussen suggested our early primate ancestors evolved grasping hands and feet as they climbed on slender branches in search of fruits, flowers and insects, much as Sussman had suggested. Later they evolved enhanced vision to catch more insects, as Cartmill had suggested. So both ideas could be right.

Carpolestes fits nicely with this flowers first, insects later scenario. But in 2008, theoretical neurobiologist Mark Changizi at 2AI Labs in Boise, Idaho, threw a spanner in the works by suggesting that the whole rationale behind the insect predation idea was wrong. Animals, including predators, didn't evolve forward-facing eyes to judge distances, he argued – it helps, but there are other ways that the brain can do this. Instead, its primary advantage is to help animals see in environments cluttered with leaves and branches.

Hold a finger in front of you and look at what's behind it. With both eyes open, you can effectively see through your finger. Close either eye, though, and part of the background disappears. "Our eyes give us X-ray vision," says Changizi.

This "X-ray vision", however, only works for

CHRISTIAN ZIEGLER/MINDEN PICTURES/FLPA

objects narrower than the distance between our eyes. So large animals with far-apart eyes will be able to see through most branches and leaves. If they live in a leafy environment, they will get the best view of their world if both eyes face forwards – the increased view ahead more than compensates for lost vision behind. Small animals like mice don't benefit from this effect because most leaves are wider than the distance between their eyes. They are better off with sideways-facing eyes.

If this theory is right, Changizi realised, the degree of overlap in the visual fields of the eyes of animals should depend on two things: their body size (which largely determines the distance between the eyes) and whether they live in a leafy environment. In a study of 319 diverse mammals, he showed that there was a correlation between body size and overlap in mammals living in forests, but not in uncluttered environments. So once primates took to the trees, a relatively large ancestral primate may have evolved forward-facing eyes to see better in forest canopies.

This fits well with the flower idea, but would rule out the insect-hunting hypothesis. Cartmill, now at Boston University, dismisses Changizi's challenge, pointing out that Thomson's gazelles and cheetahs both live in grasslands, but only the predator has eyes facing forwards. "Optic orientation in mammals doesn't correlate with clutter," he says.

Changizi, however, says that stalking cheetahs will be trying to see through grasses and bushes, whereas gazelles' views will be largely uncluttered when they stand tall to check for predators. Small predators like weasels also tend to have sideways-facing eyes, he points out, which can be explained by his X-ray vision hypothesis but not by the idea that stereoscopic vision is the more important of these factors.

Put Changizi's study and the fossil of *Carpolestes* together, and the flower idea looks like the clear winner. But there is another twist to the tale. Many primatologists, including Bloch and Sussman, think that the group *Carpolestes* belongs to, the Plesiadapiformes, were close cousins of the early primates and thus very similar to them.

Others think their features are so un-primate-like that they must have been much more distant relatives. "If you put skin on them and had them run around a zoo, you wouldn't think they look like primates," says primatologist Dan Gebo of Northern Illinois University in DeKalb. If so, *Carpolestes* does not tell us what early primates were like after all. "The fossil is irrelevant," says Cartmill.

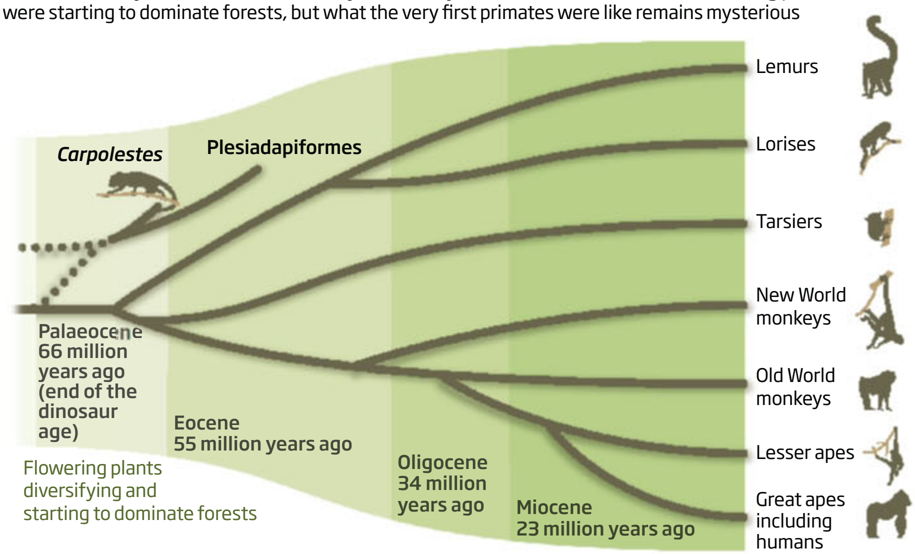
So who is right? The only way to settle the issue will be to find more fossils from that vital period that are undoubtedly those of the direct ancestors of primates. Fossil-hunters are looking, but it could take a long time and an exceptionally patient, keen pair of eyes to spot them. "They're going to be tiny," says Gebo. "We're more likely to find teeth and jaws than entire skeletons, and a jaw might only be a few millimetres long."

And, in keeping with their divided opinions, primatologists can't decide where to look. Some, like Gebo, favour sites in China, Europe and North America as this is where later primates have been found. Others think the absence of early primates in these areas suggest they originated elsewhere, so prefer to hunt in India and Africa.

Surely, though the evidence is out there, if we can only find it. Perhaps even as you read this, the rock containing that vital missing link is being painstakingly etched away by another graduate student. In the meantime, the next time you look at a flower, remember that blossoms may have made us what we are today. ■

Your family tree

Primate ancestry can be traced back nearly 60 million years, to around the time that flowering plants were starting to dominate forests, but what the very first primates were like remains mysterious



Our true dawn

The argument over when the human lineage first appeared is on the verge of being settled – with colossal consequences for our evolutionary past, finds **Catherine Brahic**

LINE them up in your head. Generation after generation of your ancestors, reaching back in time through civilisations, ice ages, an epic migration out of Africa, to the very origin of our species. And on the other side, take a chimp and line up its ancestors. How far back do you have to go, how many generations have to pass, before the two lines meet?

This is one of the biggest and hardest questions in human evolution. We know that at some point we shared a common ancestor with chimps, but exactly when, and what that ancestor was like, have been maddeningly hard to pin down. Palaeontologists have searched for fossil remains, and geneticists have rummaged through the historical documents that are human and chimp DNA. Both made discoveries, but they did not see eye to eye.

No more. New estimates for when our lineage and chimps went their separate ways suggest that some of our established ideas are staggeringly wrong. If correct, they demand a rewrite of human prehistory, starting from the very beginning.

When was that beginning? The obvious first place to look for answers is in the fossil record. But fossil humans – or more strictly hominins, the group that includes us and all our extinct relatives from after the split – are notoriously thin on the ground and difficult to interpret.

Geneticists have more to work with. DNA contains telltale traces of events in a species' past, including information about common ancestry and speciation. In theory, calculating the timing of a speciation event should be straightforward. As two species diverge from a common ancestor their DNA becomes increasingly different, largely due to the accumulation of random mutations. The amount of genetic difference between two related species is therefore proportional to the length of time since they diverged. To estimate when the human-chimp split occurred, geneticists can simply count the differences in matching stretches of chimp and human DNA and divide it by the rate at which mutations accumulate. This is known as the molecular clock method.

But there's a catch. To arrive at the answer you have to know how fast the mutations arise. And that leads you back to square one: you first need to know how long ago we split from chimpanzees.

To get around this catch-22, geneticists turned to orang-utans. Fossils suggest that they split from our lineage between 10 and 20 million years ago. Using this fudge, geneticists arrived at a mutation rate of about 75 mutations per genome per generation. In other words, the offspring of humans and chimps each have 75 new mutations that they did not inherit from their parents.

Fossils or DNA

This number rests on several big assumptions, not least that the orang-utan fossil record is a reliable witness – which most agree it is not. Even so, it led to a guess that human ancestors split from chimpanzees between 4 and 6 million years ago.

When fossil-hunters hear this number, they cry foul. The lower end of the estimate is particularly hard to swallow. *Australopithecus afarensis* – an early hominin from east Africa – already has distinctly human characteristics yet dates back at least 3.85 million years. Its canines were small, for instance. And it walked upright.

Both of these traits are considered hominin, meaning they evolved in our lineage after the split and did not appear on the chimp side. And yet it is hard to see how they could have evolved so quickly, in perhaps as little as 150,000 years after the split.

"Geneticists ignored the palaeontologists completely," says Owen Lovejoy of Kent State University in Ohio. "We would get estimates around 4 million years, and yet there are unmistakable and highly evolved hominins that go back almost 4 million years. To claim a 4-million-year divergence date is just silly."

Even a 5 to 6-million-year split was met ›

ANDREAS PREIS

"This will affect every event in human evolution, from the divergence of our lineage to Out of Africa"

with scepticism. That's largely because of three recently discovered fossils from Africa dating from around the same period. All three predate *Australopithecus*, but still bear unmistakable marks of humanity. Though the interpretation of the remains is controversial, many regard them as being post-split.

Simply put, the palaeontologists were sure there was little chance that the DNA results were accurate. Humanity, they affirmed, had to be older than the geneticists claimed.

History looks set to prove them right. Since 2009, researchers studying human populations have for the first time been able to observe mutations almost as they happen. And that makes all the difference. Instead of relying on an estimate based on rare fossils, we can now watch the molecular clock ticking in real time. "Until we were able to compare genomes of children with their parents, we could not estimate the mutation rate in humans," says Aylwyn Scally of the University of Cambridge.

In September 2012, Augustine Kong of deCODE Genetics in Reykjavik, Iceland, and colleagues published one such groundbreaking study. After scanning the genomes of 78 children and their parents to count the number of new mutations in each child's genome, they found that every child carries an average of 36 new mutations. Crucially, that is half what was previously assumed, meaning the molecular clock ticks more slowly than we thought – pushing the human-chimp split further back in time.

How far back exactly? In 2012, Kevin Langergraber at Boston University and his colleagues solved another piece of the puzzle. Mutation rates in studies like Kong's are measured per generation. To convert this into an estimate of when our ancestors split from chimps, you need to know how long a generation is – in other words, the average age at reproduction. We have a good handle on this for humans, but not in other primates. For chimps, estimates ranged from 15 to 25 years.

Using data from 226 offspring born in eight wild chimp populations, Langergraber found that, on average, chimps reproduce when they are 24-and-a-half. Based on the new numbers, his team estimated the human lineage went its separate way at least 7 million years ago, and possibly as far back as 13 million years ago.

"It's clear that if this is right, most textbooks dealing with the history of our species will have to be rewritten," says Klaus Zuberbühler at the University of St Andrews, UK, who helped collate data for the study. "The significance can hardly be underestimated."

John Hawks of the University of Wisconsin-Madison agrees. "I think that this will affect pretty much every event in human evolution, from the initial divergence of our lineage to the dispersal out of Africa."

Perhaps the most significant implication is in the search for the earliest members of the human tribe. For now *Australopithecus* is the oldest accepted hominin, but an earlier split brings other species into the frame.

Golden age

The late 1990s and early 2000s was a golden age of discovery for palaeoanthropologists. In the space of a decade, the remains of three potential new hominins were discovered in the deserts of east and central Africa. The most complete was *Ardipithecus ramidus*, a 4.4-million-year-old skeleton from Afar, Ethiopia, nicknamed Ardi. This was later joined by *Sahelanthropus tchadensis*, 6 to 7 million years old, and *Orrorin tugenensis*, about 6 million years old.

Ardipithecus is by far the best known of the three. Roughly the size of a chimp, the skeleton includes human-like teeth, a small skull and the lower limbs of an animal that could walk upright (though it also had an opposable big toe for clasping branches). A possible relative – *Ardipithecus kadabba* – has also been identified from teeth and a few bone fragments, pushing back the origin of the genus to around 5.8 million years ago.

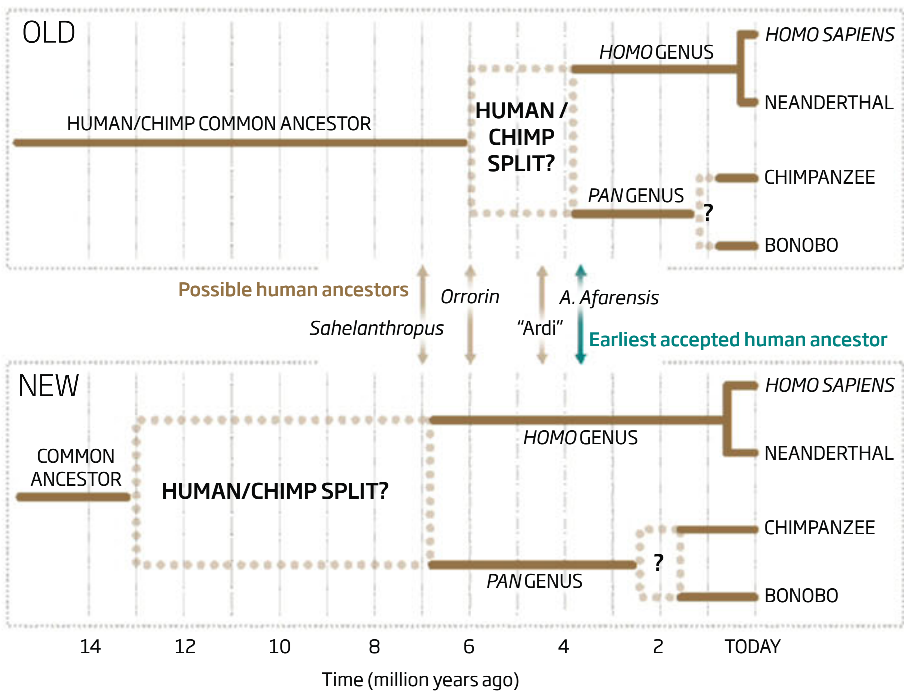
Sahelanthropus is known from a single skull from Chad, nicknamed Toumai (see photo, right). Like *Ardipithecus*, its teeth are small and human-like, and the middle of its face is short – another human trait. The shape of the hole where the spine would have inserted at the base of the skull hints that it could walk on two legs, although this is hotly debated.

Orrorin, meanwhile, is known only from a handful of teeth plus some leg and finger bones, which suggest it also walked upright but still climbed trees.

All together the bones would barely fill two shoeboxes, but they made a big noise. It was generally thought that when we finally managed to dig up the earliest hominins, we would find something that looked like a chimp. And yet Ardi, Toumai and *Orrorin* had distinctly human characteristics. "They upset the received wisdom," says Tim White of the University of California, Berkeley, who led the Ardi discovery.

Fork in the evolutionary road

We used to think our ancesters diverged from those of chimps 4 to 6 million years ago (top) but new discoveries have pushed it back in time (bottom), with big consequences for our understanding of the human family tree



DIDIER DESCOUENS

The human-like skull of Toumai; is it our earliest known ancestor?

Some were quick to claim them as human ancestors. But the old molecular clock said otherwise: they were too early. And so they were dismissed as side branches on the family tree, dead-end experiments in evolution with little or no relevance to the main event.

Now, with the new molecular clock estimates, they are being welcomed back into the fold. "The argument that they are too early has evaporated," says White, who thinks all three are members of the same genus.

The timing certainly looks right. "If you look at the consensus of recent mutation-rate measurements, *Sahelanthropus* is just about on the boundary," says Scally, who published a review in 2012 of the revisions and their consequences for evolution. "Whether it's a human, a proto-human, or in a period when humans and chimpanzees are gradually separating, I don't think anyone can say. But from a genetic perspective, I certainly don't think you can rule it out, which people used to do."

The anatomy makes sense too, says White. "It seems to those of us who study these fossils that the way you get from the last common ancestor to *Australopithecus* is via something like Ardi. It had already evolved in the direction of *Australopithecus*. In other words, it's post-split."

"Does Ardi represent a species that is on the direct line?" he continues. "We don't know because we don't have enough fossils from other places yet. But we can't rule it out."

Another possibility that cannot be ruled out is that the split is even further back in time. The slow accumulation of mutations means that new estimates of the mutation rate still have big margins for error. In general, geneticists and palaeoanthropologists seem comfortable with a revised figure of 7 to 8 million years. Some, however, go further.

"For me, a 13-million-year-old split could be right on the button," says Lovejoy. "If you go back 10 to 15 million years, the planet was covered in apes, many beginning to show the kinds of anatomical adaptations that you see in modern humans."

Lovejoy is out on his own, though. A week after Kong and colleagues published their new estimate, another team – including many of the same researchers – published another. They analysed DNA from more than 85,000 Icelanders, focusing on short stretches of DNA called microsatellites. According to co-author David Reich of Harvard University, these are a more reliable record of mutations.

"15 million years ago the planet was covered in apes, many beginning to show adaptations you see in us"

The rate they found was not quite as slow as Kong's. As a result, their estimate of the timing of the split is a more constrained 7.5 million years.

There are a few other loose ends to tidy up. Another problem with Kong's estimate, says Reich, is that if you use it to date the split between orang-utans and African apes – humans, chimps and gorillas – you get something in the range of 30 million years, wildly inconsistent with the maximum 20 million years suggested by the fossil record.

In an attempt to reconcile the two, Scally has proposed that as our ancestors evolved from small primates into large apes, the number of mutations they accumulated with each passing generation decreased. This is in keeping with what is seen in other mammals. "It is observed quite widely, including in primates, that species with larger body size tend to have longer generation times," says Scally. Longer generations mean slower mutation rates.

This would be plausible, says Reich, if it weren't that for it to be right, mutation rates in our ancestors and in orang-utans would have had to have dropped at exactly the same time. "I find such an extreme event hard to believe," he says. Despite that, Reich says, "Scally's hypothesis is probably the best one out there."

Quibbles aside, it now seems certain that our lineage is considerably older than we once thought. And that has consequences for the rest of human prehistory. The molecular clock has been used to date a number of key events, not least when our ancestors left Africa. That has been estimated by looking at genetic differences between the Yoruba people of Nigeria and Europeans and Asians.

Early genetic estimates suggested this happened 50,000 years ago. So when fossil remains in Israel and archaeological sites in India were found to be around 100,000 years old, there was some explaining to do. The Israeli bones were dismissed as the remains of an early, dead-end excursion, and the Indian sites as an error, pure and simple. The new molecular clock resolves the discrepancy, pushing the departure back to between 90,000 and 130,000 years ago.

It does something similar for the split between us and Neanderthals. Bones found in a cave in Atapuerca, Spain, and attributed to the probable ancestor of Neanderthals, *Homo heidelbergensis*, date to between 400,000 and 600,000 years ago. But this created a problem as the molecular clock suggested *H. heidelbergensis* appeared after that. But the new estimates mean it is in fact around 500,000 years old.

Other key events await revision. But the main finding is clear. The human lineage is significantly older, and our closest living relatives more distant, than we once thought. We are used to thinking of ourselves as separate and distinct from the rest of the animal kingdom. We just got a bit more separate, and a bit more distinct. ■

BRENT STIRTON/REPORTAGE BY GETTY

New to the family

Recent fossil discoveries are forcing us to rethink a crucial period in human evolution. **Colin Barras** reports

***Australopithecus sediba*, a possible direct ancestor**

IT'S instantly recognisable – one of the most iconic scientific illustrations of all time. The original version of *The March of Progress*, drawn for a popular science book in 1965, lined up all the early relatives of humans known at the time in chronological order. The artist, Rudolph Zallinger of the Peabody Museum of Natural History, sketched them striding purposefully across the page, seemingly becoming more advanced with each step. It gave the impression – despite the book saying otherwise – that human evolution was a linear progression from small-brained tree climbers to bipedal big-brained modern humans.

This much-copied image has been criticised for oversimplification, but until recently our evolutionary past was not thought to be a great deal more complex, give or take the odd dead-end side shoot. Now, however, a string of new fossils are forcing a rethink.

In particular, it looks if as many species of human-like apes were around during the crucial period from 2.5 to 1.8 million years ago, when the first upright apes with relatively large brains evolved. What's more, the East African hominin long seen as our direct ancestor may be just a cousin, with our true roots lying further south. Our family tree may have to be completely redrawn.

The story once looked so straightforward. Around the beginning of the 20th century, anthropologists began unearthing fossils of a big-brained, bipedal species later dubbed *Homo erectus*. It lived from around 1.8 million to 550,000 years ago in both Africa and Asia, and there is now little doubt that it was one of our direct ancestors. It could make sophisticated stone tools and probably controlled fire, too.

Soon afterwards, fossils of even earlier human relatives began to emerge in Africa. The australopiths, as they are collectively known, first appeared around 4.5 million years ago, long before *Homo erectus*. They walked on two legs like us but had much smaller brains. So how were they related to *Homo erectus*? A few years before *The March of Progress* was published, anthropologists thought they had found the "missing link".

A hominin found in Tanzania's Olduvai gorge in 1960 neatly fits the australopith-*Homo* gap. The fragmentary remains belong to a species with a brain roughly 50 per cent larger than the average australopith, but half the size of our own brains. It first appeared around 2.3 million years ago, just as most australopiths were vanishing but before *Homo erectus* had evolved. And the East African region it lived in had formerly been home to small-brained australopiths, and was later inhabited by *Homo erectus*.

Its discoverers opted to make this hominin the first member of our genus, naming it *Homo habilis*. For the last 50 years, *Homo habilis* has been central to the story of our origins, says Lee Berger at the University of the Witwatersrand in Johannesburg, South Africa. Put simply, *Homo habilis* was the right hominin in the right place at the right time to be our direct ancestor.

It wasn't the only hominin around in this place at this time. In the years before *Homo habilis* was discovered, another australopith now known as *Paranthropus boisei* had been found. *P. boisei* has some unusual, almost gorilla-like features, though, and is clearly a side branch rather than a direct ancestor.

The evidence, then, seemed to point to a simple picture not wildly different from *The March of Progress*. And despite the many discoveries made since the 1960s, a few researchers still think the basic picture is this simple. According to Tim White at the University of California in Berkeley, the hominin evolutionary tree looks rather like a classic cactus, with one central lineage and only the occasional side branch, such as *P. boisei* (see diagram, page 28).

But others think recent discoveries point to a much more complicated picture. Hints that our origins were more tangled appeared just a few years after the discovery of *Homo habilis*. In 1972, a research team working in the Koobi Fora region of northern Kenya found a skull from the time that *Homo habilis* was alive with a brain slightly larger, and a face considerably broader and flatter – that is, with prominent cheekbones – than that of any known specimen of *Homo habilis*.

So where does this 2-million-year-old skull fit within our evolutionary tree? Is it related to *Homo habilis*, despite its unusual appearance? Or was it a separate species?

Direct ancestor

Anticipating the second outcome, one researcher called it *Homo rudolfensis*. But Meave Leakey, based at the Turkana Basin Institute in Nairobi, Kenya, and a member of the team that found the skull, prefers to stick to specimen numbers. The skull's number is KNM-ER 1470, or 1470 for short.

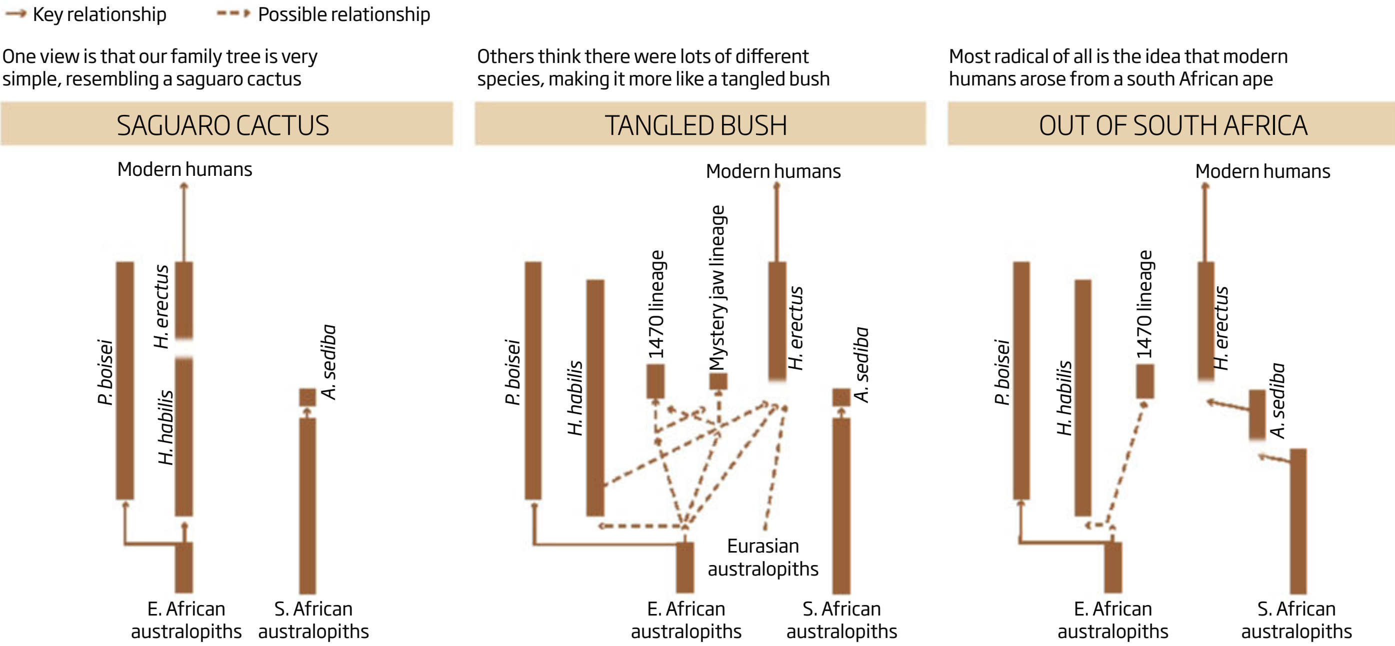
For almost 40 years, the 1470 skull remained an anomaly. That changed in 2007 when Leakey and her colleagues began finding similar fossils in the same region. "It's incredibly satisfying to finally have found fossils that match 1470," she says.

The discoveries, which include a new skull fragment with the flat facial features of the 1470 skull, were revealed in 2012. The new find belonged to a juvenile, not an adult. This shows that 1470 was no anomaly, say the team, but instead belonged to a distinct species with a flat face. Although in some respects that flat face is rather like ours, it is far too broad to be one of our direct ancestors, says Fred Spoor of the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, who worked with Leakey on the new Koobi Fora fossils.

With *Homo habilis* and *P. boisei*, this means at least three species of hominins were living in East Africa around 2 million years ago. Or were there more? One of the enduring mysteries in human evolution is where the first species widely accepted as our direct ancestor – *Homo erectus* – originated. Its roots are a mystery, with some researchers even suggesting it came out of Eurasia about 1.8 million years ago. ›

Three competing visions of our family tree

The fossils found so far can be interpreted in many different ways



However, a scrap of skull from Koobi Fora that dates back 2 million years calls this theory into question. It might be small, but this fragment is strikingly reminiscent of *Homo erectus*, raising the tantalising possibility that it lived in East Africa at the same time as *Homo habilis* and the 1470 lineage. The fact that they coexisted doesn't rule out *Homo habilis* as the direct ancestor of *Homo erectus*, but it does suggest a more complex relationship than we thought.

Four hominin species living at the same time would be exceptional. And yet Bernard Wood at George Washington University in Washington DC suggests another hominin was also present.

This species is the least known of them all. In the 1990s, Wood analysed all the Koobi Fora material discovered up until then. Although the 1470 skull lacked a jawbone, Wood predicted that it would have had a powerful jaw with large teeth. As it happened, a lone jawbone in the Koobi Fora collections matched his expectations. Ever since, this fossil has been thought to belong to the 1470 lineage.

No longer. Leakey and her team have since found two jawbones that are a much better fit for the new flat-faced specimen – and the 1470 skull – than the jawbone Wood identified. "You win some, you lose some," says Wood.

But that leaves the unusual fossil jaw. In a commentary published alongside the 2012 Koobi Fora research, Wood made a bold suggestion: the jawbone may be evidence of yet another hominin lineage alive 2 million years ago. Leakey's team doesn't necessarily share this interpretation, Spoor stresses.

Potentially, then, East Africa was home to five species of hominin just as our genus was finding its feet. How they are all related is far from clear (see above), but *Homo habilis* still looks like our most likely direct ancestor.

Out of South Africa

Or so it seemed until an unexpected discovery thousands of kilometres to the south of Koobi Fora and Olduvai Gorge. In 2008, Berger's then 9-year-old son Matthew found the first fossil of yet another hominin, at a site in South Africa called Malapa. Berger's team soon unearthed a pair of 2-million-year-old skeletons so exquisitely preserved that there may even be bits of skin still attached to some of the bones. They unveiled this new hominin in 2010, calling it *Australopithecus sediba*.

Along with the East African hominins, this means that there were as many as six species living in Africa 2 million years ago – a level of diversity unprecedented in 7 million years of hominin evolution. *A. sediba* is arguably the most surprising of the six.

In some ways, such as brain size, *A. sediba* resembles other australopiths. But what makes it a strange ape is that in other ways it resembles humans (see "A curious ape", opposite). "Across the body, head to toe, *A. sediba* shares a remarkable number of characters with *Homo*," says Berger.

The more Berger looked at the skeletons, the more convinced he became that *A. sediba* is a pivotal species in our ancestry. He thinks the characteristics *A. sediba* possesses, including small *Homo*-like teeth and a tapered *Homo*-like waist, put it on the lineage leading to *H. erectus*.

But *A. sediba*, as critics are quick to point out, is everything that *Homo habilis* is not: it's a small-brained australopith living in southern Africa 2 million years ago – a good 300,000 years after the larger-brained *Homo habilis* first appeared in East Africa. They say *A. sediba* is the wrong hominin in the wrong place at the wrong time to be our direct ancestor. "It's just too young to lead to *Homo*," says Spoor.

Berger has a simple answer to this criticism: *Homo habilis*, the oldest member of our genus, is not one of our direct ancestors. Its relatively large human-like brain gives the impression that it is, but appearances can be deceptive. "*A. sediba* is a better candidate for the origin of *erectus* than *habilis* ever was," he says. "Its hand, dentition and what we can see of its skull – other than the cranial capacity – are more like those of *Homo erectus*."

What this means, he says, is that large brains evolved twice. A small-brained East African australopith evolved into the larger-brained *Homo habilis* around 2.3 million years ago, but this lineage died out. A little later, a southern African australopith closely related to *A. sediba* evolved into the large-brained *Homo erectus*, and this lineage went on to give rise to the rest of humanity. So Berger is not claiming that *A. sediba* itself is our direct relative, but that our actual ancestor was a very similar australopith that lived in around the same region at around the same time.

Berger's ideas have met strong criticism. White, for instance, dismisses Berger's claims for *A. sediba*. Where Berger sees a suite of *Homo*-like characteristics, White sees a peculiar mixed anatomy that couldn't possibly serve as the blueprint for our genus. But *A. sediba* is, at least, indisputably a new species, says White. The same can't be said of all the East African finds.

"Wood and his colleagues are partitioning the record too finely by saying these minor variations are indicative of separate lineages," White says. There are differences between modern humans, but we all belong to the same species, he says. Likewise, he argues, all the finds from Koobi Fora belong to one species, despite the differences in shape.

Spoor rejects White's argument for the Koobi Fora fossils. "I'd like to see Tim present some statistics that show there is any primate species diverse enough to combine all of the features we found," he says.

With the shapes of the bones open to interpretation, is there any other way to address the issue? Remarkably, there is. The carbon in the enamel of teeth holds clues about the kinds of food their owner ate. If the owners of the differently shaped bones had distinctive diets, it would boost the argument that they are separate species.

Until recently, researchers thought all hominin diets were relatively similar. Most australopiths probably ate seeds and tubers, while members of the *Homo* genus may have added a little meat to their vegetables. We now know things were a lot more complicated.

A curious ape

Australopithecus sediba **has a strange mix of characteristics**

Apelike

- **Small brain not much larger than a chimpanzee's**
- **Shrugged shoulders best for climbing, not running**
- **Long arms, again suited for climbing**
- **Conical rib cage prevented arms swinging. Humans have a cylindrical ribcage**
- **Narrow, weak heel forced it to shuffle along with short, quick steps**

Human-like

- **Brain shape shows expansion of prefrontal cortex, crucial for reasoning**
- **Small teeth**
- **Precision grip suited for tool use**
- **Pelvis, knee and hip adapted for upright walking**

LEE BERGER, COURTESY OF THE UNIVERSITY OF THE WITWATERSRAND

In 2011, Thure Cerling at the University of Utah in Salt Lake City led an analysis of *P. boisei* teeth. The species had such large, durable teeth that it had always been considered a quintessential seed and nut eater. But Cerling's analysis suggested, surprisingly, that *P. boisei* might have spent its days grazing grass – a specialist diet unique for a hominin and virtually unheard of among apes.

In 2012, Berger and his colleagues took a look at the carbon isotopes in *A. sediba*'s teeth. They revealed a diet unusually rich in tree leaves, fruits – even bark – despite the fact that grasses dominated its environment. Again, it's a specialist diet unlike that of any other hominin.

A 2013 study by Cerling hints at dietary specialisations in some of the other hominins alive 2 million years ago. Most significantly, the unusual flat-faced 1470 lineage may have shared a similar diet to *P. boisei* – teeth that have been associated with the 1470 lineage carry the same unusual grass-rich isotopic signature. Fossils normally associated with *Homo habilis*, meanwhile, suggest this species was less reliant on grasses for its food.

Dietary work, then, supports the idea that there were indeed several hominin species living cheek by jowl, by showing that they were exploiting different resources. "This work really does open up the issue of exactly how these guys were parsing up the space," says Cerling.

What it doesn't do is resolve the issue of whether *Homo habilis* or a *sediba*-like australopith was our direct ancestor. Only the discovery of clear intermediates will help settle this argument. But if the past few years are anything to go by, new finds are likely to raise far more questions than they answer.

Wood, at least, is confident of the way the wind is blowing. He predicts that by 2064 – a century after the first *Homo habilis* finds were described, and 99 years on from *The March of Progress* – our family tree will be even bushier and more tangled than he currently envisions it. If the discoveries keep coming thick and fast, we might not have to wait that long to find out whether or not he is right. ■

Lee Berger unearthed a new species of hominin at Malapa, South Africa

BRENT STIRTON/REPORTAGE BY GETTY

CERTIFICATE
OF
REGISTRATION
This is to certify that
HUMANITY
was born
CIRCA 2 MILLION YEARS AGO
in ~~AFRICA~~ EURASIA
REGISTRAR.
DEPUTY REGISTRAR.
DATE 21ST CENTURY
AUTHENTICATED
Official
AUTHENTICATED

Out of Asia?

To suggest that our ancestors might have hailed from anywhere but Africa was once heretical. The famous hobbit has changed all that, says **Colin Barras**

IT WAS the evolutionary find of the century: a diminutive human-like fossil that called into question basic assumptions about the origin of our species. The discovery in 1924 of the Taung child astonished and unsettled researchers because it didn't fit the orthodox picture of human evolution. It came from a continent few thought was key: Africa.

Hardly anyone now doubts that Africa was the cradle of humanity – the idea goes back to Darwin after all – but early in the 20th century most researchers believed we evolved in Eurasia. The Taung child was the first fossil to challenge that orthodoxy. Its discoverer, anthropologist Raymond Dart of the University of the Witwatersrand in Johannesburg, South Africa, earned himself an academic mauling for placing it in a brand new hominin category he named *Australopithecus* ("southern ape"). It would take his critics several decades to admit they were wrong.

But could they have been right about Eurasia after all? Recently, some prominent researchers have come round to the idea that hominins may have left their African cradle much earlier than we thought and undergone critical evolutionary transitions further north. There are even whispers that one of the most important evolutionary events of all – the appearance of our genus, *Homo* – may have occurred under Eurasian rather than African skies. And the catalyst behind this radical rethink? Another diminutive hominin called *Homo floresiensis*, aka the hobbit, discovered in Indonesia in 2003.

From the beginning, the hobbit, like the Taung child, did not fit the standard picture of human evolution. Some of the remains found on the Indonesian island of Flores were just 18,000 years old. So the hobbit was alive at least 10,000 years after every other hominin except our own species had become extinct. The one relatively complete skeleton belonged to an individual barely a metre tall. Bone fragments suggested other individuals were even shorter.

Then there was the skull. The cranial volume of the single hobbit skull found so far is around 420 cubic centimetres, about one-third the size of a modern human's. Yet stone tools found with hobbit bones suggested that the hominin was capable of sophisticated behaviour. "It drove me nuts in 2003," says Peter Brown at the University of New England in Armidale, Australia, who led the team that made the discovery. "What do you compare a unique small-bodied, small-brained hominin dated to only 18,000 years with?"

Some felt the answer was obvious. Some modern humans are born with unusual diseases that arrest growth of the cranium. The hobbit skull could have belonged to one such individual and, in fact, be human.

Robert Martin at the Field Museum in Chicago is a proponent of this idea. He points out that hominin brains have gradually got bigger throughout our lineage's evolutionary history. If the 18,000-year-old hobbit was really a product of human evolution, it should have had a skull roughly the same size as ours, he says. Instead it is similar to one of Dart's australopiths, which went extinct about 1.2 million years ago. The body size is also unusual, he adds, but then again some human populations today are small. "The most likely explanation for that small brain is a pathology – especially considering we only have the skull from one individual," says Martin. Unusual asymmetries in the hobbit skull also suggest that there was something unhealthy about this individual, according to two more supporters of the idea, Robert Eckhardt at Pennsylvania State University in University Park and Maciej Henneberg at the University of Adelaide, Australia.

For Dean Falk at Florida State University in Tallahassee, this kind of scepticism is no more than a repeat of the reception that greeted Dart in the 1920s. Having studied scans of ›

TELEGRAMME STUDIO

DAVID MDZINARISHVILI/REUTERS

> "The idea that the 'hobbit' evolved directly from an australopith threatens the central narrative of human evolution"

the hobbit skull to work out the shape of its brain, she concludes that *Homo floresiensis* is indeed a new species because of its tiny skull – not in spite of it. Any unusual asymmetry is simply down to crushing during burial. But she accepts that this interpretation attracts criticism because it threatens the orthodoxy. "The moment the first *Homo floresiensis* paper was published there was a vociferous group of scientists screaming 'no, no, no'," she says. "It was the same old story as Taung – things haven't changed."

Falk's work suggests *Homo floresiensis* is closely related to a larger extinct hominin called *Homo erectus*, which we know lived in Indonesia between about 1.7 million and 550,000 years ago. With evidence of 840,000-year-old stone tools on Flores, it is possible that a population of *Homo erectus* arrived on the island around that time and became isolated there. Animals often shrink when isolated on islands, so that may partly explain the hobbit's small size.

It is another point on which Martin begs to differ. "There is simply no good precedent for island dwarfism affecting brain size in any primate," he says. The debate continues to rage. "It's very acrimonious," says Falk.

Meanwhile, Brown and others have shifted their attention below the hobbit's neck. There may be only one skull, but there is a veritable treasure trove of bones belonging to at least four hobbits. These show a consistent pattern of features, and together they indicate that hobbits had shoulders, wrists, limb proportions and feet that are, if anything, even more bizarre than the contentious skull. "There were just so many primitive features that the hobbit team began to talk seriously about *Homo floresiensis* being derived from something more primitive than *Homo erectus*," says William Jungers at Stony Brook University in New York, who led some of the analyses. According to Brown, somewhere towards the very top of the list of the hobbit's likely recent ancestors is one of Dart's australopiths.

This idea borders on the incendiary. It is one thing to declare the hobbit a valid species and break the cardinal rule that hominin brains get bigger over time. But to go further and suggest the tiny hominin evolved directly from an australopith threatens the decades-old central narrative of the human evolutionary story.

"We're taught that *Australopithecus* only ever lived in Africa – that's textbook," says Falk. Conventional wisdom suggests the australopiths evolved in Africa about 4 million years ago and died out there 2.8 million years later. Perhaps it was their short legs that discouraged them from making the long trek out of Africa. Certainly it wasn't until the taller members of our own genus appeared, right towards the end of the australopith age, that hominins began to explore the wider world.

Out of Africa, then back again?

The hobbit remains hint at an alternative. Perhaps an australopith did manage to escape Africa before the *Homo* genus evolved, and perhaps it survived long enough in Eurasia to evolve into the hobbit.

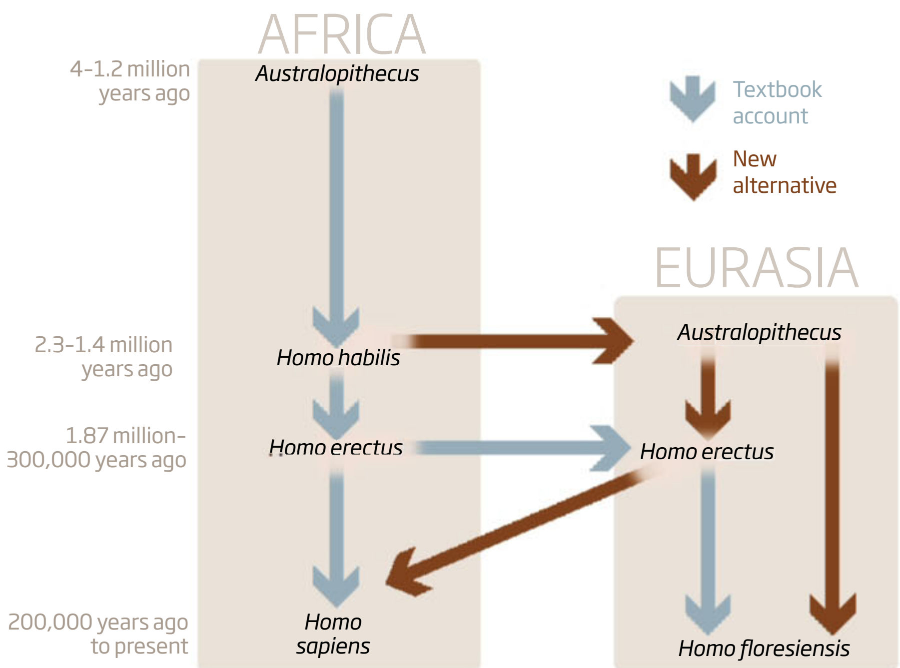
If so, shouldn't we have found some fossil evidence for these ancient Eurasian australopiths by now? Not necessarily, says Brown. Environmental conditions in East and South Africa favoured preservation of human fossils in a way that conditions across Asia did not, he says. For Martin, however, the very idea of Eurasian australopiths is untenable. "I can't understand my colleagues," he says. "They are incredibly careful to stamp all over suggestions of anything remotely out of the ordinary in human evolutionary thought, and yet some of them swallow this notion completely. There's not a scrap of fossil evidence to support this idea."

That's not entirely true, though. There is one site in Eurasia that could fit with the idea that australopith-like hominins made it out of Africa. What's more, there are hints that these enigmatic Eurasian australopiths did more than evolve into the hobbits found on Flores: they may have given rise to our own genus.

In 1991, researchers excavating the medieval town of Dmanisi, Georgia, in the Caucasus came across the earliest hominin remains found outside Africa so far. There is still some debate over exactly where the 1.77-million-year-old Dmanisi hominins fit in the human evolutionary tree, but most would classify them as *Homo erectus*. Their age and primitive features suggest they were among the earliest members of this species, implying that *H. erectus* wasted little time in leaving the East African region in which it first appeared perhaps 1.87 million years ago. Conventional thinking has it that this was the first time a hominin ventured out of Africa, with Dmanisi

Globetrotting ancestors

We used to think our genus, *Homo*, evolved in Africa, but recent finds could mean that our forebears took a detour to Eurasia




UNIVERSITY OF NORTH TEXAS/AP/PA

Excavations in the Caucasus could add a twist to the "out of Africa" tale of human evolution

offering a unique snapshot into the very moment that humans went global.

Then, in 2011, came surprising news from Dmanisi that challenged this picture. Continued excavations had found evidence that the Georgian site was first occupied at least 1.85 million years ago – essentially at the same time that *Homo erectus* appeared in East Africa. This led David Lordkipanidze of the Georgian National Museum in Tbilisi and his colleagues to consider an extraordinary alternative human history. *Homo erectus* could have evolved in Eurasia, they say. If so, the fossils at Dmanisi are not a snapshot of the first hominin migration north out of Africa, but rather catch *Homo erectus* in the act of migrating south into the land of its forefathers. "It has to be a feasible idea," says Lordkipanidze.

More broadly, the new dates of occupation at Dmanisi mean that *Homo erectus* could have evolved from an australopith that left Africa around the 2-million-year mark. Falk says her work on the hobbit skull is consistent with this view. The similarities she identified between its brain shape and that of *Homo erectus* could be explained if both arose from a common ancestor in Eurasia, rather than the hobbit being descended from *Homo erectus*.

While the Dmanisi fossils add extra spice to the hobbit story, when it comes to understanding our own evolution it's the *Homo erectus* story that really matters.

"I think *Homo erectus* is the first hominin for which you can make a case that it belongs to our genus, *Homo*, without having to explain away any important exceptions," says Bernard Wood at George Washington University in Washington DC. A more primitive species, *Homo habilis*, often placed in our genus, may not belong there or be a direct ancestor, he adds. Crucially, *Homo erectus* is often seen as the direct ancestor of our species. So if it evolved in Eurasia before moving into Africa where our species evolved about

"Others have called this kind of thing 'X-Files palaeontology'. It does smell a bit like that"

200,000 years ago, modern humanity is arguably the product of both an African and a Eurasian cradle (see diagram, opposite).

Wood stresses that the evidence from Flores and Dmanisi is compatible with these radical new ideas rather than strongly supporting them. The fossil evidence from Eurasia is still meagre. That won't change until researchers accept the possibility that australopiths made it into Eurasia and birthed our genus there, and start looking for evidence. "Unless we open our minds to the possibility that some of that innovation happened outside Africa, we'll never find it," he says.

However, the African fossil record is also surprisingly silent on the origin of *Homo erectus*. "There's a difficult gap between 2 and 3 million years ago in East Africa where the material is incredibly fragmentary," says Fred Spoor of the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany. During this time interval, when *Homo erectus* was evolving, "there is nothing that screams *erectus*" in the African fossil record. It's an absence that certainly could be explained if this pivotal species evolved outside the continent, he says.

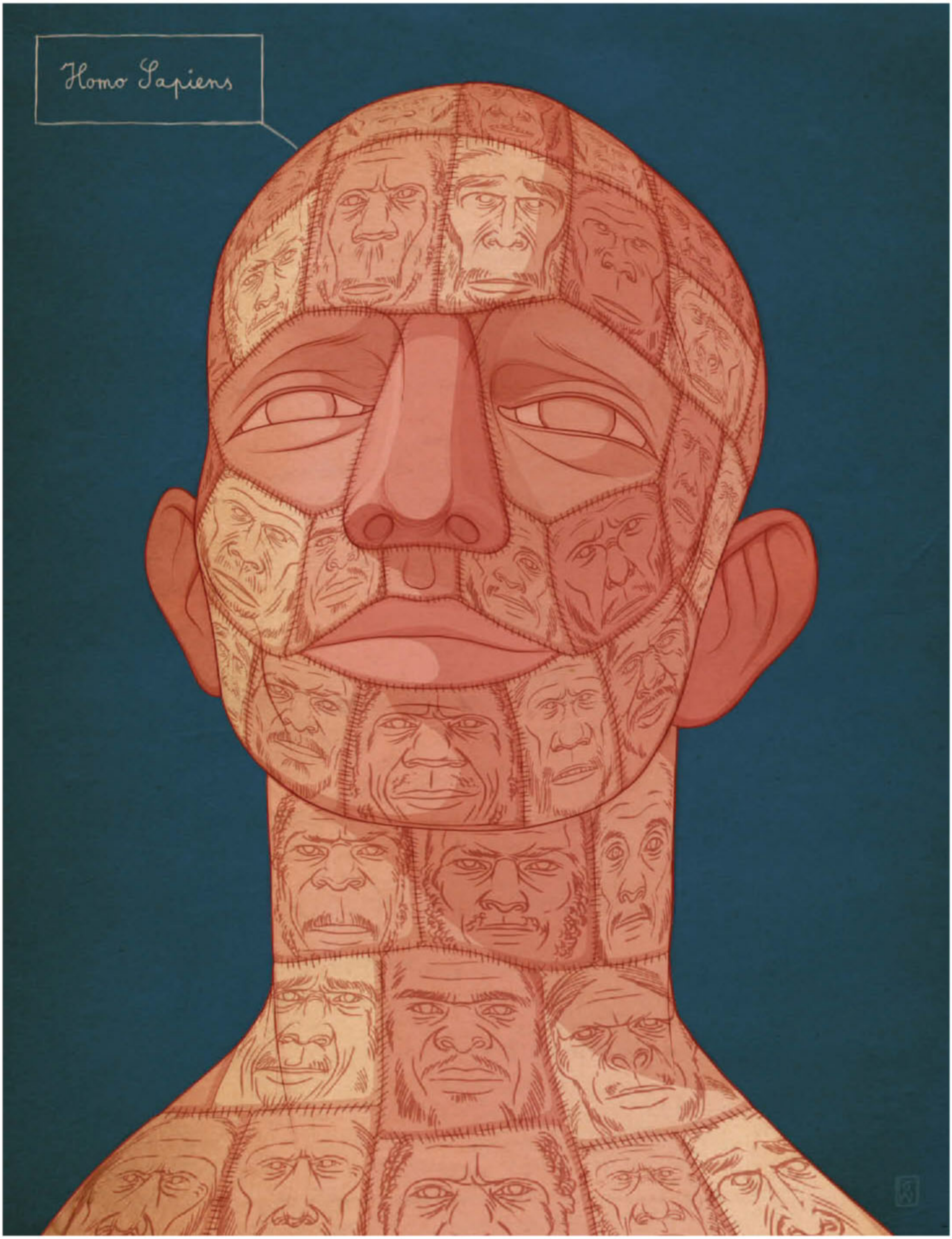
Nevertheless, Spoor is not convinced this is what happened. "It's an interesting exercise to think of an early pre-*Homo erectus* migration out of Africa, but there's really no hard evidence in the form of fossils or stone tools to support it," he says. He studies hominin skulls, and still thinks the hobbit is best seen as a dwarfed species that evolved from something like *Homo erectus*, not one that descended from a common ancestor of them both. "Others have called this kind of thing '*X-Files* palaeontology'. It does smell a little like that."

Despite the considerable problems with the African fossil record, Wood thinks that it will be tough to get researchers to take Eurasian alternatives seriously – perhaps, ironically, because Dart and his successors did such a good job of building up the African story. "The struggle to get people to talk about Eurasia wouldn't necessarily be as hard as Dart found it to get people thinking about Africa in the first place, but it would certainly be a similar kind of fight," says Wood.

Eckhardt, Henneberg and Martin take a different view. They think that Wood underestimates the power of a seductive new twist in the tale of human evolution, even with a lack of supporting fossil evidence. They suggest that the true modern-day Darts are not those struggling to get people thinking about the Eurasian australopith idea, but those fighting to oppose it.

What both sides can agree on is that there will be important academic clashes in the years ahead as new fossils come to light that either support or refute the ideas that were let loose when the hobbit was unearthed. With those tussles looming on the horizon, it is not surprising that Raymond Dart's name is mentioned so frequently – after all, he triumphed in the end.

"It took Dart 30 years to be vindicated," says Eckhardt. "We're only coming up on year 10 since the finds on Flores." Keep watching to find out which way the fossil evidence falls. ■



RICHARD WILKINSON

Hybrid species

Interbreeding between our ancient relatives was more common than you might want to think, says Ed Yong

ONCE upon a time the human story seemed so simple. Between 5 and 7 million years ago, our ancestors split from those of chimpanzees. Since then, numerous human-like species have roamed the Earth, but we outcompeted them all. Today we are the sole survivors.

Then came the news that these other hominins live on inside many of us. In a groundbreaking study of ancient DNA, a team led by Svante Pääbo at the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, revealed that many people carry the genetic legacy of Neanderthals. Everyone of non-African descent can trace between 1 and 4 per cent of their genes directly back to our *Homo* cousins. These genes even turn up in people living in areas where no Neanderthal fossils have ever been found, such as China and Papua New Guinea. The implication is clear: at some point in human history, populations that left Africa interbred with other ancient people. *Homo sapiens* is a hybrid.

That bombshell was dropped in May 2010. Seven months later, the team was at it again. This time they had sequenced DNA from a lone pinky finger bone, excavated from the Denisova cave in Siberia and dated to between 30,000 and 50,000 years old. Once again, they were able to unpick the full genome, revealing it to belong to a young woman from a previously unrecognised group of ancient hominins, which they named the Denisovans. And, once again, comparisons with modern humans showed that some of the ancient DNA lives on, comprising between 5 and 7 per cent of the genes of people from Melanesia, which includes Papua New Guinea, Fiji and nearby islands.

These two studies look set to spark a revolution. Pääbo and colleagues are the first to decipher entire genomes of ancient hominins. In doing so they bring a new approach to understanding human origins – one that has the potential to upend much of what we thought we knew. Already, the results have settled a long-standing argument about whether early modern humans bred with other hominins as they spread around the world.

They also raise an intriguing possibility. The percentage of genes involved may be small, but with two positive results from two studies, it seems likely that further research will show genes from other extinct groups of hominins in modern humans too. In other words, it looks like we have a mosaic genome. Researchers are itching to get their hands on more hominin DNA to explore this possibility as well as other key questions about human origins. "Once, we just had fossils and we'd argue about what they really show," says John Hawks from the University of Wisconsin, Madison. "With DNA, you know when things are the same. It changes everything."

For a start, DNA analysis gives us a new way to identify the various groups of early humans. Before now, they have always been defined on the basis of their bones, but the Denisovans are the first to reveal themselves by their genes alone. Analysis of their genome places them as cousins of the Neanderthals – their common ancestor split from our own ancestral line around 800,000 years ago, before dividing again around 640,000 years ago. But the paths of these three would cross again. "As populations increased in size and came into contact with one another, they started to interbreed," says Milford Wolpoff at the University of Michigan in Ann Arbor.

This interbreeding happened at least twice. We cannot be sure exactly when or where, but the most likely scenario is that when the ancestors of modern humans left Africa they bred with Neanderthals in the Middle East, around 60,000 years ago, picking up a small proportion of their genes before spreading throughout Europe and Asia. Then, in east Asia, they encountered Denisovans and repeated the same cycle of interbreeding and genetic acquisition,

›

REBUILDING ANCIENT GENOMES

The sequencing of ancient DNA has been a massive technical achievement. That's because DNA degrades with age, especially in hot and humid conditions. Even when DNA is present, it is usually swamped by genetic material from bacteria and fungi that have infiltrated the sample while it lay in the ground.

Working in a clean room to avoid contamination from their own DNA, researchers remove these unwanted sequences using enzymes. They then isolate the tiny fragments of ancient DNA, amplify them and use a computer to pinpoint overlapping segments so that they can stitch the genome back together. In this way, a team led by Svante Pääbo from the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, was able to sequence 40,000-year-old DNA to get rough drafts of both the Neanderthal and Denisovan genomes.

To find out whether these two early hominins interbred with early modern humans, their genomes were compared with those of modern humans. Because of our common ancestry we share the vast majority of our genes with these groups, but the differences are telling. Pääbo's team focused on "single nucleotide polymorphisms", or SNPs, which are sites on the genome that vary from person to person by a single DNA "letter". Neanderthals share as many SNPs with Europeans as they do with Asians, but they share fewer with Africans. That makes them genetically closer to those living outside of Africa than those living in the continent.

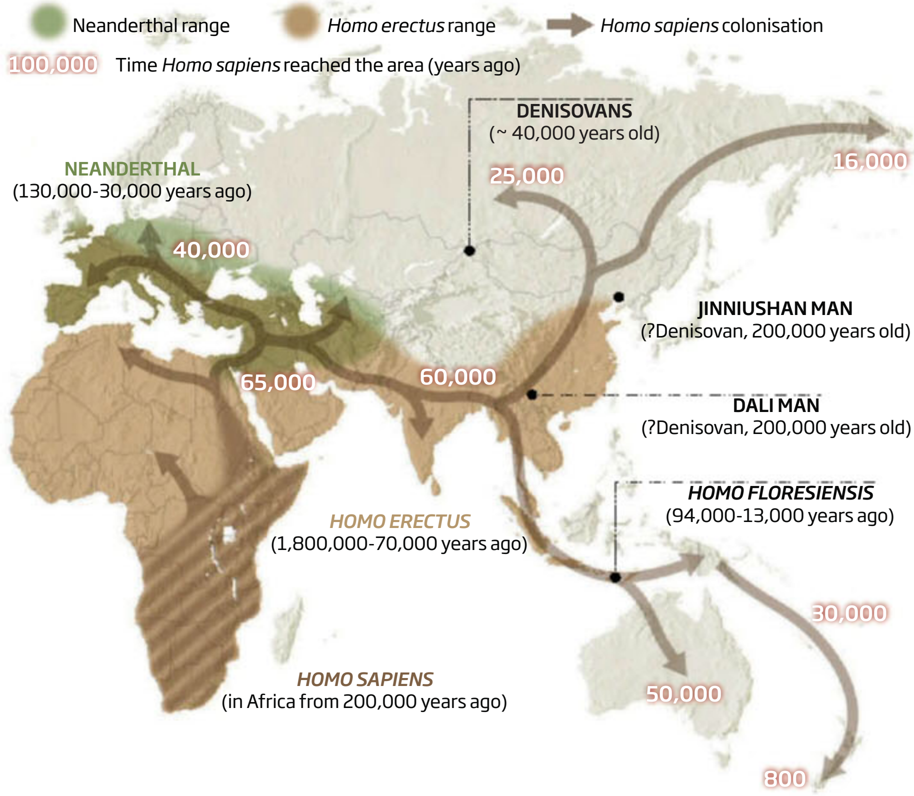
The team also found that Denisovans share the same number of SNPs with almost all non-Africans, but they share even more with Melanesians.

Taken together, these small differences show that Neanderthal DNA entered the modern human genome after *Homo sapiens* left Africa, and that Denisovan DNA came in after the Melanesians split from the rest of Asia.

The next step is to discover what these ancient genes do. "It's possible that early modern humans could have used the Neanderthal or Denisovan genetic material to adapt to their environment," says David Reich from Harvard Medical School in Boston. Indeed, more recent studies indicate that interbreeding allowed early humans to acquire genes that helped protect them against local diseases as they migrated across the globe.

All mixed up

Genome analysis suggests that after early modern humans left Africa they interbred with Neanderthals in the Middle East around 60,000 years ago and with Denisovans some time before 45,000 years ago



before colonising Melanesia 45,000 years ago. "Population mixture is not an exception in human evolution. It's perhaps the rule and it has been going on for a long period of human history," says geneticist David Reich at Harvard Medical School in Boston, who was involved in the studies.

These findings have catapulted geneticists into a controversial battle between two groups, each espousing a different story of human evolution. The first, supporters of the Out of Africa model, believe that all living humans trace their ancestry to a small African population that swept the world, replacing other species of early humans and consigning their genes to history. Their rivals, supporters of the so-called "multiregional model", see these prehistoric groups, scattered across Eurasia, as all part of a single evolving species that met and mated extensively over tens of thousands of years, ultimately giving rise to modern humans.

Neither fossils nor modern genomes could settle the debate, and for decades the same evidence would often be used to support both sides. "It was pretty polarised and personal at times," recalls Chris Stringer at the Natural History Museum in London, who championed the then-dominant Out of Africa model.

The ancient genome studies have reopened the debate. "It's nice to be on the right side of this," says Wolpoff, multiregionalism's fiercest champion. "The DNA we have shows three lineages of humans in the Pleistocene that can interbreed with each other. It's very much what we interpreted the fossils to mean." Stringer disagrees. "The implication [from the multiregional model] was that we would see Neanderthals gradually changing into modern humans," he says. "Instead, we see Neanderthals going up to around 30,000 or 40,000 years ago and then disappearing. They've passed some DNA on but that didn't change their evolutionary history."

Stringer also points out that only the most extreme versions of the Out of Africa model ruled out the possibility of sex between different groups. "I've never said there couldn't be interbreeding, but I argued that it was trivial." He could still be right – it doesn't necessarily take a lot of sex for genes from a resident population to infiltrate the genomes of colonisers. When an incoming group mates with an established one, the genes they pick up quickly rise to prominence as their population grows. The truth is, it could be that interbreeding was not the norm for ancient hominins, but something of a fringe activity.

Two teeth and a bone

Meanwhile, the sequencing of ancient DNA has also triggered a new wave of excitement among fossil-hunters. The Denisovans are a particular source of inspiration because so far they are known only by one finger bone and two teeth found in the Denisova cave. Yet as their genes turn up in modern Melanesians, they must have spread across Asia. "We're starting to find fossils in southern China and South-East Asia that could well be connected to Denisovans," says Alan Cooper from the University of Adelaide in South Australia. "Things are afoot, and the ancient DNA provoked that."

In fact, both Stringer and Wolpoff believe it is likely that Denisovan fossils have already been found. Several skulls unearthed in China, for example, don't look like Neanderthals or modern humans, and could be Denisovans hidden in plain sight. They include remains like the Dali man found in central China, and Jinniushan man from the country's north-east. Analysis of DNA from fossils like these could help us work out when and where the Denisovans lived, and how this overlapped with the habitat of early modern humans.

While others concentrate on learning more about the Denisovans, Pääbo and Cooper have their sights set on the so-called "hobbit", a small hominin that lived on the Indonesian island of Flores from about 90,000 years ago. Since its discovery in 2003, there has been heated debate about how *Homo floresiensis*, as it is officially known, fits into our family tree. What makes it particularly intriguing is that despite it having a brain just a third the size of ours, it made tools, controlled fire and lived in much the same way as our direct ancestors, from whom it was geographically isolated. The hobbit genome doubtless has some stories to tell, but ancient DNA is easily degraded and contaminated and, so far, Pääbo and Cooper have been unable to obtain any from the fossils available. "We didn't get at the samples until every physical anthropologist in South-East Asia had handled the things," says Cooper. But he remains hopeful.

"Given that the hobbits survived until 12,000 years ago, it's just a question of finding the right specimen, one that has been preserved in clay or something similar." A single tooth was found more recently, and may prove more fruitful.

Others would dearly love to sequence DNA from ancient African hominins. As the continent where humans evolved, Africa has a long history of diverse populations with lots of regional differences. "I think anything found in Africa has a chance of making things a lot more complicated," says Hawks. Until now, the various groups have been distinguished from one another by the


BENCE VIOLA/MPI EVA

Ancient DNA found in a Siberian cave lives on in modern Melanesians

morphology of fossils alone, but DNA analysis offers a new and more probing way of sorting out the relationships between them. That will be easier said than done, though. The problem is Africa's largely hot and humid climate – the worst conditions for preserving DNA.

Luckily there is another approach. "DNA can be dug up in a 40,000-year-old cave but it can also be passed down from parent to child," says Reich. Even without ancient genomes to hand, geneticists can look for signatures of interbreeding in the DNA of living people. They can hunt for parts of the genome that travel down the generations as a unit even though they are far apart; these could be heirlooms from other ancient hominins. They can also search for regions of the genome that seem older than their neighbours, which would hint at an origin that predates the rise of modern humans.

Another approach is to identify parts of the genome that are considerably more diverse in people living in one part of the world than another. Rasmus Nielsen at the University of California, Berkeley, did exactly that, comparing the DNA of people living in Africa with those living elsewhere and, without any ancient DNA, identified 13 sections of DNA in humans of non-African descent that could have come from Neanderthals. Sequencing of the Neanderthal genome confirmed that 10 of these predictions were right.

"The trick is to sequence the genomes of a diverse range of people from all across the world," says Reich. This work is already under way. Since 2008 an international consortium called the 1000 Genomes Project has been sequencing genomes from populations that have been ignored by previous studies, including some in Africa, the Americas and the Indian subcontinent. These diverse genomes will be a source of important details about our history.

And the rest?

The prospects look promising. Tantalising hints that other extinct hominins have left echoes in many of our genomes have already been found. For example, many European and Asian people have a version of a gene called *microcephalin*, involved in brain development, which was thought to be inherited from Neanderthals. However, none of the three female Neanderthals that Pääbo and Reich analysed carried this variant, so either it was rare among Neanderthals or we acquired it from another hominin. Then there is the study by Jeffrey Wall from the University of Southern California, Los Angeles, which estimated that up to 14 per cent of Eurasian genomes could be heirlooms from ancient hominin groups. Neanderthals only contributed between 1 and 4 per cent, so who did the rest come from?

These approaches can tell us a lot about how much interbreeding early humans got up to, but they have limits. They rely on mathematical models that make several assumptions about how genes change over time. If these assumptions are wrong, the studies could detect phantom signs of mixed DNA, where none exists. "In this context, it is very useful to have an ancient genome to directly test these predictions," says Reich. The ancient DNA acts like a cheat sheet, allowing scientists to run their models, check their "answers", and refine their methods. Ultimately, it was DNA that sealed the case that early humans interbred with other hominins, and we need more of it to really understand the mosaic nature of human evolution.

It must only be a matter of time. Fossil-hunters are starting to handle their finds with the care of crime-scene analysts. "Everyone now treats new material as if it had DNA in it," says Wolpoff. "There are a lot of people who would like to have the next specimen that we get ancient DNA out of. Everybody knows the pay-off is good. I think we're at the very beginning of the information explosion." ■

JUST ANOTHER PROMISCUOUS PRIMATE?

The animal world is rife with examples of incoming migrants replacing resident populations. Mammoths, cave bears, bison and others all show a similar pattern of migration and replacement to the one that characterises the spread of early modern humans across Eurasia. Whether these animals inbred with resident populations or simply outcompeted them will only be resolved when their genomes are scrutinised.

However, we do know that hybridisation is fairly common in the natural world. For example, the surprising lack of genetic diversity among Old World monkeys suggests that as they evolved, many subspecies and species mated with one another to produce a complex tangle of hybrid lineages. "When species meet, they do have sex with each other," says Svante Pääbo of the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany. So perhaps we should not be surprised to find that early humans mated with individuals from other hominin groups that they came across, including Neanderthals and Denisovans.

Studies of ancient genomes may even reveal that early humans were more inclined to hybridise than other species. One underlying reason might be that human behaviour is driven by culture as well as biology.

"Most cultures require you to seek mates someplace else: get your mates from another village, get your mates from the guys across the river," says Milford Wolpoff at the University of Michigan in Ann Arbor. "And that leads to a level of mixture that other species may not have. It remains to be seen whether we're one of many cases or whether we're special."

A brief history of the brain

We can now trace the evolution of our most important organ right back to its earliest origins. David Robson reports

IT IS 30,000 years ago. A man enters a narrow cave in what is now the south of France. By the flickering light of a tallow lamp, he eases his way through to the furthest chamber. On one of the stone overhangs, he sketches in charcoal a picture of the head of a bison looming above a woman's naked body.

In 1933, Pablo Picasso creates a strikingly similar image, called *Minotaur Assaulting Girl*.

That two artists, separated by 30 millennia, should produce such similar work seems astonishing. But perhaps we shouldn't be too surprised. Anatomically at least, our brains differ little from those of the people who painted the walls of the Chauvet cave all those years ago. Their art, part of the "creative explosion" of that time, is further evidence that they had brains just like ours.

How did we acquire our beautiful brains? How did the savage struggle for survival produce such an extraordinary object? This is a difficult question to answer, not least because brains do not fossilise. Thanks to the latest technologies, though, we can now trace the brain's evolution in unprecedented detail, from a time before the very first nerve cells right up to the age of cave art and cubism.

The story of the brain begins in the ancient oceans, long before the first animals appeared. The single-celled organisms that swam or crawled in them may not have had brains, but they did have sophisticated ways of sensing and responding to their environment. "These mechanisms are maintained right through to the evolution of mammals," says Seth Grant of the University of Edinburgh, UK. "That's a very deep ancestry."

The evolution of multicellular animals depended on cells being able to sense and respond to other cells – to work together. Sponges, for example, filter food from the water they pump through the channels in their bodies. They can slowly inflate and constrict these channels to expel any sediment and prevent them clogging up. These movements are triggered when cells detect chemical messengers like glutamate or GABA, pumped out by other cells in the sponge. These chemicals play a similar role in our brains today .

Releasing chemicals into the water is a very slow way of communicating with distant cells – it can take a good few minutes for a demosponge to inflate and close its channels. Glass sponges have a faster way: they shoot an electrical pulse across their body that makes all the flagellae that pump water through their bodies stop within a matter of seconds.

This is possible because all living cells generate an electrical potential across their membranes by pumping out ions. Opening up channels that let ions flow freely across the membrane produces sudden changes in this potential. If nearby ion channels also open up in response, a kind of Mexican wave can travel along a cell's surface at speeds of several metres a second. Since the cells in glass sponges are fused together, these impulses can travel across their entire bodies.

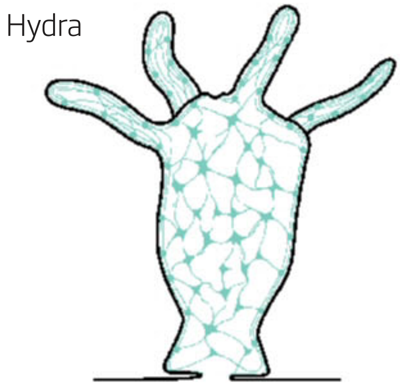
Deep roots

Recent studies have shown that many of the components needed to transmit electrical signals, and to release and detect chemical signals, are found in single-celled organisms known as choanoflagellates. That is significant because ancient choanoflagellates are thought to have given rise to animals around 850 million years ago.

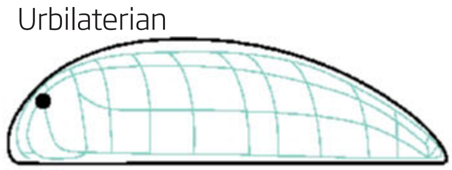
So almost from the start, the cells within early animals had the potential to communicate with each other using electrical pulses and chemical signals. From there, it was not a big leap for some cells to become specialised for carrying messages.

These nerve cells evolved long, wire-like extensions – axons – for carrying electrical signals over long distances. They still pass signals on to ›

BURN EVERYTHING/AGENCYRUSH



The first nerves formed a simple network



Next they began to group together

other cells by releasing chemicals such as glutamate, but they do so where they meet them, at synapses. That means the chemicals only have to diffuse across a tiny gap, greatly speeding things up. And so, very early on, the nervous system was born.

The first neurons were probably connected in a diffuse network across the body (see diagram, far left). This kind of structure, known as a nerve net, can still be seen in the quivering bodies of jellyfish and sea anemones.

But in other animals, groups of neurons began to appear – a central nervous system. This allowed information to be processed rather than merely relayed, enabling animals to move and respond to the environment in ever more sophisticated ways. The most specialised groups of neurons – the first brain-like structure – developed near the mouth and primitive eyes.

Our view of this momentous event is hazy. According to many biologists, it happened in a worm-like creature known as the urbilaterian (see diagram, left), the ancestor of most living animals including vertebrates, molluscs and insects. Strangely, though, some of its descendants, such as the acorn worm, lack this neuronal hub.

It is possible the urbilaterian never had a brain, and that it later evolved many times independently. Or it could be that the ancestors of the acorn worm had a primitive brain and lost it – which suggests the costs of building brains sometimes outweigh the benefits.

Either way, a central structure like a brain was present in the ancestors of the vertebrates. These primitive, fish-like creatures probably resembled the living lancelet, a jawless filter-feeder. The brain of the lancelet barely stands out from the rest of the spinal cord, but specialised regions are apparent: the hindbrain controls its swimming movements, for instance, while the forebrain is involved in vision. "They are to vertebrates what a small country church is to Notre Dame cathedral – the basic architecture is there though they lack a lot of the complexity," says Linda Holland at the University of California, San Diego.

Some of these fish-like filter-feeders took to attaching themselves to rocks. The swimming larvae of sea squirts have a simple brain, but once they settle down on a rock it degenerates and is absorbed into the body.

We would not be here, of course, if our ancestors had not kept swimming. And around 500 million years ago, things went wrong when one of them was reproducing, resulting in its entire genome getting duplicated. In fact, this happened not just

ANGELO GIAMPICCOLO/NATUREPL.COM

Anemones survive and thrive despite the lack of a brain once but twice. These accidents paved the way for the evolution of more complex brains by providing plenty of spare genes that could evolve in different directions and take on new roles. "It's like the time your parents bought you the biggest Lego kit – with loads of different components to use in different combinations," says Grant. Among many other things, it enabled different brain regions to express different types of neurotransmitter, which in turn allowed more innovative behaviours to emerge.

As early fish struggled to find food and mates, and dodge predators, many of the core structures still found in our brains evolved: the optic tectum, involved in tracking moving objects with the eyes; the amygdala, which helps us to respond to fearful situations; parts of the limbic system, which gives us our feelings of reward and helps to lay down memories; and the basal ganglia, which control patterns of movements (see diagram, below).

Brainy mammals

By 360 million years ago, our ancestors had colonised the land, eventually giving rise to the first mammals about 200 million years ago. These creatures already had a small neocortex – extra layers of neural tissue on the surface of the brain responsible for the complexity and flexibility of mammalian behaviour. How and when did this crucial region evolve? That remains a mystery. Living amphibians and reptiles do not have a direct equivalent, and since their brains do not fill their entire skull cavity, fossils tell us little about the brains of our amphibian and reptilian ancestors.

What is clear is that the brain size of mammals increased relative to their bodies as they struggled to contend with the dinosaurs. By this point, the brain filled the skull, leaving impressions that provide telltale signs of the changes leading to this neural expansion.

In 2011, Timothy Rowe at the University of Texas at Austin used CT scans to look at the brain cavities of fossils of two early mammal-like animals, *Morganucodon* and *Hadrocodium*, both tiny creatures resembling shrews that fed on insects. This kind of study has only recently become feasible. "You could hold these fossils in your hands and know that they have answers about the evolution of the brain, but there was no way to get inside them non-destructively," he says. "It's only now that we can get inside their heads."

Rowe's scans revealed that the first big increases in size were in the olfactory bulb, suggesting mammals came to rely heavily on their noses to sniff out food. There were also big increases in the regions of the neocortex that map tactile sensations – probably the ruffling of hair in particular – which suggests the sense of touch was vital too . The findings fit in beautifully with the widely held idea that early mammals were nocturnal, hiding during the day and scurrying around in the undergrowth at night when there were fewer hungry dinosaurs running around.

After the dinosaurs were wiped out, about 65 million years ago, some of the mammals that survived took to the trees – the ancestors of the primates. Good eyesight helped them chase insects around trees, which led to an expansion of the visual part of the neocortex. The biggest mental challenge, however, may have been keeping track of their social lives.

If modern primates are anything to go by, their ancestors probably lived in groups. Mastering the social niceties of group living requires a lot of brain power. Robin Dunbar at the University of Oxford thinks this might explain the enormous expansion of the frontal regions of the primate neocortex, particularly in the apes. "You need more computing power to handle those relationships," he says. Dunbar has shown there is a strong relationship between the size of primate groups, the frequency of their interactions with one another and the size of the frontal neocortex in various species.

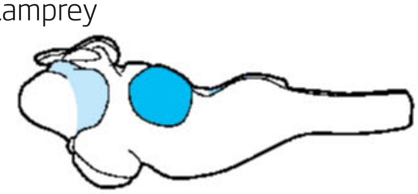
"The brains of mammals increased in size as they struggled to compete with the dinosaurs"

Besides increasing in size, these frontal regions also became better connected, both within themselves and to other parts of the brain that deal with sensory input and motor control. Such changes can even be seen in the individual neurons within these regions, which have evolved more input and output points.

All of this equipped the later primates with an extraordinary ability to integrate and process the information reaching their bodies, and then control their actions based on this kind of deliberative reasoning. Besides increasing their overall intelligence, this eventually leads to some kind of abstract thought: the more the brain processes incoming information, the more it starts to identify and search for overarching patterns that are a step away from the concrete, physical objects in front of the eyes.

Which brings us neatly to an ape that lived about 14 million years ago in Africa. It was a very smart ape but the brains of most of its ›

Lamprey



Specialised brain regions formed in early fish

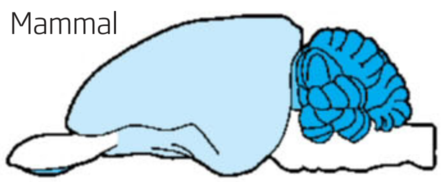
Amphibian

Living amphibians have the same basic brain structure as fish

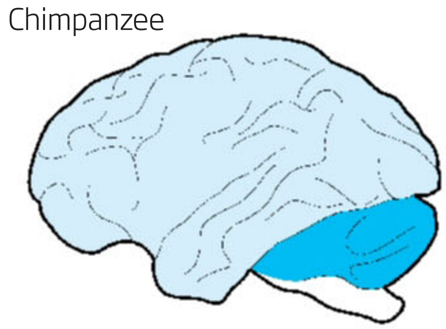
Cerebrum Tectum Cerebellum

The brains of living amphibians tell us little about our own evolution

MARTIN SHIELDS/FLICKR/GETTY



Mammal brains slowly grew much larger



Folding increased the surface area

descendants – orang-utans, gorillas and chimpanzees – do not appear to have changed greatly compared with the branch of its family that led to us. What made us different?

It used to be thought that moving out of the forests and taking to walking on two legs led to the expansion of our brains. Fossil discoveries, however, show that millions of years after early hominids became bipedal, they still had small brains.

We can only speculate about why their brains began to grow bigger around 2.5 million years ago, but it is possible that serendipity played a part. In other primates, the "bite" muscle exerts a strong force across the whole of the skull, constraining its growth. In our forebears, this muscle was weakened by a single mutation, perhaps opening the way for the skull to expand. This mutation occurred around the same time as the first hominids with weaker jaws and bigger skulls and brains appeared.

Once we got smart enough to innovate and adopt smarter lifestyles, a positive feedback effect may have kicked in, leading to further brain expansion. "If you want a big brain, you've got to feed it," points out Todd Preuss of Emory University in Atlanta, Georgia.

He thinks the development of tools to kill and butcher animals around 2 million years ago would have been essential for the expansion of the human brain, since meat is such a rich source of nutrients. A richer diet, in turn, would have opened the door to further brain growth.

Primatologist Richard Wrangham at Harvard University thinks that fire played a similar role by allowing us to get more nutrients from our food. Eating cooked food led to the shrinking of our guts, he suggests. Since gut tissue is expensive to grow and maintain, this loss would have freed up precious resources, again favouring further brain growth.

Mathematical models by Luke Rendell and colleagues at the University of St Andrews in the UK not only back the idea that cultural and genetic evolution can feed off each other, but suggest this can produce extremely strong selection pressures that lead to "runaway" evolution of certain traits. This type of feedback might have played a big role in our language skills. Once early humans started speaking, there would be strong selection for mutations that improved this ability, such as the famous *FOXP2* gene, which enables the basal ganglia and the cerebellum to lay down the complex motor memories necessary for complex speech.

The overall picture is one of a virtuous circle involving our diet, culture, technology, social relationships and genes. It led to the modern human brain coming into existence in Africa by about 200,000 years ago.

Evolution never stops, though. According to one recent study, the visual cortex has grown larger in people who migrated from Africa to northern latitudes, perhaps to help make up for the dimmer light up there.

Downhill from here

So why didn't our brains get ever bigger? It may be because we reached a point at which the advantages of bigger brains started to be outweighed by the dangers of giving birth to children with big heads. Or it might have been a case of diminishing returns.

Our brains are pretty hungry, burning 20 per cent of our food at a rate of about 15 watts, and any further improvements would be increasingly demanding. Simon Laughlin at the University of Cambridge compares the brain to a sports car, which burns ever more fuel the faster it goes.

One way to speed up our brain, for instance, would be to evolve neurons that can fire more

THE FEATHERED APES

Would intelligent dinosaurs rule the world if a meteorite impact had not wiped out their kind?

We cannot answer that question, of course, but there is no doubt that dinosaurs had the potential to evolve into very smart animals. The proof is sitting in a tree near you.

Certain birds, particularly the crow family, have evolved complex behaviours that match the ingenuity of many primates. Tool use, deception, face recognition – you name it, they can do it. Why are some birds so brainy? Stig Walsh of National Museums Scotland thinks that foundations were laid in their dinosaur ancestors, which probably climbed around in trees before eventually taking to the air. This behaviour would have favoured the same abilities that evolved in the tree-climbing primates: excellent vision, motor coordination and balance, which came about through the expansion of the brain areas known as the optic tectum and the cerebellum.

To compete with other animals, these tree-climbing dinosaurs might have also begun to evolve new foraging strategies that needed more brainpower, leading to the growth of the forebrain. There are plenty of fossils of dinosaurs, he says, whose brains already possess some of these enlarged structures.

So the ancestors of birds had relatively big brains compared with their body size, and their brains grew proportionately even bigger once they took to the air and evolved even more advanced behaviours. These abilities might have enabled them to survive the mass extinction that killed the other dinosaurs, Walsh says, since their ingenuity would have helped them to find new ways of foraging for food in the wake of the catastrophe.

Bird brains are structured in a very different way to mammalian ones. The mammalian lineage developed new outer layers, known as the neocortex, which birds lack. Despite this, it is likely that the enlarged frontal cortex of the mammals, and the enlarged forebrain of the birds, perform similar functions. "There's been a convergence, along different routes," says Walsh.

How smart could birds get? For all the tool-making talents of crows, a beak is clearly not as good for manipulating objects as the hands of primates. That may limit the development of bird brains, though some have speculated that the wings of ground-living birds could yet re-evolve into grasping forelimbs.

We'd have to eat far more than top athletes if our brains ran faster

times per second. But to support a 10-fold increase in the "clock speed" of our neurons, our brain would need to burn energy at the same rate as Usain Bolt's legs during a 100-metre sprint. The 10,000-calorie-a-day diet of Olympic swimmer Michael Phelps would pale in comparison.

Not only did the growth in the size of our brains cease around 200,000 years ago, in the past 10,000 to 15,000 years the average size of the human brain compared with our body has shrunk by 3 or 4 per cent. Some see this as no cause for concern. Size, after all, isn't everything, and it's perfectly possible that the brain has simply evolved to make better use of less grey and white matter. That would seem to fit with some genetic studies, which suggest that our brain's wiring is more efficient now than it was in the past.

Others, however, think this shrinkage is a sign of a slight decline in our general mental abilities. David Geary at the University of Missouri-Columbia, for one, believes that once complex societies developed, the less intelligent could survive on the backs of their smarter peers, whereas in the past they would have died – or at least failed to find a mate.

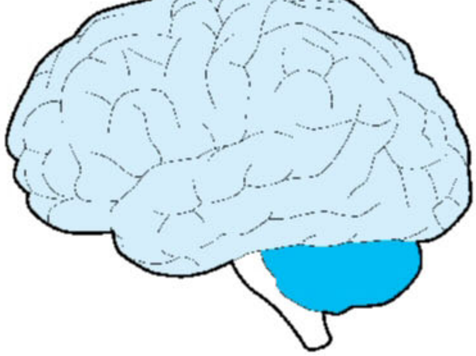
This decline may well be continuing. Many studies have found that the more intelligent people are, the fewer children they tend to have. More than ever before, intellectual and economic success are not linked with having a bigger family. If it were, says Rendell, "Bill Gates would have 500 children."

This evolutionary effect would result in a decline of about 0.8 IQ points per generation in the US if you exclude the effects of immigration, a 2010 study concluded. However, nurture matters as well as nature: even if this genetic effect is real, it has been more than compensated for by improved healthcare and education, which led a steady rise in IQ during most of the 20th century.

Crystal-ball gazing is always a risky business, and we have no way of knowing the challenges that humanity will face over the next millennia. But if they change at all, it appears likely that our brains are going to keep "devolving" – unless, of course, we step in and take charge. ■

"In the past 10,000 years the average size of the human brain has shrunk"

Human



Our brains are the largest relative to body size

The story in the stones

Stone tools contain a remarkable record of 2.6 million years of human evolution, says **David Robson**

SPARKS fly as stone meets stone, and shards of rock ricochet off the furniture around me. Each strike makes me flinch, but Bruce Bradley is the picture of cool concentration as he chips away at his axe head. It is, after all, a skill he has been honing since before he can remember. "I was a natural born flint-knapper. Laugh at that if you want, but I've got video to prove it." As a baby, he says, he was often seen banging two rocks together in his parents' garden. Then, when his family moved to Arizona, he developed his talents by copying the Native American arrowheads scattered across the desert.

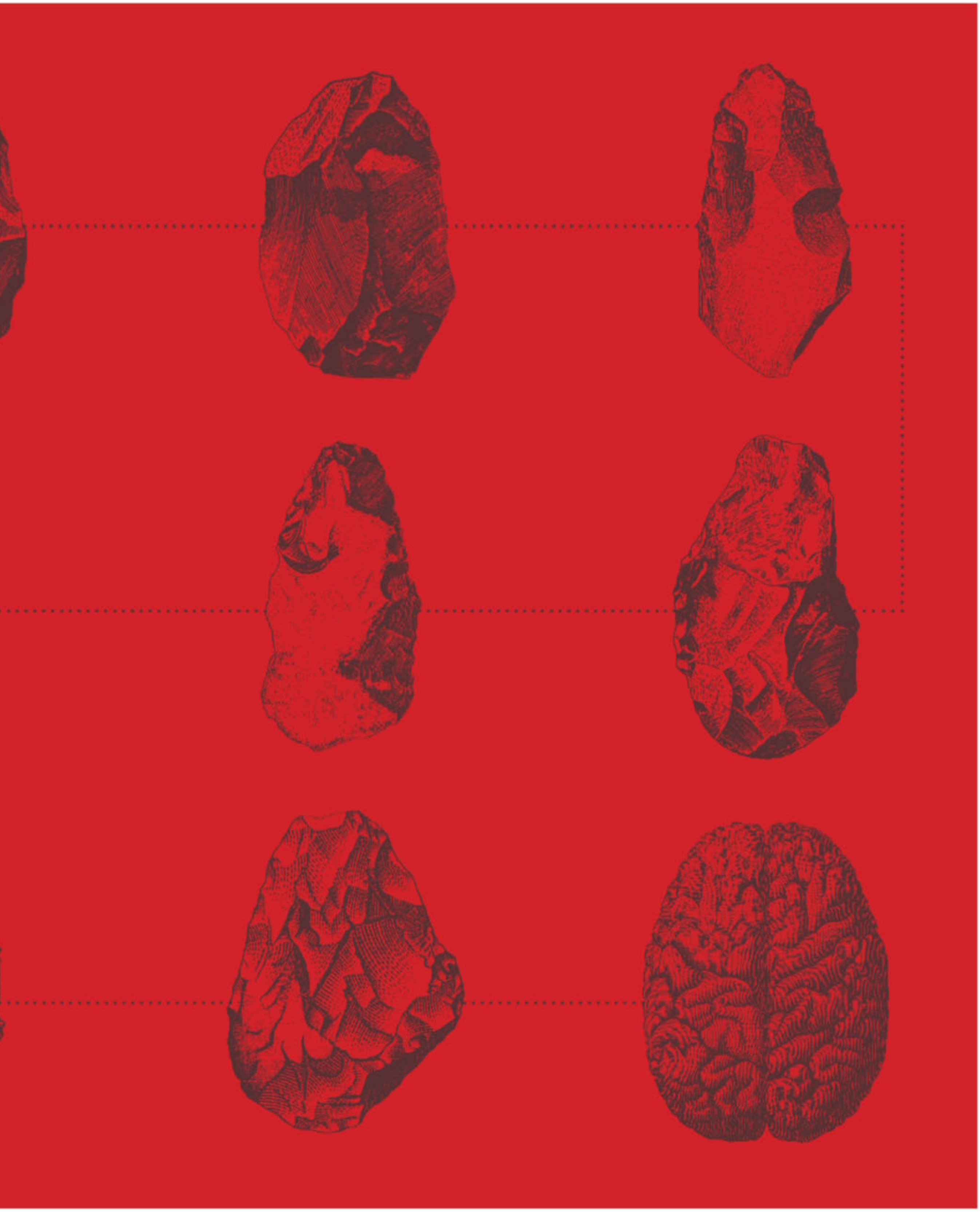
Decades later, Bradley makes stone tools spanning the breadth of human history. His workshop at the University of Exeter, UK, is full of this handiwork. Piles of rocks line the walls, and to one side a deerskin with a dark stain hangs on a wooden frame. It was butchered using some of his team's handmade tools, he tells me. "We've got a freezer out there full of dead parts – you could eat them if you wanted."

My interests lie elsewhere. The stone tools on the table in front of me are not just useful, but tell the story of our journey from simple ape to thinking human. Previous attempts to trace the history of the mind have relied on speculation as much as hard evidence but, over the past few years, Bradley's Learning to be Human project has taken a more precise approach to looking inside the heads of the people who made these tools. Combining findings about stone-tool construction with neuroscience, psychology and archaeology, we can now estimate the origins of distinctly human mental abilities, such as when we first began to order our thoughts and actions, when our visual imagination blossomed, when we started to think about the past and future, and when we first played make-believe. There are even hints about the emergence of our capacity for patience, shame and suspicion – and the nature of our ancestors' dreams.

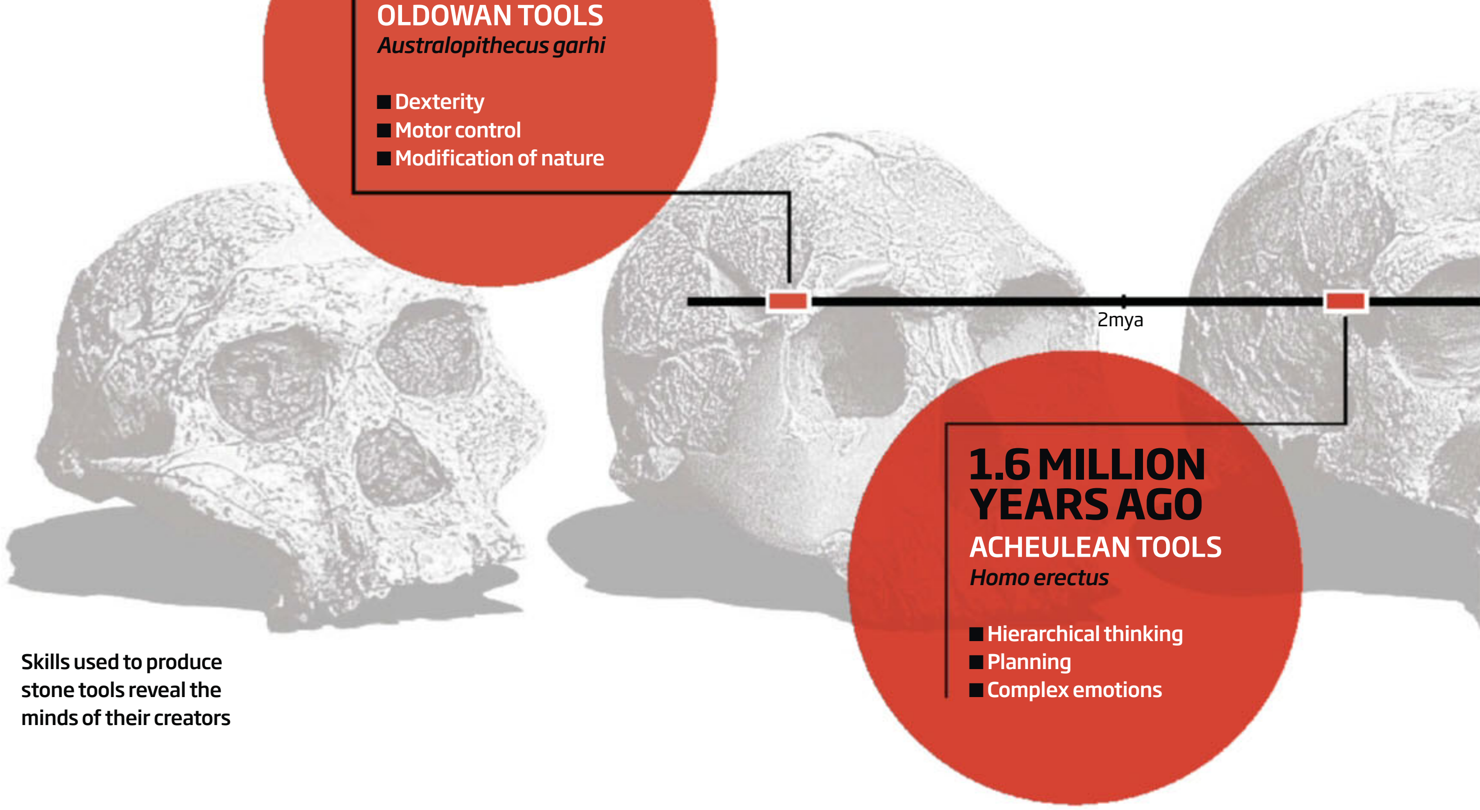
People have long sought a "secret ingredient" unique to human intelligence that could explain our extraordinary cognitive abilities. Most recently, the spotlight has fallen on size – the idea that a big brain is the key. However, it is becoming increasingly clear that there is no secret ingredient. Instead, our peculiar way of thinking results from a reorganisation of the different brain regions, as much as from their expansion (see "Size isn't everything", page 48). What's more, this began long before we diverged from chimps. Indeed, comparable but more modest changes can be seen in many of our nearest relatives. "In a way we're just an extreme great ape," says Jeroen Smaers at Stony Brook University, New York, who in 2013 compared the brain evolution of 17 species of primates.

So what accelerated this evolution in our ancestral line beyond what was happening in other apes – and how did this give rise to new ways of thinking? Only by re-examining the archaeological record can we map out that path. And that's why I am in Bradley's workshop.

He pauses in his work to show me three stone tools. The first and crudest of them is a jagged rock that signals perhaps the first landmark moment in that journey. Aside from walking on two legs, our earlier ancestors were distinctly apelike, and like chimps and other primates, they probably had limited tool use, picking pebbles off the ground to crush nuts. But things change about 2.6 million years ago, with *Australopithecus garhi*. Rather than just using nature as they found it around them, ›



"I'm willing to bet there would be no consciousness on this planet if we didn't have flakable rocks"



Skills used to produce stone tools reveal the minds of their creators

Sweet dreams

Until about 2 million years ago, human ancestors probably settled for the night in trees. Some psychologists have proposed that the sensation of falling that we sometimes feel when we drop off is a remnant of an early warning system that stopped us descending so deeply into sleep that we ended up on the forest floor. Dozing on branches is likely to have ended with *Homo erectus*. "At 6 feet and 140 pounds, it was way too tall and heavy," says Frederick Coolidge at the University of Colorado in Colorado Springs. Instead, *Homo erectus* slept on the ground, and this, Coolidge suggests, resulted in a great leap in cognition.

A more peaceful night's slumbers, without the constant risk of falling from a branch, would have allowed *Homo erectus* to spend longer in rapid-eye-movement sleep and slow-wave sleep, says Coolidge. These stages are known to be crucial for the consolidation of memories and associative thinking, and that's not all. "It probably allowed many more creative dreams," he says. These could have had an impact on waking life.

Coolidge even speculates that the idea of the leaf-shaped Acheulean hand axe - a complex tool that signals a new way of thinking (see main story) - might have come to a *Homo erectus* knapper in one of those dreams.

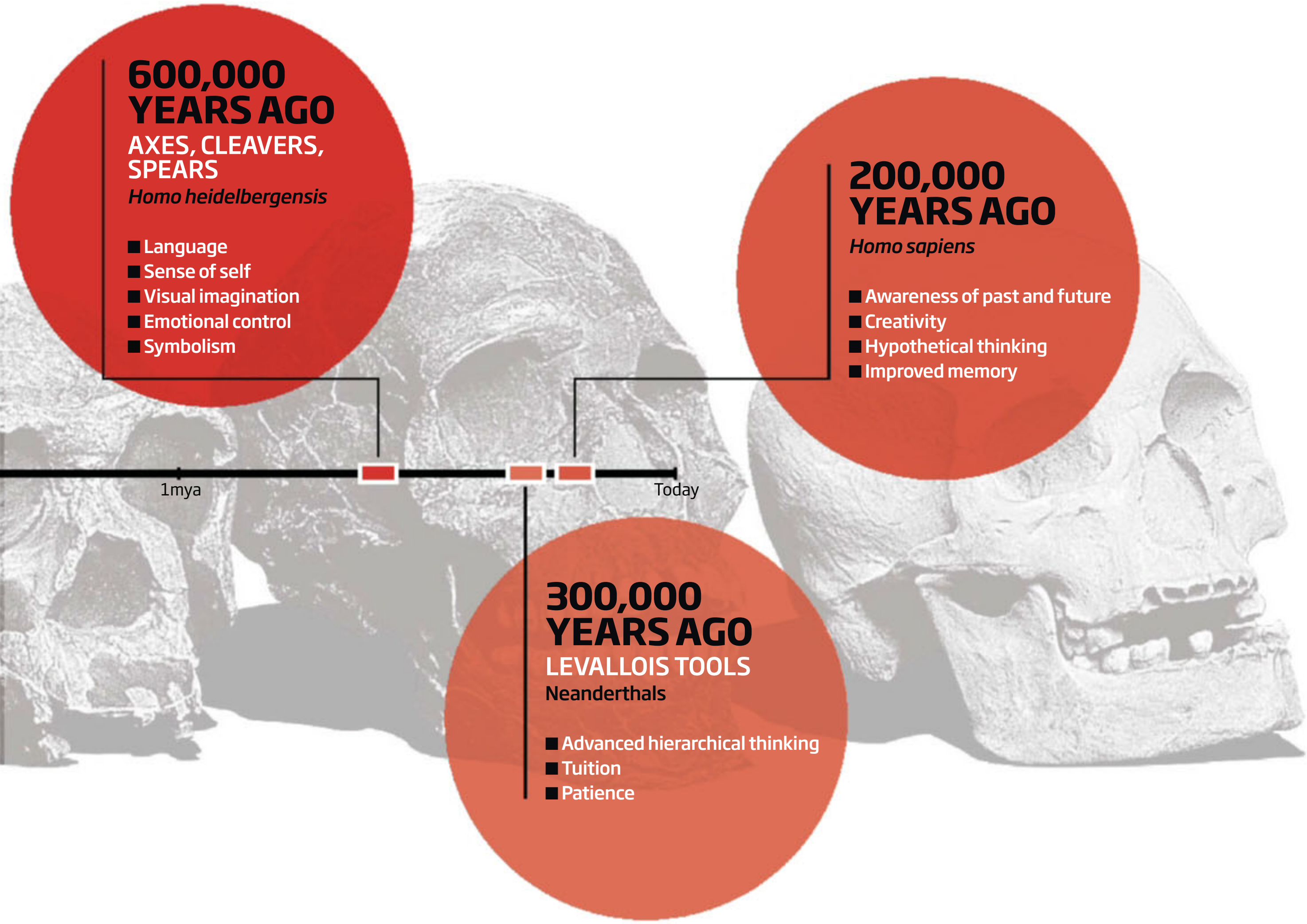
Our ancestors stopped napping in trees when they became too big

BACKGROUND: PASCAL GOETGHELUCK/SCIENCE PHOTO LIBRARY; LEFT: MICHAEL HALL/GETTY

they began to modify it, wielding one stone to chip the end off another and using the resulting sharp edge to butcher meat.

The idea of using one tool to create a more useful implement is itself a conceptual leap. But just as important is Bradley's discovery that it takes a dexterity and motor control not seen in other apes to create the jagged Oldowan-style tool in front of me. This includes coordinating your limbs so that one hand is doing a different job from the other. "You need one hand for support, one for striking," says Nada Khreisheh, Bradley's colleague – movements that chimps struggle to master even with training. If such bodily control seems like more of a hop than a leap, consider all the new opportunities it opened up – including the creation of better tools – that would reward increased intelligence, accelerating our evolution compared with the other apes. "I'm willing to bet there would be no consciousness on this planet if we didn't have flakable rocks," says Bradley.

Even with that trigger, our ancestors were slow to progress. Things didn't begin to take off until *Homo erectus*, about a million years later. *Homo erectus* is significant for many reasons. As well as having broadly similar bodies to modern humans, they lived in



bigger social groups than their predecessors. Successful communal living requires cooperation and the ability to detect and punish cheats who try to get something for nothing. According to Eva Jablonka at Tel Aviv University in Israel, those challenges may have spurred the evolution of complex emotions such as shame and embarrassment, which would help individuals toe the party line. "We became emotionally modern before we became cognitively modern," she says. But what really marks out the thinking of *Homo erectus* is encapsulated in the second tool in front of me, an exquisite leaf-shaped object known as an Acheulean hand axe.

Better by design

We do not know what inspired this revolutionary design – it may even have come in a dream (see "Sweet dreams", opposite). The first attempts, which date from around 1.5 million years ago, were fairly crude, but over the following million years Acheulean axes became thinner and more symmetrical as they began to embody a more systematic style of working. Bradley's demonstrations show that to achieve the more sophisticated designs, you need to prepare the surface of the rock – working away smaller chips to create an angle before striking off the larger, flatter flakes. "They take a lot more planning and understanding of force," he says as he chips away at his own rock. Breaking down a goal into a series of smaller actions in this way shows the beginnings of hierarchical thinking. Chunking and sequencing our actions seems so central to the way we operate today – whether we are making a cup of tea or running a bath – that it's almost impossible to imagine our minds working in any other way. But the refined Acheulean axes offer some of the first signs that our ancestors were beginning to develop the ability to organise their thoughts in these more complicated ways.

This innovation in axe design has been linked to another milestone in human cognition: language. It is such a complex system, dependent on many different thought processes, that its origins are sometimes described as evolution's biggest mystery, but there is some evidence suggesting that tool-making could have been a catalyst. Bradley's collaborator, Dietrich Stout at Emory University in Atlanta, Georgia, points out that articulate vocalisation requires precise movement of the lips and tongue. Chimps and other primates are unable to achieve these, but in our ancestors tool-making drove the development of the brain areas involved in motor control that could later be co-opted for speech. Stout also notes that the sequential thinking needed to create the leaf-shaped hand axes is similar to the thinking that allows us to understand and construct sentences.

To test the theory, Stout used brain scans to try to pick apart the cognitive skills used in each type of tool-making. As predicted, they show that people making replicas of the Oldowan tools have greatest activity in areas associated with the motor control needed to speak, while brain activity in those making the Late Acheulean tools shows an overlap with that normally associated with linguistic grammar. That includes the inferior frontal gyrus along the bottom of the frontal lobe – an area that expanded rapidly in the human line compared with other apes.

Language is, arguably, our only unique feature, and its emergence set us on a road that led away from every other animal. Unfortunately, this turning point in our journey is virtually invisible in the archaeological record: Bradley can show me no tools that definitively signify the first words. But there are hints that our ancestors had begun speaking by the time of *Homo* ›

“Time spent playing may have helped develop ‘counterfactual thinking’”

heidelbergensis, thought to have evolved from *Homo erectus* at least 600,000 years ago.

Homo heidelbergensis was certainly more human in other respects. Its brain, at about 1200 cubic centimetres, was just a shade smaller than ours, providing a cognitive power that is evident in the variety of tools it used, including refined hand axes, cleavers and spearheads. To envisage an amorphous lump of rock transformed into these shapes and styles would have required good spatial cognition, perhaps signalling the birth of the visual imagination. *Homo heidelbergensis* also revisited certain places again and again, sometimes scattering hand axes across the ground. Some read this apparently inexplicable waste of good handiwork as an early attempt to signpost sites of significance. That is skirting close to the mindset needed for symbolism. Crucially, *Homo heidelbergensis* also possessed refinements in its vocal anatomy. For instance, traces in bones indicate they had more nerves linking the brain and tongue than their predecessors, and their voice boxes seem to lack a balloon-like appendage that constrains vocalisations in other apes. Both of these changes would be needed to produce eloquent sounds.

Whenever it emerged, language brought a whole new set of mental challenges. “When I tell you a story, I can frighten you very easily,” says Jablonka. “And you have to control this fear.” It’s easy to take that ability for granted, but chimps fail to make a good distinction between symbols and real things – they go wild when they see a picture of a banana, for instance. In a similar way, our ancestors may have struggled at first to understand the mental images conjured up by language. To deal with their immediate visceral reactions, Jablonka says, they must have developed greater control over their emotions – and they would have learned to be more sceptical and suspicious of others in the process. They also needed a better verbal memory, so that they could remember what others had told them, to differentiate it from what happened in their own lives. Out of that emerged the ability “to tell my own story, the autobiography”, she says. If Jablonka is right, language contributed to our sense of self.

Beautifully crafted

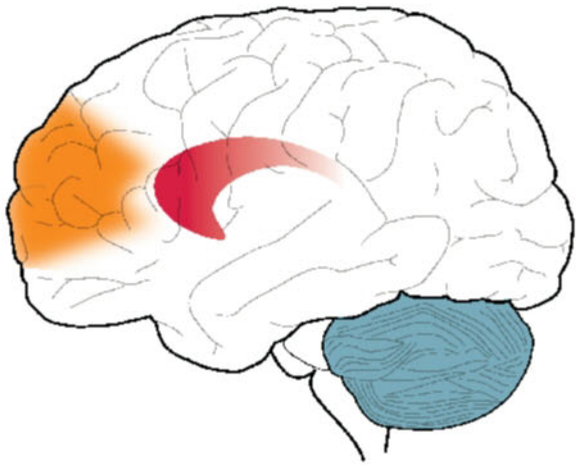
Our ancestors were probably still navigating these difficulties as the human mind approached the last stretch of its journey. To demonstrate this final mental leap, Bradley draws my attention to the third object on the table in front of us. The beautiful Levallois tool is carved from shiny black stone. With dimples lining its edge, it looks a little like an oyster shell. Bradley tells me the tool is little more use for cutting and scraping meat than the cruder hand-axes – its value was probably aesthetic, rather than practical. To make it, a base stone had to be fashioned into a circle before the “lid” was removed with one strike. That craftsmanship takes great skill and patience, as Bradley and Khreisheh’s modern apprentices discovered. “People like making hand axes,” says Khreisheh, “but they hate making Levallois tools.” Since the process comprises many different stages, and the apprentices often need specific instruction, the mind that originally created this tool was probably capable of advanced hierarchical thinking and complex communication for tuition. These intricate objects first appear at least 300,000 years ago, but although they are found among the remains of our own species, they are most commonly associated with the Neanderthals.

Levallois tools provide some of the best evidence that Neanderthals shared much of the cognitive toolkit possessed by humans living at the same time. And herein lies the mystery. “Whatever the Neanderthals’ cognitive leap was, it stopped; it didn’t continue,” says Bradley. So why did we develop more ambitious inventions and rich artistic cultures, while they hit a dead end? Answer that question, and you get a glimpse of the final stage in the evolution of the human mind.

Some think the solution is child’s play – literally. Since our ancestors first diverged from the other primates, childhood has continued to get longer, giving the brain more time to develop outside the womb. From the remains of bones and teeth, it seems that early human children took longer to develop

Size isn’t everything

Human intelligence has more to do with the organisation of brain regions than it does with overall size. Tools may have played a key role in shaping parts of this complex organ



PREFRONTAL CORTEX

Self-control, introspection, social cognition

Lots of signal-transmitting “white matter” reflects this area’s role in combining data from the senses and the rest of the brain. That could help with precise tool-making actions and with the insight needed for complex social relationships

FRONTOSTRIATAL SYSTEM

Incremental learning of skills

As our ancestors evolved there was a rapid increase in the size of this area relative to other brain regions. This would have improved their capacity for learning, allowing for the production of more complex tools

CEREBELLUM

Sequential thinking

High connectivity between here and the frontal motor areas enables fine control of movement. This area may have grown as the tool-making and language skills of our ancestors developed

than Neanderthal ones. Child psychologist Alison Gopnik at the University of California, Berkeley, argues that the extra time spent playing may have helped them develop "counterfactual thinking" – the ability to consider how things might be, not just how they are. That allowed them to imagine the environment in more creative ways, giving them greater control over their surroundings, she says. As a result, they could do things that might not have occurred to earlier humans, like inventing new tools and building shelters.

Frederick Coolidge and Thomas Wynn at the University of Colorado in Colorado Springs see a more dramatic trigger. They argue that our last cognitive leap was down to a chance mutation that increased our ability to hold several ideas in mind and manipulate them. Even in modern humans, this "working memory" is limited to about seven items. However, a small increase would have had huge consequences. An improved ability to remember what had just been said would have increased the sophistication of conversation, allowing more complex grammar with many different clauses. That means you can think and plan more hypothetically, using "what if" and "if, then" statements, for instance.

Working memory is also associated with creativity and innovation, because it allows you to mentally explore different solutions to a problem. Wynn and Coolidge also point to research suggesting that enhanced working memory could have improved our long-term memory and future planning, because it provides a bigger mental "blackboard" on which we can assemble the details of our past experiences, and draw on them to work out the best way to proceed with the task ahead.

A recipe for success

This hypothesis has been strengthened in recent years by a wave of circumstantial evidence. For example, Lyn Wadley at the University of the Witwatersrand in Johannesburg, South Africa, has looked at the steps involved in making glues used to stick spearheads to poles. Earlier humans had simple adhesives such as plant gum, but she has found that in Sibudu cave, South Africa, about 70,000 years ago, they began to cook up the tree sap with red ochre and beeswax to produce a superior glue that doesn't break on impact or dissolve in water.

When Wadley tried to replicate the complex recipes, she found that she had to pay attention to many different factors, including the temperature of the fire, the moisture

PHILIPPE PSAILA/SCIENCE PHOTO LIBRARY

Recreating stone tools opens a window into the minds of those who invented them

and different proportions of ingredients depending on the quality of the tree gum. "It took a lot of coordination to ensure success," she says. That's only possible with an enhanced working memory to keep all the different elements in mind at once.

Further clues come from the food the Sibudu cave-dwellers were eating. Around this time, early modern humans began to hunt small game, such as rodents and small deer species. Former army survival expert Klint Janulis, now at the University of Oxford, tried the methods they used and found he needed to place 10 to 15 traps to capture enough food to make it worthwhile. "Within a couple of hours you can set enough traps to feed yourself, and maybe another person, for a day," he says. But that requires forethought, and keeping track of their locations needs just the kind of advanced cognition that Wynn and Coolidge suggest.

The timing of these advances at 70,000 years ago is particularly significant because they come just after the eruption of the Toba supervolcano in Indonesia, which plunged the world into a mini ice age and caused a human population crash in Africa. Any beneficial mutations within the small remaining population could spread quickly, leaving a permanent mark on their descendants. "All extant humans are descendants of those 2000 or so humans," says Coolidge. If he and Wynn are right, then the explosion at Toba marked the beginning of the home stretch to modern thinking. Armed with this slightly superior thinking, we left Africa and took over the globe, while the Neanderthals and our other evolutionary cousins became extinct.

Of course, our journey isn't over and it is tempting to speculate how the human mind will evolve in the future. Wynn wonders if we will see further changes in working memory. "It's variable within populations," he says. "We suspect it may still be under evolutionary change."

It is also possible that advances in technology could substantially change the mental challenges we face, just as stone tools did in the past. Claims that the internet is making us stupid have so far proven to be unfounded, but the way we interact with one another is certainly changing, and so are the mental skills associated with success.

Bradley is more interested in the past than the future. The air is now thick with flint dust as he hands me the finished axe. There are still many questions left to answer, he says, as we try to fill in the gaps between the known landmarks of cognitive evolution. "From our point of view it's just scratching the surface of what could be done." But he has already achieved one of his goals – he wanted to teach a new generation of flint-knappers the skills he has been refining since childhood.

There's also a chance that his handiwork will find a place next to the artefacts he so admires. The Smithsonian Institution in Washington DC, he says, is interested in collecting his life's work to demonstrate the progression of a modern day flint-knapper. "My body could even be a permanent exhibit there too, when I shuffle off this mortal coil," he jokes. It would be a fitting place of rest for the "natural born knapper" who has spent his life trying to understand how we learned to be human. ■

Are you thinking what I'm thinking...

The explosion of art in Europe 40,000 years ago was once thought to signal the birth of the modern mind. But recent finds suggests otherwise, says **Alison George**

WHEN I leave the sunshine and enter the gloom of the El Castillo cave in northern Spain, I'm just the latest in a long line of human visitors stretching back 150,000 years. Once inside, I walk past a wall of muddy debris 20 metres high – the household remains of the cave's inhabitants – and enter the labyrinth beyond.

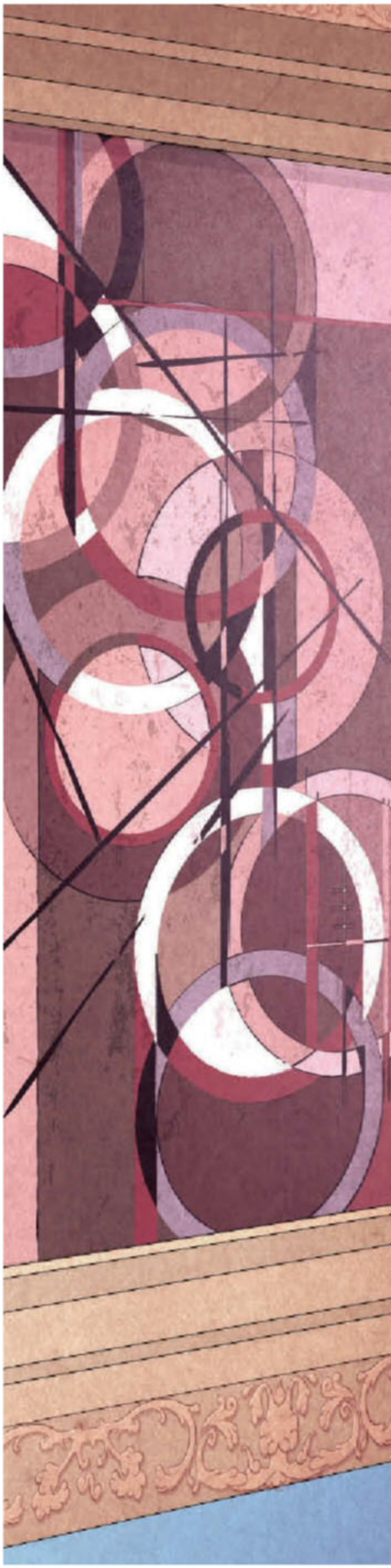
The first chamber is vast, and I catch glimpses of aurochs, deer and bison painted on the walls, but I'm here to see something more enigmatic: a series of abstract marks that seem to be a kind of Stone Age code.

My journey leads me to a hidden chamber so small that I have to lie down so as not to damage the images overhead. They are unlike anything I've ever seen – abstract art composed of large rectangles filled with lines and dots. There's a large cross made from small dots, and two rectangles overlying to make another cross. These geometric shapes are so intricate that it's hard not to imagine they conveyed some kind of information (see photo, page 54).

My guide, anthropologist Genevieve von Petzinger, is here to catalogue these abstract signs in an attempt to understand the minds that produced them. What prompted those people to come into the dark interior of the cave and sketch complex diagrams on the wall with ochre? And were they already capable of the same kinds of thinking that occupy us today? "I spend a lot of time imagining myself in their shoes," says von Petzinger, who is based at the University of Victoria, Canada.

At more than 15,000 years old, these symbols were painted towards the end of the "creative explosion" – a rapid proliferation of cave art and symbolic artefacts like jewellery and sculpture that began around 40,000 years ago. The transition was once thought to be a sign of a sudden cognitive change – perhaps the result of genetic mutations that swept through the human population and ultimately resulted in the modern mind.

But scattered archaeological remains, stretching from Spain to China, South Africa to Serbia, now suggest that our talent for art and symbolism is much older (see map, page 53). "These sites are tipping the whole thing on its head, because you've got art that's not supposed to be there," says von Petzinger. Indeed, in another chamber of the El Castillo, there is evidence that painting might not even be confined to our species. As researchers like von Petzinger begin to discover the factors that drove this creativity, they are able to decipher new meanings in the signs themselves, as the Stone Age code finally gives up its secrets.



RICHARD WILKINSON

For most of the 20th century, we had little idea what might be going on in the heads of our ancient ancestors. Although the stunning artwork in the caves of France and Spain seemed to show a fully formed modern mind, those artists' predecessors were thought to lack the basic toolkit for any kind of abstract or symbolic thought. As the influential anthropologist Jared Diamond put it in 1989, humans were little more than "glorified baboons" before this "great leap forward".

The cognitive leap theory has always had its detractors, though, since it seemed to occur well after our ancestors left Africa roughly 100,000 years ago. If the breakthrough was indeed caused by a mutation in Europe, how did the genetic change filter through to populations in Australia, Asia or the Americas, that had long since lost contact with their European relatives? A far simpler explanation was that our common ancestors had already evolved the necessary brain power before leaving Africa – but the evidence was lacking.

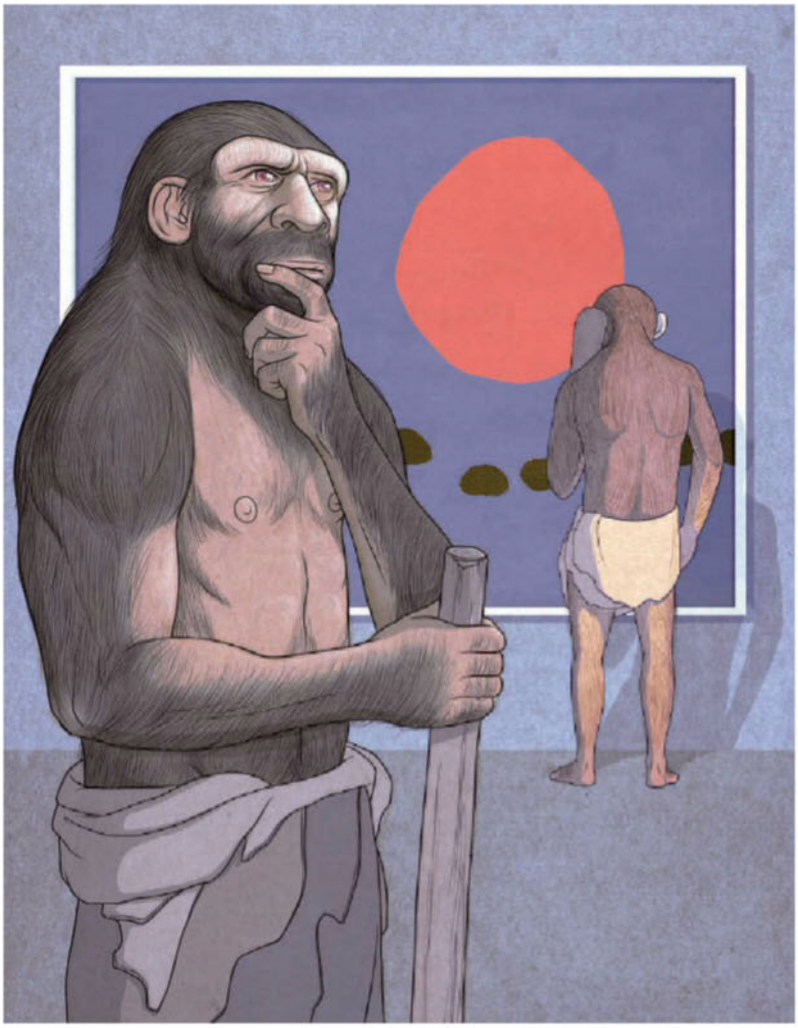
That changed with a series of intriguing finds at the Blombos cave, South Africa. Featuring artefacts such as ostrich shell beads and blocks of ochre etched with geometric shapes, the site seemed to show signs of symbolic art, 30,000 years earlier and 10,000 kilometres farther south than the artists who fuelled the "creative explosion" in Europe. Drawing on these early finds, anthropologists Sally McBrearty and Alison Brooks wrote a full-on attack in 2000 on the "Eurocentric" view of human origins in a paper entitled "The Revolution That Wasn't" .

Their blistering criticisms spurred others to look far and wide for the origins of symbolic thought, and in the last 10 years many old finds have been reappraised and new ones uncovered. Among the more notable discoveries are ostrich eggshells from the Diepkloof rock shelter in South Africa engraved with five distinct geometric patterns that are at least 52,000 years old. Collections of seashells in Qafzeh cave, Israel, and the Grotte des Pigeons in Morocco, meanwhile, show that modern humans were already collecting personal ornaments 80,000 years ago. And in one of the few finds in Asia, some jewellery from Zhoukoudian upper cave near Beijing, China, may be 34,000 years old, again suggesting that groups across the world were experimenting with different ways of communicating and decorating themselves.

As the finds have pushed the emergence of abstract thought deeper and deeper into our evolutionary past, some archaeologists are even questioning whether art and symbolism are unique to *Homo sapiens*. After all, Neanderthals had roughly similar-sized brains to modern humans – and the lack of available evidence so far might just be down to the nature of those species' cultures. "Perhaps they were using feathers or vegetable pigments that left no traces," says Francesco d'Errico of the University of Bordeaux, France.

There are certainly some tantalising hints that they may have experimented with art, as I can see for myself in one of the chambers of the El Castillo cave. Littered with red dots, outlines of bison and handprints, it is quite a spectacle, but I almost miss the most remarkable artefact – a red painted disc, almost completely masked by an opaque layer of calcite. An analysis of the uranium content of the calcite suggests it was painted at least 40,000 years ago, making it the oldest evidence of painting to have been identified in Europe. Since modern humans were only just arriving in Europe at the time, some researchers have concluded that it could have Neanderthal origins.

"Neanderthal crayons may have been made for body paint, but they could have been scraped on walls too"



RICHARD WILKINSON

Along similar lines, d'Errico has found blocks of manganese pigments in caves at the Pech de l'Azé site in France, which were occupied by Neanderthals. Shaped like crayons, the blocks might have been used to paint designs on the body – in itself a symbolic act. "There's no reason why they couldn't scrape them on walls too," says Christopher Henshilwood of the University of the Witwatersrand in South Africa. Perhaps eventually they would have been capable of creating the elaborate, figurative art in the *Homo sapiens* cave painting. "I think they were on the path to modernity. If they had survived, it would have been interesting to see the trajectory," he says.

That would seem to tally with finds from another French cave, the Grotte du Renne, that was once inhabited by Neanderthals. First reported in 2011, there are numerous ornaments, including perforated teeth presumably worn on a necklace, as well as pigments and decorated bone tools. All of this suggests an advanced material culture, although detractors point out that they could be *Homo sapiens* artefacts mixed in with Neanderthal remains.

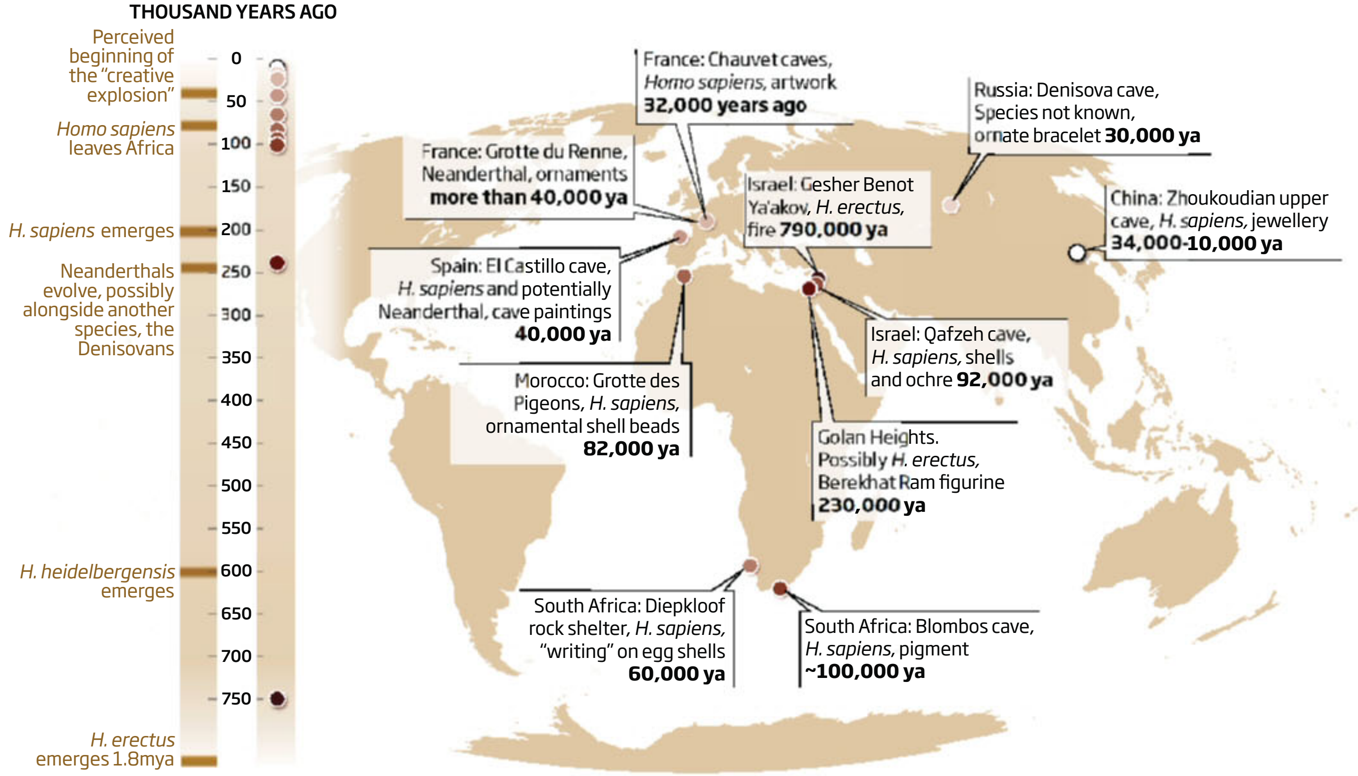
It's even possible that more distant relatives were budding artists. In the Golan Heights, for instance, Israeli researchers found the 230,000-year-old Berekhat Ram figurine, which appears to resemble the so-called Venus figurines carved in Europe some 30,000 years ago. The object is crude, and could be nothing more than a conveniently shaped pebble, though some microscopic analyses suggest there was deliberate carving around the neck to sculpt it into the right proportions. If so, the timing and location suggests it was the handiwork of *Homo erectus*. While the idea remains contentious, there are rumours that we might soon see some more dramatic evidence of symbolic behaviour in this extinct ancestor.

Family history

For the time being, more tangential lines of evidence may help flesh out the picture. It can take a long time for a behavioural or cognitive change to leaves its traces in the archaeological record, says Johan Lind at Stockholm University in Sweden, but there are ways to reconstruct those hazy periods. For instance, many researchers are turning to software normally used to trace the genetic lineages connecting different organisms. Although it was designed to work with genes, it can be modified to reconstruct the evolution of traditions like marriage from archaeological

The revolution that wasn't

Art and symbolism were once thought to have emerged suddenly in Europe around 40,000 years ago. Discoveries from around the world suggest abstract thinking emerged much earlier and perhaps even in other species



finds and linguistic records. Casting their net wide, Lind's team included data on the *FOXP2* gene, which is thought to be associated with linguistic development, and changes in the vocal tract, as well as archaeological clues for things like fire use and complex tool technology – traits that should rely on the same "abstract" toolkit that gave rise to symbolism. In a paper published in 2013, they estimated that the modern mind arose at least 170,000 years ago, and perhaps as far back as 500,000 years in an ancestor like *Homo erectus*. "Things seen as uniquely human traits are deep in the phylogeny," says Lind.

Whatever the conclusions on other species' abilities, it seems clear that the capacity for abstract thought had arisen long before our ancestors had left Africa. But that doesn't solve the mystery of the creative explosion, with its figurative art and mythical creatures. What caused our ancestors to make the leap from those early efforts to the intricate creations that I can see on the El Castillo cave?

One possibility is that their populations had reached a critical mass that somehow promoted innovation – an idea supported by recent findings showing that *Homo sapiens* experienced a population explosion once they reached Europe. Advanced cultures, after all, are the product of many smaller innovations – and that needs many minds thinking and inventing over many years. "You need a lot of culture to make a new culture," says Lind. Or, as he also puts it, the pop group Abba wouldn't have emerged if you'd put 100 Swedes on the moon in the 1970s.

"Culture needs many inventors. Abba wouldn't have emerged if you'd put 100 Swedes on the moon"

The population boom created a fundamentally different social environment, where people were living in larger groups and with bigger social networks. The result was a social pressure cooker that demanded different ways of creating a shared identity and coordinating larger groups. "These symbolic developments are the cultural glue that held these people together and allowed them to interact constructively," says Nicholas Conard of the University of Tübingen in Germany, who has uncovered many ancient artefacts in the Swabian Alps region of the country. "The people who use these symbols do better on the competitive landscape than people who don't."

Understanding these changing dynamics might even help us to reinterpret the meaning of the artwork. If El Castillo, for instance, was a meeting point for different groups, then it could help decode those complex red rectangles on the cave wall. "I don't see why they couldn't be clan signs or some sort of affiliation marker," says von Petzinger. "They are all the same overall format. You start with a rectangle, then divide it into sections, and this is where the real differences appear – some are decorated with cross-hatching, some with lines or dots, some left empty." The individual configurations may then represent different families or groups, she says.

There are many other types of geometric ›

DILLON VON PETZINGER

Are these the signs of different clans that lived in El Castillo cave?

signs in the caves of Europe, and von Petzinger is investigating whether they became more complex to help mark out the different groups as the social pressures mounted. She has found that the earliest symbols tend not to be configured in any particular way, but around 20,000 years ago the marks start to be grouped together. For example, visiting the nearby Ojo Guareña cave, I saw neat rows of triangles painted on the walls.

Driven to abstraction

This change in behaviour might relate to the climatic conditions at the peak of the ice age that occurred between 26,000 and 19,000 years ago, von Petzinger says, as the cold forced people south. "Suddenly they were living in closer proximity than before," she says. "If you are dealing with strangers, you need to know who they are, and also 'who am I?'," she says – and perhaps they needed to expand their artistic vocabulary to take into account the growing number of people. The symbols may also have been used as territorial markers, so that a new group would know the cave had already been explored by others.

A similar forensic approach might shed light on the abstract signs engraved on thousands of Palaeolithic bones and antlers – including lines, chevrons and crosses. The signs had previously been interpreted as lunar cycles, or a tally system, but when Sarah Evans at the University of Cambridge built a "dictionary" of these marks, she found that symbols and objects often coincide. For, example, three distinct line groups appear on lissoirs – bone tools used to smooth animal hide – but not on other tools. That kind of systematic patterning suggests it was a tradition passed from one person to another, she says. While it's possible such engravings might have been used for something like counting, the particular style might have helped signal group membership, she says.

"As we shine our torches on a bison carved from the rock, its silhouette seems to dance across the wall"

That could have been crucial in certain situations. If you encountered strangers carrying tools with similar engravings, you would know that they came from a similar background and were likely to think and act in a similar way to you, easing your interactions. "Social networking is a key aspect of our lives," says Evans. "I wouldn't go as far as saying that these bones were the Facebook of their time, but they created a link between people that could have enabled their survival."

Of course, different factors might have driven advances in different regions. D'Errico thinks the developments appeared in a kind of mosaic, with ideas such as cave painting emerging and fading according to the local conditions. "There is no one simple pattern. Innovation appears and disappears as populations test out their cultural experiments." Together with Henshilwood, he recently set up a major research project called Tracsymbols to examine how the local climate might have driven key behavioural innovations and their loss in both modern humans and Neanderthals. For instance, as part of the investigations, they are exploring whether changes to the climate in southern Africa 70,000 years ago might have stalled their burgeoning cultures. If so, it may be analogous to the situation in Tasmania 14,000 years ago, when rising sea levels cut the island off from Australia, causing its inhabitants to abandon many technological innovations.

While our understanding of the origins of human cognition has greatly improved in recent years, we can expect far greater developments to come, as genetic research helps to pick apart more of the differences between human species. "There will be no simple answers," says Conard. "It's going to be complicated, but that makes it all the more exciting."

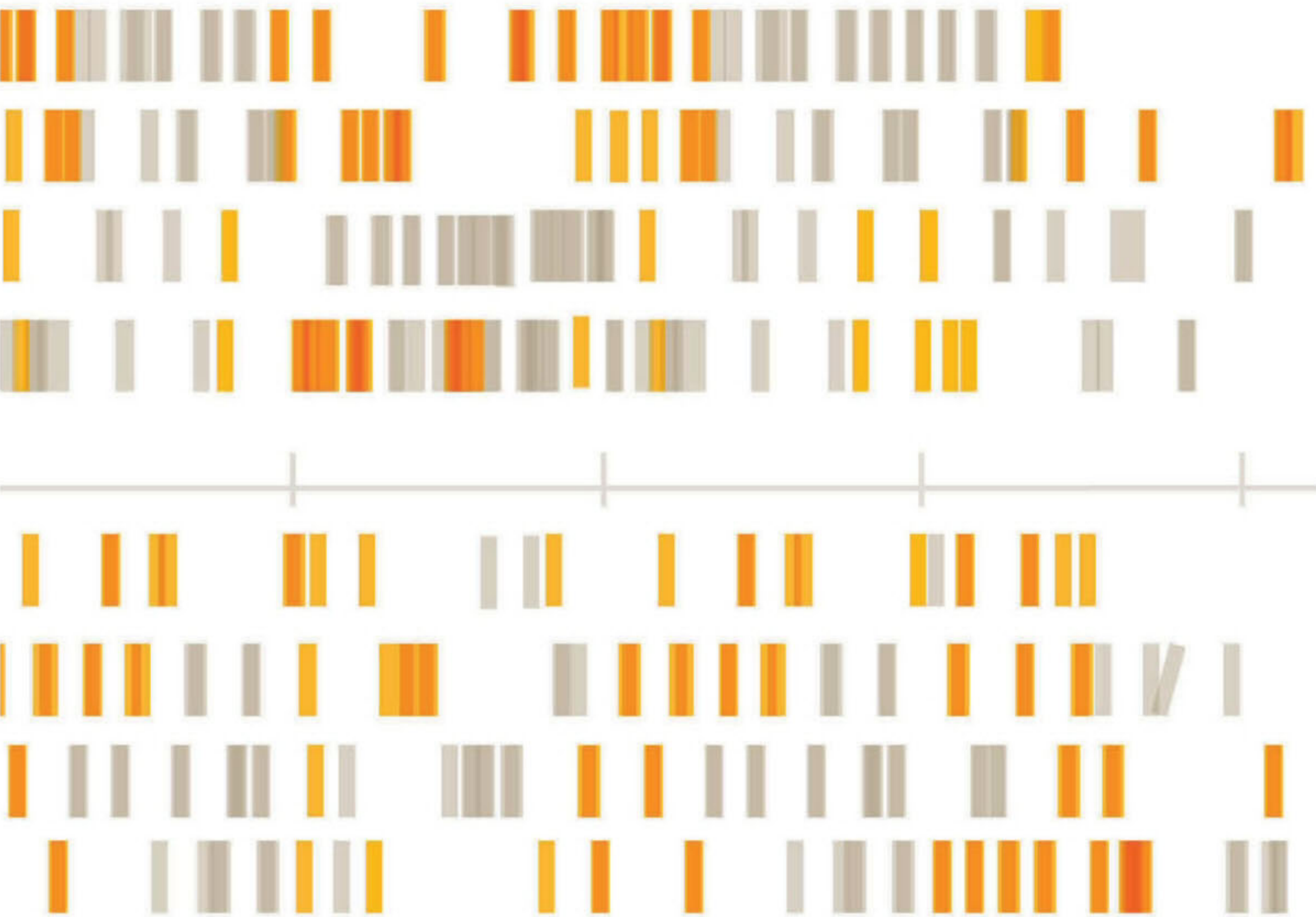
Back in the El Castillo cave, I reluctantly leave the small cavern with the rectangular signs to explore the rest of the cave complex. The ancient art is mind-blowing. Large red discs line the walls of corridors – were they once path markers? Elsewhere, a weird upright bison figure is carved from the rock formation, and as we shine our torches on it, its silhouette seems to dance across the cave wall. Some researchers have interpreted this as a form of shadow theatre.

Eventually, I emerge, get into my car and am instantly back in the 21st century. Driving along the coast to Bilbao, it occurs to me that if ancient humans hadn't developed the ability to scrawl those abstract designs, perhaps none of the technology around me – my car, phone, satnav – would have been invented. As von Petzinger says, "There's more of a story to these geometric signs than we give credit for." ■


Be afraid.
Be very afraid.
Complexity can be hard to fathom. But ignore it, and you could miss real dangers—or real opportunities.
Discover **free** online courses on complexity from some of science's leading thinkers. They might just transform how you view the hidden traps and emerging possibilities in your own complex world.
SANTA FE INSTITUTE
complexityexplorer.org

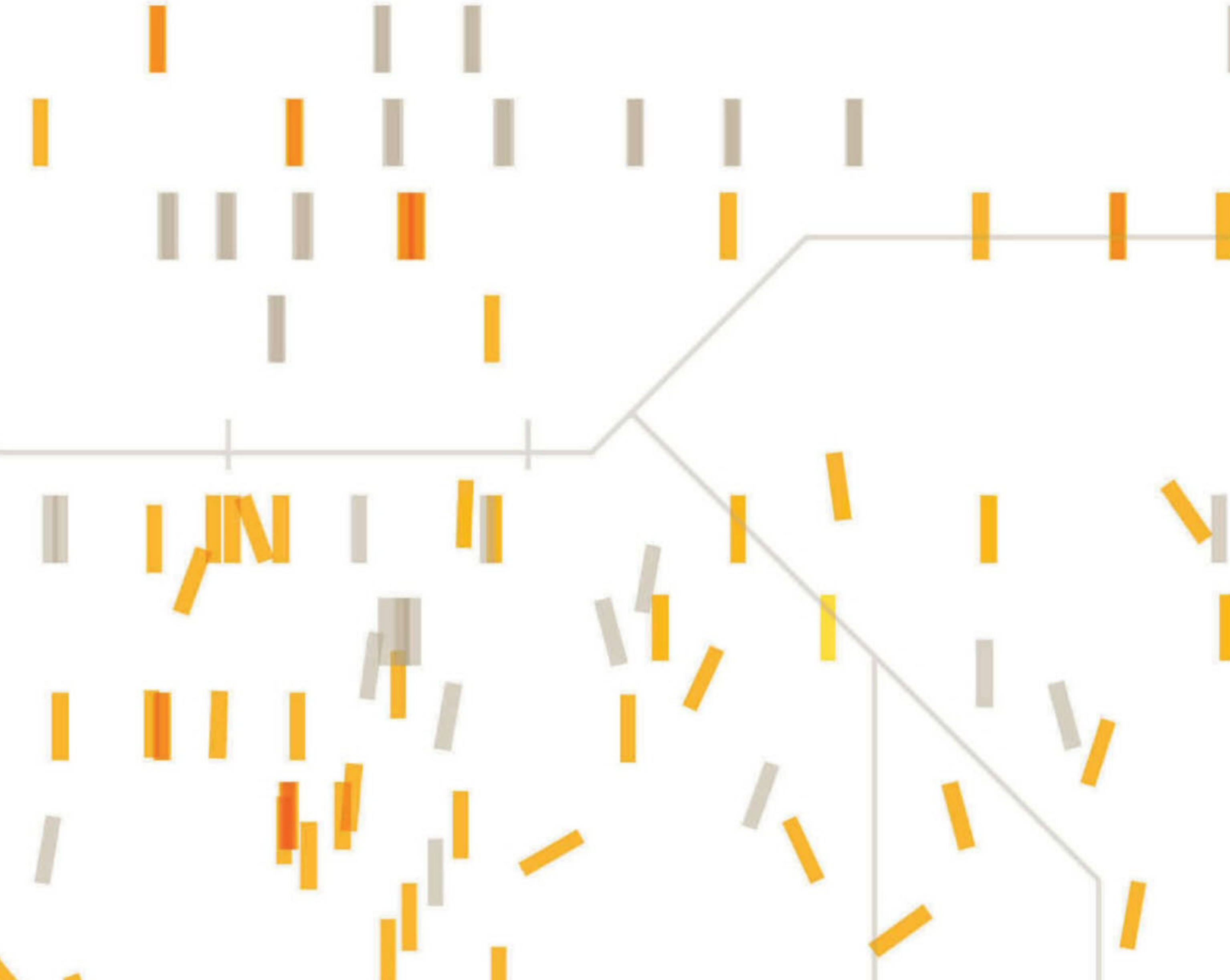
CHAPTER FOUR

YOUR ANCIENT GENOME



LIVING HISTORY

The human genome contains a record of three billion years of evolution. **Michael Le Page** tells its eventful and turbulent story



GTGCCAGCAGCCGCGGTAATTCCAGCTCCAATA GCGTATATTAAAGTTGCTGCAGTTAAAAAG
It looks like gibberish, but this DNA sequence is truly remarkable. It is present in all the cells of your body, in your cat or dog, the fish on your plate, the bees and butterflies in your garden and in the bacteria in your gut. In fact, wherever you find life on Earth, from boiling hot vents deep under the sea to frozen bacteria in the clouds high above the planet, you find this sequence. You can even find it in some things that aren't technically alive, such as the giant viruses known as mimiviruses.

This sequence is so widespread because it evolved in the common ancestor of all life, and as it carries out a crucial process, it has barely changed ever since. Put another way, some of your DNA is an unimaginable 3 billion years old, passed down to you in an unbroken chain by your trillions of ancestors.

Other bits of your DNA are brand new. You have around 100 mutations in your genome that are not present in your mother or father, ranging from one or two-letter changes to the loss or gain of huge chunks of DNA.

We can tell which bits of our DNA are old or new by comparing genomes. Comparing yours with those of your brother or sister, for instance, would reveal brand new mutations. Contrasting the genomes of people and animals reveals much older changes.

Our genomes, then, are not just recipes for making people. They are living historical records. And because our genomes are so vast, consisting of more than 6 billion letters of DNA – enough to make a pile of books tens of metres high – they record our past in extraordinary detail. They allow us to trace our evolution from the dawn of life right up to the present.

While we have only just begun to decipher these records, we have already discovered that our ancestors didn't just face a harsh struggle for survival in a world red in tooth and claw. There were also epic battles going on in our genomes, battles that transformed the way our genome works and ultimately made us what we are today. ›

FERNANDO ROSALES

The universal ancestor

In the beginning there was RNA. This multitalented molecule can store information and catalyse reactions, which means some RNAs can replicate themselves. As soon as one RNA molecule, or set of molecules, began replicating itself, the first genome was born.

The downside of RNA is that it isn't particularly stable, so very early on life switched to storing information in a molecule with a slightly different chemical backbone that is less likely to break apart – DNA. Proteins also replaced RNA as catalysts, with RNA relegated to the role of a go-between. DNA stored the recipes for making proteins, sending out RNA copies of the recipes to the protein-making machinery.

Many traces of the ancient RNA-dominated world remain in our genome. The ubiquitous sequence at the beginning of this article, for instance, codes for part of an RNA enzyme that still plays a key role in the synthesis of proteins.

By around 4 billion years ago, a living entity had evolved with a genome that consisted of recipes for making RNAs and proteins – the last universal common ancestor of all life. At least 100 genes can confidently be traced all the way back to LUCA, says Eugene Koonin of the National Institutes of Health in Bethesda, Maryland, who studies the evolution of life, and LUCA probably had more than 1000 genes in total.

LUCA had a lot of the core machinery still found in all life today, including that for making proteins. Yet it may have been quite unlike life as we know it today. Some researchers believe that LUCA wasn't a discrete, membrane-bound cell at all but rather a mixture of virus-like elements replicating inside some non-living compartment, such as the pores of alkaline hydrothermal vents.

Split and reunion

One possible scenario for the next stage is that subsets of LUCA's virus-like elements broke away on two separate occasions, acquiring cell membranes and becoming simple cells. This would explain why there are two kinds of simple cell – bacteria and archaea – each with a completely different cell membrane. "It's a very appealing hypothesis," Koonin says. What is certain is that life split into two major branches very early on.

Bacteria and archaea evolved some amazing molecular machinery and transformed the planet, but they remained little more than tiny bags of chemicals. It wasn't until an extraordinary event reunited the two great branches of life that complex cells, or eukaryotes, emerged – an event that transformed the genome and paved the way for the evolution of the first animals.

Around a billion years ago, a bacterium ended up inside an archaeon. Instead of one killing the other, the two forged a symbiotic relationship, with the descendants of the bacterium gradually evolving to take on a crucial role: they became mitochondria, the power factories inside cells that provide our energy.

Without this union, complex life might never have evolved at all. We tend to assume that it is natural for simple organisms to evolve into more complex ones, but individual bacteria and archaea have never evolved beyond a certain level of complexity. Why?

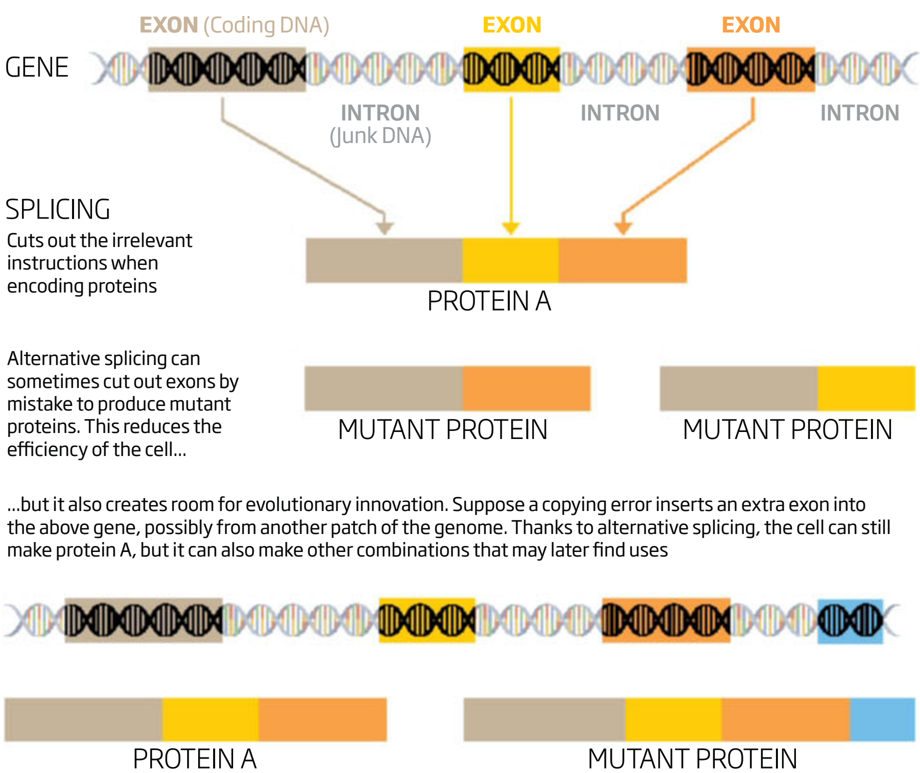
According to Nick Lane of University College London, it's because they hit an energy barrier. All simple organisms generate energy using their cell membranes. As they get bigger, the ratio of surface area to volume falls, making it harder to produce enough energy. The upshot is that simple cells have to stay small – and small cells don't have room for big genomes. Mitochondria eliminated this barrier by providing modular, self-contained power sources. Cells could now get bigger simply by producing more mitochondria, allowing them to expand their genomes and so their information-storing capacity.

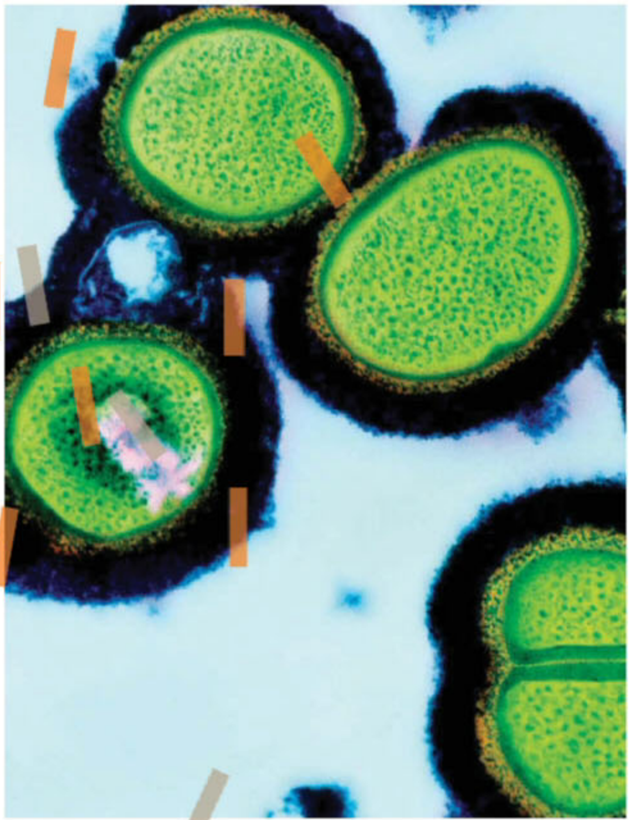
Besides freeing cells from this energy constraint, the ancestor of mitochondria was also the source of up to three-quarters of our genes. The original bacterium probably had 3000 or so genes, and over time most were either lost or transferred to the main genome, leaving modern mitochondria with just a handful of genes.

Despite the obvious benefits, the forging of this alliance was fraught with peril. In particular, the genome of the ancestral mitochondrion was infested with pieces of parasitic DNA, or transposons, that did nothing except create copies of themselves. They sometimes landed in the middle of

The cutting room

In our genes, coding regions called exons are interspersed with non-coding regions called introns. Introns need to be "spliced" out before proteins are made




KARI LOUNATMAA/SCIENCE PHOTO LIBRARY

Up to three-quarters of our genes ultimately derive from an ancient bacterium

genes, leaving them with big chunks of irrelevant DNA known as introns. It's the equivalent of sticking a recipe for soup into the middle of a cake recipe.

Yet the result was not always a recipe for disaster, because these introns were "self-splicing": after an RNA copy of a gene was made – the first step of the protein-making process – they cut themselves out. This didn't always happen, though, so their presence was a disadvantage. Most bacteria have no introns in their genes, because in large populations with a lot of competition between individuals, natural selection is strong and weeds them out. But the population of the ancestral eukaryote was very small, so selection was weak. The genetic parasites that arrived with the ancestor of the mitochondrion began to replicate like crazy, littering the main genome with hundreds of introns.

Today, each of our genes typically contains about eight introns, many of which date back to the very first eukaryotes – our ancestors never did manage to get rid of most of them. Instead, they evolved ways of dealing with them that altered the structure of our genes and the way that cells reproduce. One was sex.

The benefits of sex

The crucial thing about sex is not just the mingling of genes from different individuals, important as this is for bringing together evolutionary advances made in separate lineages. Simple cells had long been swapping genes without bothering with sex.

It's also a process known as recombination, in which pairs of chromosomes swap corresponding pieces before being divided into sperm or eggs. Recombination helps solve a fundamental problem with having a genome consisting of many genes linked together like beads on a necklace.

Imagine a necklace with a truly magnificent pearl right next to a flawed one. If you can't swap one pearl for another, you either have to get rid of the whole thing or take the necklace as it is. Similarly, if a beneficial mutation ends up next to a harmful one, either the beneficial mutation will be lost or the harmful mutation will spread through a population, dragged along by its neighbour.

Recombination gives you the opportunity to swap pearls. Just as you can produce one perfect necklace and one with defects, so some offspring will get a disproportionate number of good genes, while others get lots of bad ones, perhaps with disruptive introns. The unlucky individuals are likely to die out while those with the good genes thrive.

In large populations, so many mutations arise that some will counteract the effects of the harmful genes, so there is no need to resort to recombination. But in a small population, sex wins out. This is why it became the norm for the first eukaryotes and thus for most of their descendants. So next time you make love, remember to thank the genetic parasite harboured by your ancient bacterial ancestor for the joy of sex.

"You can thank the genetic parasite harboured by our ancient bacterial ancestor for the joy of sex"

By the time sex had evolved, there were too many introns to get rid of them all. So early eukaryotes soon faced another serious problem: as introns acquired more and more mutations, the self-splicing mechanisms began to fail. In response, these early eukaryotes evolved special machines, called spliceosomes, that could cut out the introns from the RNA copies of genes.

Spliceosomes are the kind of mindless solution typical of evolution: cutting the junk out of the RNA copies of genes, rather than out of the original DNA, is very inefficient. What's more, spliceosomes are slow. Many RNAs would have reached the protein-making factories before their introns were spliced out, leading to defective proteins.

This is why the nucleus evolved, Koonin has proposed. Once a cell's DNA was enclosed in a compartment separate from the protein-making machinery, only spliced RNAs could be allowed out, preventing cells from wasting energy by producing useless proteins.

Even this didn't solve all the problems, though. Spliceosomes often cut out coding sections of genes – known as exons – by mistake, resulting in mutant versions of the proteins. "Alternative splicing was not an adaptation," says Koonin. "It was something that organisms had to deal with."

So our ancient ancestors evolved layer upon layer of complex machinery to cope with the proliferation of introns, yet still hadn't solved all the problems they caused. But unlike simple cells, they could afford this wastefulness because they were flush with energy – and in the long run all this extra complexity led to new opportunities. ›

Versatility and control

The presence of introns, and thus exons, in effect made genes modular. In an uninterrupted gene, mutations that add or remove sections usually change the way the rest of the gene is read, producing gibberish. Exons, by contrast, can be moved around without disrupting the rest of the gene. Genes could now evolve by shuffling exons within and between them.

Suppose, for instance, that random mutations add an extra exon to a gene. Thanks to alternative splicing, the original version of the protein can still be made, but it also means a new protein can come from the same gene (see "The cutting room", page 58). The mutation might have little effect and so wouldn't be eliminated by selection, but over time, the new protein might take on a new function. Quite by accident, eukaryotes' mindless efforts to deal with introns had made their genes more versatile and more evolvable.

Introns may have acquired other uses too. It is now clear, for instance, that some help regulate protein-building.

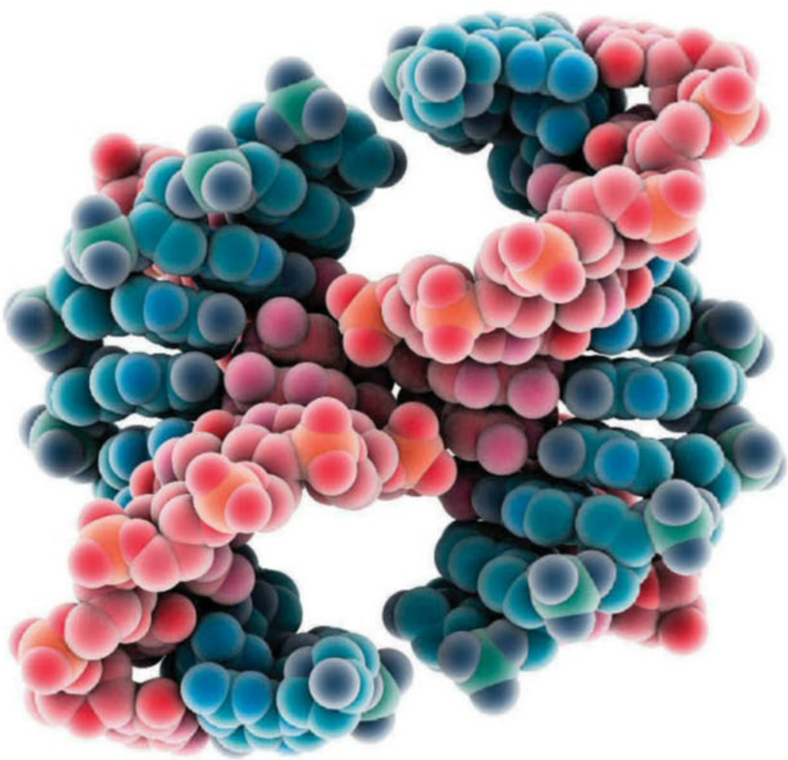
If this view of the evolution of complex cells is correct, many of the key features of our genome, from modular genes to sex, evolved as a direct result of the acquisition of parasite-bearing mitochondria. Alternative ideas cannot be ruled out, but none provides such a beautiful explanation. "It's my favourite scenario," says Koonin.

All these novel features led to a burst of evolutionary innovation, and eukaryotes thrived and soon began to diversify. Even so, they still faced a relentless onslaught from the invasion of new kinds of parasitic DNA and viruses. Having transcended the size constraints on simple cells, however, complex cells were free to evolve more sophisticated defence mechanisms.

One was to "silence" the transposons' parasitic genes by adding tags to the DNA that stop RNA copies being made – a process called methylation. Another was to destroy the RNAs of invading viruses to stop them replicating themselves. These defences were only partly successful. Today, around 5 per cent of the human genome consists of the mutated and mostly inert remains of viruses, and an astonishing 50 per cent consists of the remnants of transposons, a testament to the many occasions on which these parasites somehow got into the genomes of our ancestors and ran rampant.

Such defence mechanisms were soon co-opted for another purpose: to control the activity of a cell's own genes. "Mechanisms for controlling transposons became mechanisms for controlling genes," says Ryan Gregory of the University of Guelph, Canada, who studies the evolution of genomes.

Swapping genes during sex helps organisms weed out the bad mutations from the good



"They say history is written by the victors. Our genome is a record of victories, of successful experiments"

Building bodies

The stage was now set for the next big step in evolution, roughly 800 million years ago, when cells began to cooperate more closely than ever before. Although a few bacteria are multicellular, the constraints on their complexity have never allowed them to go far down this road. Eukaryotes, by contrast, have evolved multicellularity on dozens of occasions, giving rise to hugely complex organisms such as fungi, seaweeds, land plants and, of course, animals.

One reason was their bigger repertoire of genes, which could be co-opted for new purposes such as binding cells together and communicating with other cells. Even more importantly, the modular nature of their genes allowed more rapid evolution. The proteins that join cells together, for instance, consist of a part that straddles the cell membrane and a part that protrudes outwards. With modular genes, all kinds of different protruding bits can be tacked on to the membrane-straddling part, like different attachments on a vacuum cleaner. Many crucial genes for multicellularity evolved via exon shuffling.

In addition, eukaryotes' more sophisticated mechanisms for controlling genes could be used to allow cells to specialise. By switching different sets of genes on or off, different groups of cells could take on distinct roles. As a result, organisms could begin to develop different types of tissue, allowing early animals to evolve from simple sponge-like creatures to animals with increasingly sophisticated bodies.

The next great leap forward was the result of a couple of genetic accidents. When things go wrong during reproduction, the entire genome can occasionally be duplicated – and this happened not once but twice in the ancestor of all vertebrates.

These genome duplications produced lots of extra copies of genes. Many were lost but others took on new roles. In particular, the duplications produced four clusters of the master genes that establish body plans during development – the *Hox* genes – and these clusters are thought to have played a crucial role in the evolution of an internal skeleton.

Whole-genome duplications are rare, and most new genes arise from smaller duplications, or from exon shuffling, or both. Evolution is shameless – it will exploit any DNA that does something useful regardless of where it comes from. Some crucial genes have evolved from bits of junk DNA, whereas others have been acquired from elsewhere.

About 500 million years ago, for instance, the genome of our ancestors was invaded by a genetic parasite called a hAT transposon, which copies itself using a "cut and paste" mechanism. The cutting is done by two enzymes that bind to specific DNA sequences.

At some point in an early vertebrate, the sequences bound to by the DNA-cutting enzymes ended up near or in a gene involved in recognising invading bacteria and viruses. The result was that during the course of an individual's life, as their cells multiplied, the hAT enzymes cut bits out of the gene. Crucially, different bits got cut out in different cell lines, generating lots of mutant versions of the protein.

In some cases, this turned out to be a lifesaver, because the mutant proteins were better at latching on to invading pathogens. Soon a mechanism evolved for recognising the cells producing the most effective versions and encouraging them to multiply – the adaptive immune system. The human immune system is now mind-bogglingly complex, but the two enzymes that cut up and rearrange genes – the crucial process that allows it to target invaders – are direct descendants of the hAT enzymes. So we have an ancient parasite to thank for our most effective weapon against disease.

The human genome

Armed with these advanced defences, and with a genetic toolkit that could be tweaked to produce a huge variety of body shapes, early vertebrates were extremely successful. They conquered the seas, colonised the land, took to the trees and then came back down and started walking on two legs.

What made us so different from other apes? There is one apparently big difference: we have 23 chromosomes and our ape ancestors have 24. But chromosomes are essentially bags of genes: it makes little difference if they split apart or fuse together as long as we still have the genes that we need. Rather, it seems a long series of smaller changes gradually altered our brains and bodies. We've identified a few key mutations , but there may be thousands more.

Looking back at the bigger picture, it is clear that increases in the complexity of cells and bodies began with increases in the complexity of genomes. What is striking, though, is that many of the initial increases in complexity were not driven by evolutionary selection, but by a lack of it. "Most of what's going on at the genomic level is probably neutral," says Gregory.

In other words, mutations arise that have little if any effect, such as a duplicate gene. In a large population, such mutations would soon be lost. But in a tiny population, they can spread by chance, through genetic drift. It is only later that such complexity is selected for, such as when a duplicate gene acquires a new role.

Many key events in our history, such as the genome duplications that produced our *Hox* genes, may be a result of relaxed selection in a tiny population. Indeed, a population bottleneck right at the beginning of human evolution might explain the spread of some of the mutations that make us so different to other apes, such as our loss of muscle strength.

The other striking thing is that viruses and parasites have played a huge role. Many of the main features of our genome, from sex to methylation, evolved in response to their attacks. What's more, a fair number of our genes and exons, like the immune enzymes, derive directly from these attackers. "Viruses have been necessary parties to cellular life from the very beginning," says Koonin (for more on this see "I, virus", page 62).

Necessary but not pleasant. Our evolution has come at a tremendous cost. They say history is written by the victors – well, our genome is a record of victories, of the experiments that succeeded or least didn't kill our ancestors. We are the descendants of a long line of lottery winners, a lottery in which the prize was producing offspring that survived long enough to reproduce themselves. Along the way, there were uncountable failures.

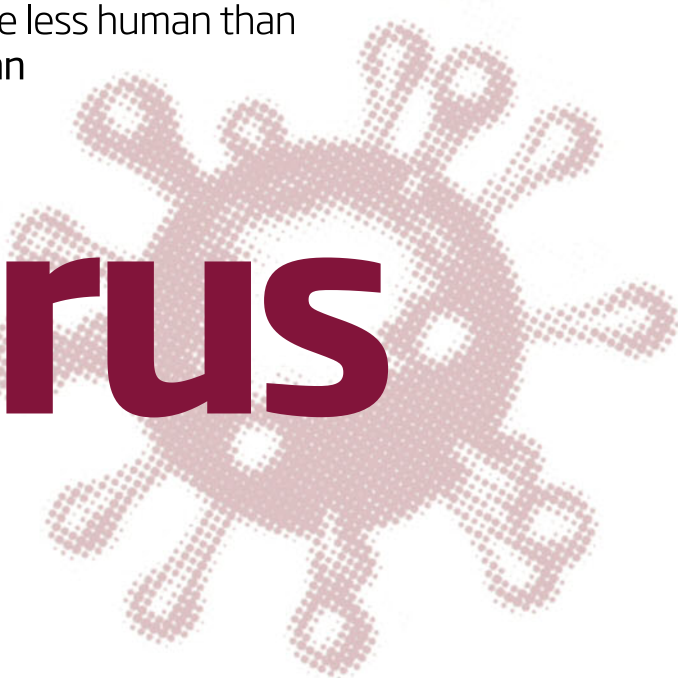
Our genome is far from a perfectly honed, finished product. Rather, it has been crudely patched together from the detritus of genetic accidents and the remains of ancient parasites. It is the product of the kind of crazy, uncontrolled experimentation that would be rejected out of hand by any ethics board. And this process continues to this day – go to any hospital and you'll probably find children dying of horrible genetic diseases. But not as many are dying as would have happened in the past. Thanks to methods such as embryo screening, we are starting to take control of the evolution of the human genome. A new era is dawning. ■

GLOSSARY

Archaeon - one of two kinds of simple organism
Bacterium - one of two kinds of simple organism
Eukaryote - a complex cell with intricate internal structures
Exon - one of the parts of a gene that codes for a protein
Gene - a recipe for making a protein or functional RNA
Intron - a part of a gene that does not code for a protein. Introns are usually cut out of a gene's RNA copy before it reaches the protein-making factory
LUCA - last universal common ancestor
Splicing - the process of removing introns from RNA
Transposon - a genetic parasite. Contains code for enzymes that allow it to copy and paste itself into other parts of the genome

Invaders have been infiltrating our genome for millions of years. You're less human than you think, says **Frank Ryan**

I, virus



WHEN, in 2001, the human genome was sequenced for the first time, we were confronted by several surprises. One was the sheer lack of genes: where we had anticipated perhaps 100,000 there were actually as few as 20,000. A bigger surprise came from analysis of the genetic sequences, which revealed that these genes made up a mere 1.5 per cent of the genome. This is dwarfed by DNA deriving from viruses, which amounts to over 8 per cent.

On top of that, huge chunks of the genome are made up of mysterious virus-like entities called retrotransposons, pieces of selfish DNA that appear to serve no function other than to make copies of themselves. These account for no less than 34 per cent of our genome.

All in all, the virus-like components of the human genome amount to almost half of our DNA. This would once have been dismissed as mere "junk DNA", but we now know that some of it plays a critical role in our biology. As to the origins and function of the rest, we simply do not know.

The human genome therefore presents us with a paradox. How does this viral DNA come to be there? What role has it played in our evolution, and what is it doing to our physiology? To answer these questions we need to deconstruct the origins of the human genome – a story more fantastic than anything we previously imagined, with viruses playing a bigger part than you might care to believe.

Around 20 years ago, when I was researching my book *Virus X*, I came to the conclusion there was more to viruses than meets the eye. Viruses are often associated with plagues – epidemics accompanied by great mortality, such as smallpox, flu and AIDS. I proposed that plague viruses also interact with their hosts in a more subtle way, through symbiosis, with important implications for the evolution of their hosts. Today we have growing evidence that this is true, and overwhelming evidence that viruses have significantly changed human evolution.

Symbiosis was defined by botanist Anton de Bary in 1878 as the living together of dissimilar organisms. The partners are known as symbionts and the sum of the partnership as the holobiont. Types of symbiotic relationships include parasitism, where one partner benefits at the expense of the other; commensalism, where one partner profits without harming the other; and mutualism, in which both partners benefit.

Symbiotic relationships have evolutionary

JIMMY TURRELL

implications for the holobiont. Although selection still operates on the symbionts at an individual level since they reproduce independently, it also operates at partnership level. This is most clearly seen in the pollination mutualisms involving hummingbirds and flowers, where the structure of flower and bill have co-evolved to accommodate each other and make a perfect fit. When symbiosis results in such evolutionary change it is known as symbiogenesis.

Viruses as partners

Symbiosis works at many different levels of biological organisation. At one end of the spectrum is the simple exchange of metabolites. Mycorrhizal partnerships between plant roots and fungi, which supply the plant with minerals and the fungus with sugars, are a good example. At the other end are behavioural symbioses typified by cleaning stations where marine predators line up to have their mouths cleared of parasites and debris by fish and shrimps.

Symbiosis can also operate at the genetic level, with partners sharing genes. A good example is the solar-powered sea slug *Elysia chlorotica*, which extracts chloroplasts from the alga it eats and transfers them to cells in its gut where they supply the slug with nutrients. The slug's genome also contains genes transferred from the alga, without which the chloroplasts could not function. The slug genome can therefore be seen as a holobiont of slug genes and algal genes.

This concept of genetic symbiosis is crucial to answering our question about the origin of the human genome, because it also applies to viruses and their hosts. Viruses are obligate parasites. They can only reproduce within the cells of their host, so their life cycle involves forming an intimate partnership. Thus, according to de Bary's definition, ›

"Genetic symbiosis is crucial to understanding the origin of the human genome, because it also applies to viruses" virus-host interactions are symbiotic.

For many viruses, such as influenza, this relationship is parasitic and temporary. But some cause persistent infections, with the virus never leaving the host. Such a long-term association changes the nature of the symbiosis, making the evolution of mutualism likely. This process often follows a recognisable progression I have termed "aggressive symbiosis".

Rabbits kicked the bucket

An example of aggressive symbiosis is the myxomatosis epidemic in rabbits in Australia in the 1950s. The European rabbit was introduced into Australia in 1859 as a source of food. Lacking natural predators, the population exploded, leading to widespread destruction of agricultural grassland. In 1950, rabbits infected with myxoma virus were deliberately released into the wild. Within three months, most of the rabbits of south-east Australia were dead.

Although the myxomatosis epidemic was not planned as an evolutionary experiment, it had evolutionary consequences. The myxoma virus's natural host is the Brazilian rabbit, in which it is a persistent partner causing no more than minor skin blemishes. The same is now true of rabbits in Australia. Over the course of the epidemic the virus selected for rabbits with a minority genetic variant capable of surviving infection. Plague culling was followed by co-evolution, and today rabbit and virus coexist in a largely non-pathogenic mutualism.

> "Although the myxomatosis epidemic in Australia in the 1950s was not planned as an evolutionary experiment, it had evolutionary consequences"

Now imagine a plague virus attacking an early human population in Africa. The epidemic would have followed a similar trajectory, with plague culling followed by a period in which survivors and virus co-evolved. There is evidence that this happened repeatedly during our evolution, though when, and through what infectious agents, is unknown.

Even today viral diseases are changing the course of human evolution. Although the plague culling effect is mitigated by medical intervention in the AIDS pandemic, we nevertheless observe selection pressure on humans and virus alike. For example, the human gene *HLA-B* plays an important role in the response to HIV-1 infection, and different variants are strongly associated with the rate of AIDS progression. It is therefore likely that different *HLA-B* alleles impose selection pressure on HIV-1, while *HLA-B* gene frequencies in the population are likely to be influenced by HIV. This is symbiogenesis in action.

How does that move us closer to understanding the composition of the human genome? HIV-1 is a retrovirus, a class of RNA virus that converts its RNA genome into DNA before implanting it into host chromosomes. This process, known as endogenisation, converts an infectious virus into a non-infectious endogenous retrovirus (ERV). In humans, ERVs are called HERVs.

Endogenisation allows retroviruses to take genetic symbiosis to a new level. Usually it is an extension of the normal infectious process, when a retrovirus infects a blood cell, such as a lymphocyte. But if the virus happens to get incorporated in a chromosome in the host's germ line (sperm or egg), it can become part of the genome of future generations.

Such germ-line endogenisation has happened repeatedly in our own lineage – it is the source of all that viral DNA in our genome. The human genome contains thousands of HERVs from between 30 and 50 different families, believed to be the legacy of epidemics throughout our evolutionary history. We might pause to consider that we are the descendants of the survivors of a harrowing, if brutally creative, series of viral epidemics.

Endogenisation is happening right now in a retroviral epidemic that is spreading among koalas in Australia. The retrovirus, KoRv, appeared about 120 years ago and has already spread through over 75 per cent of the koala's range, culling animals on a large scale and simultaneously invading the germ line of the survivors.

Retroviruses don't have a monopoly on endogenisation. Genes from a bornavirus were identified in the genomes of several mammals, including humans, in 2009. This was the first time a virus not in the retrovirus class has been identified in an animal genome. The virus appears to have entered the germ line of a mammalian ancestor around 40 million years ago. Many more such discoveries are anticipated, perhaps explaining the origin of some of that mysterious half of the genome.

The ability of viruses to unite, genome-to-genome, with their hosts has clear evolutionary significance. For the host, it means new material for evolution. If a virus happens to introduce a useful gene, natural selection will act on it and, like a beneficial new mutation, it may spread through the population.

Could a viral gene really be useful to a mammal? Don't bet against it. Retroviruses have undergone a long co-evolutionary relationship with their hosts, during which they have evolved the ability to manipulate host defences for their own ends. So we might expect the genes of viruses infecting humans to be compatible with human biology.

This is also true of their regulatory DNA. A virus integrating itself into the germ line brings not just its own genes, but also regulatory regions that control those genes. Viral genomes are bookended by regions known as long terminal repeats (LTRs), which contain an array of sequences capable of controlling not just viral genes but host ones as well. Many LTRs contain attachment sites for host hormones, for example, which probably evolved to allow the virus to manipulate host defences.

Retroviruses will often endogenise repeatedly throughout the host genome, leading to a gradual accumulation of anything up to 1000 ERVs. Each integration offers the potential of symbiogenetic evolution.

Once an ERV is established in the genome, natural selection will act on it, weeding out viral genes or regulatory sequences that impair survival of the host, ignoring those that have no effect, and positively selecting the rare ones that enhance survival.

Positive selection

Most ERV integrations will be negative or have no effect. The human genome is littered with the decayed remnants of such integrations, often reduced to fragments, or even solitary LTRs. This may explain the origin of retrotransposons. These come in two types: long and short interspersed repetitive elements (LINEs and SINEs), and it now appears likely that they are heavily degraded fragments of ancient viruses.

As for positive selection, this can be readily confirmed by looking for viral genes or regulatory sequences that have been conserved and become an integral part of the human genome. We now know of many such sequences.

JIMMY TURRELL

The first to be discovered is the remnant of a retrovirus that invaded the primate genome a little less than 40 million years ago and gave rise to what is known as the W family of ERVs. The human genome has roughly 650 such integrations. One of these, on chromosome 7, contains a gene called *syncytin-1*, which codes for a protein originally used in the virus's envelope but now critical to the functioning of the human placenta. Expression of *syncytin-1* is controlled by two LTRs, one derived from the original virus and another from a different retrovirus called MaLR. Thus we have a quintessential viral genetic unit fulfilling a vitally important role in human biology.

There are many more examples. Another gene producing a protein vital to the construction of the placenta, *syncytin-2*, is also derived from a virus, and at least six other viral genes contribute to normal placental function, although their precise roles are poorly understood.

There is also tentative evidence that HERVs play a significant role in embryonic development. The developing human embryo expresses genes and control sequences from two classes of HERV in large amounts, though their functions are only only starting to be unravelled. What is more, disrupting LINE retrotransposons using the drug nevirapine causes an irreversible arrest in development in mouse embryos, suggesting that LINEs are somehow critical to early development in mammals .

It also appears that HERVs play important roles in normal cellular physiology. Analysis of gene expression in the brain suggests that many different families of HERV participate in normal brain function. *Syncytin-1* and *syncytin-2*, for example, are extensively expressed in the adult brain, though their functions there have yet to be explored.

Other research groups have found that 25 per cent of human regulatory sequences contain viral elements, prompting suggestions that HERVs make a major contribution to gene regulation . In support of that, HERV LTRs have been shown to be involved in the transcription of important proteins. For example, the *beta-globin* gene, which codes for one of the protein components of haemoglobin, is partly under the control of an LTR derived from a retrovirus.

"HIV might have the potential to enter the human germ line, taking our evolution in new and unexpected directions"

The answer to our paradox is now clear: the human genome has evolved as a holobiontic union of vertebrate and virus. It is hardly surprising that researchers who have made these discoveries have called for a full-scale project to assess the contribution of viruses to our biology.

It is also probable that this "virolution" is continuing today. HIV belongs to a group of retroviruses called the lentiviruses. Until recently virologists thought that lentiviruses did not endogenise, but now we know that they have entered the germ lines of rabbits, ferrets and the grey mouse lemur. That suggests that HIV-1 might have the potential to enter the human germ line, perhaps taking our evolution in new and unexpected directions. It's a plague to us – but it could be vital to the biology of our descendants. ■

Lucky you!

Evolution is a game of chance. **Clare Wilson** uncovers some of the winning mutations that helped us hit the jackpot

EARTH, several million years ago. A cosmic ray blasts into the atmosphere at close to the speed of light. It collides with an oxygen atom, generating a shower of energetic particles, one of which knocks into a DNA molecule within a living creature.

That DNA molecule happens to reside in a developing egg cell within an apelike animal living in Africa. The DNA is altered by the collision – mutated – and the resulting offspring is slightly different from its mother.

The mutation gives the offspring an advantage over its peers in the competition for food and mates, and so, as the generations pass, it is carried by more and more of the population. Eventually it is present in nearly everyone, so the altered sequence of DNA should really no longer be called a mutation – it's just one of the regular 23,000 or so genes that make up the human genome.

Although cosmic rays are thought to be one source of mutations, DNA-copying errors during egg and sperm production may be a more common cause. Whatever their origins, these evolutionary accidents took us on a 10-million-year journey from something similar to a great ape to us, *Homo sapiens*.

It was a remarkable transformation, yet we have only recently started to gain insight into the mutations that might have been involved. We are a million miles from a complete list, but even the first few to emerge as likely candidates are shedding light on the ascent of man. "It gives us a perspective on what it takes to become human," says John Hawks, a palaeoanthropologist at the University of Wisconsin-Madison.

For a long time, most of our knowledge of human evolution had to be gleaned from fragments of bone found in the earth – a bit like trying to work out the picture on a jigsaw when most of the pieces are missing. The fraction of animal remains that happen to be buried under the right conditions to fossilise can only be guessed at, but it is likely to be vanishingly small.

That is why the field of palaeoanthropology has been given such a boost by the explosion in genetic-sequencing technologies. In 2003, a complete read-out of the human genome was published, a project that took 13 years. Since then, thanks to the technology getting faster and cheaper, barely a year goes by without another genome rolling off the production line. We have now sequenced creatures including chimpanzees, gorillas and orang-utans, as well as Neanderthals and Denisovans, our distant cousins who left Africa before *Homo sapiens* did.

Comparing these genomes reveals a wealth of information. If a gene that is active in the brain is different in humans and chimps, for instance, that could point to a mutation that helped to make us smarter. In fact, comparing the human and chimp genomes reveals about 15 million substitutions in the "letters" that make up the genetic code. There are also wholesale deletions of DNA or duplications. Based on what we already know about DNA, the vast majority of these changes would not have affected our physical traits. That's either because the change to the DNA is so minor that it would not influence a gene's function, or because the mutation is in a region of so-called junk DNA. It is estimated that out of the 15 million differences, perhaps 10,000 were changes to genes that altered our bodies and were therefore subject to natural selection.

> "Evolutionary accidents led us on a 10-million-year journey from ape to human"

It's still a formidable target, and that's not counting mutations to the regulatory regions of our DNA, which act as on/off switches for genes. It is not yet possible to calculate a figure for this type of mutation in the human line, although they are thought to have played a crucial role in evolution.

So far several hundred mutations have been identified that affected us. More discoveries will follow, but documenting the DNA changes is not half as challenging as working out what they did. "Determining their effect requires immense experimentation and sometimes the creation of transgenic animals," says Hawks. "This is difficult science to undertake. We are at the very early stages."

Even so, we have already had a glimpse of many of the pivotal points in human evolution, including the rapid expansion of our brains, the emergence of speech and the possible origin of our opposable thumbs. Read on to discover the evolutionary accidents that made you the person you are today.

JAW DROPPER

A chimpanzee's jaws are so powerful it can bite off a person's finger in one chomp. That is not a theoretical calculation; more than one primate researcher has lost a digit that way.

Humans have wimpy jaw muscles by comparison. This could be down to a single mutation in a gene called *MYH16*, which encodes a muscle protein. The mutation inactivates the gene, causing our jaw muscles to be made from a different version of the protein. They are consequently much smaller.

This finding, which came in 2004, caused a stir when the researchers argued that smaller jaw muscles could have allowed the growth of a bigger skull. Primates with big jaw muscles have thickened supporting bone at the back of their skull, which arguably constrains skull expansion, and therefore that of the brain too.

"We are suggesting this mutation is the cause of the decrease in muscle mass and hence the decrease in bone," says Hansell Stedman, a muscle researcher at the University of Pennsylvania in Philadelphia, who led the work. "Only then do you lift the evolutionary constraint that precludes other mutations that allow your brain to continue growing."

The team dated the mutation to 2.4 million years ago – just before brain expansion took off. But another study, which sequenced a longer section of the muscle gene, came up with a much earlier estimate of 5.3 million years ago.

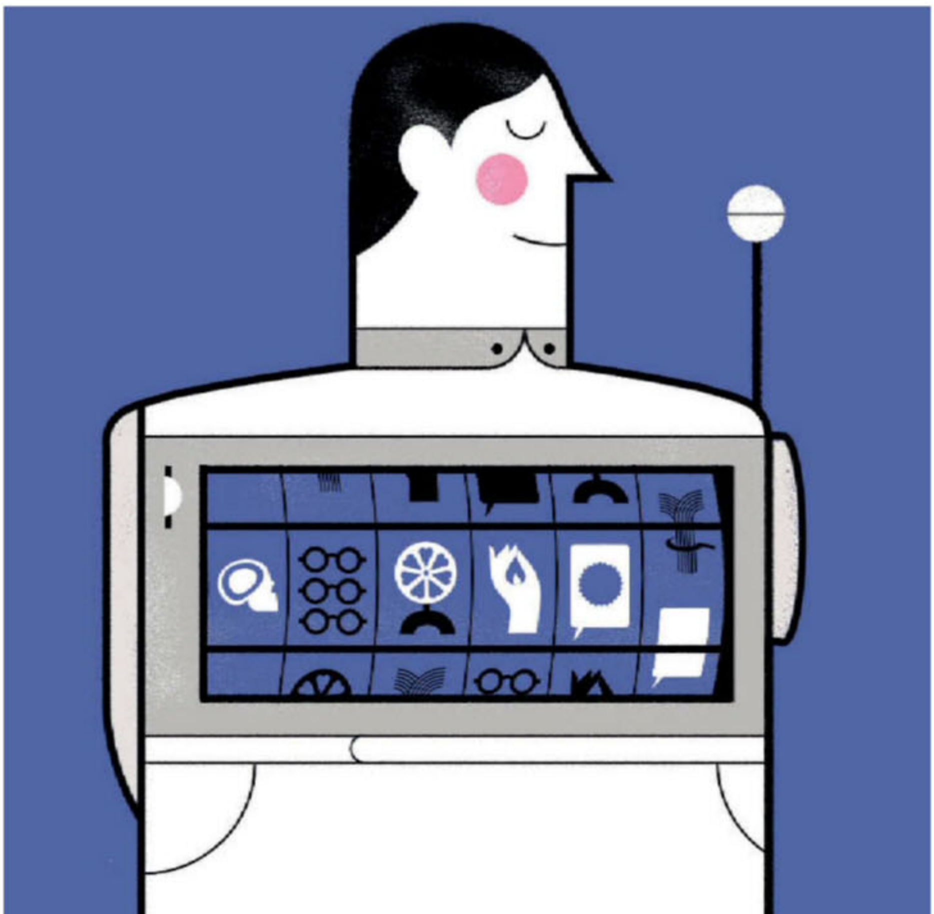
Whichever date is right, the mutation still happened after we split from our last common ancestor with chimps. Why would our ancestors switch to a weaker bite? Stedman speculates that rather than changes in diet being the catalyst, it could be that our ancestors no longer used biting as a form of attack. "At some point, perhaps through social organisation, this form of weaponry became more optional for our ancestors," he says.

"Our brains are three times the size of those of our nearest relative"

THE BRAIN GAIN

Our braininess is one of our species' defining features. With a volume of 1200 to 1500 cubic centimetres, our brains are three times the size of those of our nearest relative, the chimpanzee. This expansion may have involved a kind of snowball effect, in which initial mutations caused changes that were not only beneficial in themselves but also allowed subsequent mutations that enhanced the brain still further. "You have some changes and that opens opportunities for new changes that can help," says John Hawks at the University of Wisconsin-Madison.

In comparison to that of a chimp, the human brain has a hugely expanded cortex, the folded outermost layer that is home to our most sophisticated mental processes, such as planning, reasoning and language abilities. One approach to finding the genes involved in brain expansion has been to investigate the causes of primary microcephaly, a condition in which babies are born with



ANGUS GREIG

ENERGY UPGRADE

a brain one-third of the normal size, with the cortex particularly undersized. People with microcephaly are usually cognitively impaired to varying degrees.

Genetic studies of families affected by primary microcephaly have so far turned up seven genes that can cause the condition when mutated. Intriguingly, all seven play a role in cell division, the process by which immature neurons multiply in the fetal brain, before migrating to their final location. In theory, if a single mutation popped up that caused immature neurons to undergo just one extra cycle of cell division, that could double the final size of the cortex.

Take the gene *ASPM*, short for "abnormal spindle-like microcephaly-associated". It encodes a protein found in immature neurons that is part of the spindle – a molecular scaffold that shares out the chromosomes during cell division. We know this gene was undergoing major changes just as our ancestors' brains were rapidly expanding. When the human *ASPM* sequence was compared with that of seven primates and six other mammals, it showed several hallmarks of rapid evolution since our ancestors split from chimpanzees.

Other insights come from comparing the human and chimp genomes to pin down which regions have been evolving the fastest. This has highlighted a region called HAR1, short for human accelerated region-1, which is 118 DNA base pairs long. We do not yet know what HAR1 does, but we do know that it is switched on in the fetal brain between 7 and 19 weeks of gestation, in the cells that go on to form the cortex. "It's all very tantalising," says Katherine Pollard, a biostatistician at The Gladstone Institutes in San Francisco, who led the work.

Equally promising is the discovery of two duplications of a gene called *SRGAP2*, which affect the brain's development in the womb in two ways: the migration of neurons from their site of production to their final location is accelerated, and the neurons extrude more spines, which allow neural connections to form. According to Evan Eichler, a geneticist at the University of Washington in Seattle who was involved in the discovery, those changes "could have allowed for radical changes in brain function".

While it is tough to work out just how our brains got so big, one thing is certain: all that thinking requires extra energy. The brain uses about 20 per cent of our energy at rest, compared with about 8 per cent for other primates. "It's a very metabolically demanding tissue," says Greg Wray, an evolutionary biologist at Duke University in Durham, North Carolina.

Three mutations have now been discovered that may have helped meet that demand. One emerged with the publication of the gorilla genome in 2012. This revealed a DNA region that underwent accelerated evolution in an ancient primate ancestor, common to humans, chimps and gorillas, sometime between 15 and 10 million years ago.

The region was within a gene called *RNF213*, the site of a mutation that causes Moyamoya disease – a condition that involves narrowing of the arteries to the brain. That suggests the gene may have played a role in boosting the brain's blood supply during our evolution. "We know that damaging the gene can affect blood flow, so we can speculate that other changes might influence that in a beneficial way," says Chris Tyler-Smith, an evolutionary geneticist at the Sanger Institute in Cambridge, UK, who was part of the group that sequenced the gorilla genome.

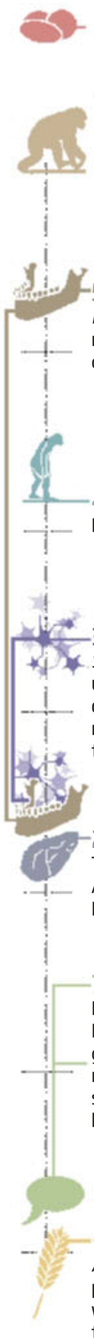
There are more ways to boost the brain's energy supply than just re-plumbing its blood vessels, though. The organ's main food source is glucose and this is drawn into the brain by a glucose-transporter molecule in the blood vessel walls.

Compared with chimpanzees, orang-utans and macaques, humans have slightly different "on switches" for two genes that encode the glucose transporters for brain and muscle, respectively. The mutations mean more glucose transporters in our brain capillaries and less in our muscle capillaries.

"It's throwing a switch so you divert a greater fraction [of the available glucose] into the brain," says Wray. In short, it looks like athleticism has been sacrificed for intelligence. ›

A brief history of you

Humans are the products of many genetic accidents. Although it's not yet possible to date all the mutations, we can start to build a timeline of some of the most important developments



15 to 10 million years ago
RNF213 gene mutates. Possibly improves blood supply to the primate brain, helping our ancestors to evolve greater intelligence

13 - 7 million years ago
Last common ancestor with chimps

5.3 or 2.4 million years ago
MYH16 gene mutates. Our jaw muscles weaken, which allows our skulls, and brains, to expand

4.2 million years ago
Humans walk upright

3.4 and 2.5 million years ago
SRGAP2 gene duplicates, twice. Speeds up the migration of neurons across the developing brain, and helps them to form more connections. May have been crucial to our intelligence

2.3 million years ago
The *Homo* genus split from the Australopithecus line of hominins. Evidence of some of the first tool use

765 - 550,000 years ago
Neanderthals and *Homo sapiens* diverge. Both have the same mutation in *FOXP2* gene, which seems to lead to better memories for vocalisations and grammar, suggesting a common ancestor may have had advanced communication

~100,000 years ago to present
AMY1 gene duplicates, increasing the production of the salivary enzyme amylase, which helps us to digest starch. May be tied to the emergence of agriculture

GIFT OF THE GAB

Bring up a chimpanzee from birth as if it were a human and it will learn many unsimian behaviours, like wearing clothes and even eating with a knife and fork. But one thing it will not do is talk.

In fact, it would be physically impossible for a chimp to talk just like us, thanks to differences in our voice boxes and nasal cavities. There are neurological differences too, some of which are the result of changes to what has been dubbed the "language gene".

This story began with a British family that had 16 members over three generations with severe speech difficulties. Usually speech problems are part of a broad spectrum of learning difficulties, but the "KE" family, as they came to be known, seemed to have deficits that were more specific. Their speech was unintelligible and they had a hard time understanding others' speech, particularly when it involved applying rules of grammar. They also had problems making complex movements of the mouth and tongue.

In 2001, the problem was pinned on a mutation in a gene called *FOXP2*. We can tell from its structure that the gene helps regulate the activity of other genes. Unfortunately, we do not yet know which ones are controlled by *FOXP2*. What we do know is that in mice (and so, presumably, in humans) *FOXP2* is active in the brain during embryonic development.

Contrary to initial speculation, the KE family had not reverted to a "chimp-like" version of the gene – they had a new mutation that set back their language skills. In any case, chimps, mice and most other species have a version of *FOXP2* that is remarkably similar to that of humans. But since we split from chimpanzees there have been two other mutations to the human version, each of which alters just one of the many amino acids that make up the FOXP2 protein.

It would be fascinating to put the human version of *FOXP2* into chimps to see if it improves their powers of speech, but we cannot do that for both technical and ethical reasons. The human version has been put into mice, though. Intriguingly, the researchers observed that the genetically modified mice pups squeak slightly differently – there was a small drop in the pitch of their ultrasound squeals.

But this may be less relevant than the changes seen within the mice brains. Recently, changes were found in the structure and behaviour of neurons in an area called the cortico-basal ganglia circuits. Also called the brain's reward circuits, these are known to be involved in learning new mental tasks.

"If you do something and all of a sudden you get a reward, you learn that you should repeat that," says Wolfgang Enard, an evolutionary geneticist now at the Ludwig-Maximilians University in Munich, Germany, who led the work.

Based on what we already know about these circuits, Enard thinks that in humans *FOXP2* plays a role in learning the rules of speech – that specific vocal movements generate certain sounds, perhaps, or even the rules of grammar. "You could view it as learning the muscle sequences of speech, but also learning the sequence of 'The cat the dog chased yesterday was black'," he suggests.

Enard reckons this is the best example yet found of a mutation that fuelled the evolution of the human brain. "There's no other mutation where we have such a good idea what happened," he says.

HELPING HAND

From the first simple stone tools, through to the control of fire and the development of writing, our progress has been dependent on our dexterity. It's not for nothing that in the science-fiction classic *2001: A Space Odyssey*, Arthur C. Clarke portrayed the day an ape-man started clubbing things with an animal bone as a pivotal moment in our evolution.

Assuming alien meddling was not responsible, can our DNA shed light on our unrivalled abilities with tools? Clues come from a DNA region called HACNS1, short for human-accelerated conserved non-coding sequence 1, which has undergone 16 mutations since we split from chimps. The region is an on/off switch that seems to kick a gene into action in several places in the embryo, including developing limbs. Cutting and pasting the human version of HACNS1 into mouse embryos reveals that the mutated version is activated more strongly in the forepaw, right in the areas that correspond to the human wrist and thumb.

Some speculate that these mutations contributed to the evolution of our opposable thumbs, which are crucial for the deft movements required for tool use. In fact, chimps also have opposable thumbs, just not to the same extent as us. "We have more fine muscle control," says Katherine Pollard, who studies this DNA region at The Gladstone Institutes in San Francisco. "We can hold a pencil, but we can't hang from the limb of a tree comfortably like a chimp."

OLIVIER CULMANN/TENDANCE FLOUE

Human life would be impossible without our capacity to communicate

SWITCH TO STARCH

Chimps and other large primates subsist mainly on fruits and leaves. These are such low-calorie foods that the animals have to forage for most of their waking hours. Modern humans get most of their energy from starchy grains or plant roots. Over several million years our diet must have undergone a number of shifts, when we started using stone tools, learned to cook with fire, and settled down as farmers.

Some of these changes are hard to date. There is an ongoing debate over what constitutes the first evidence for cooking hearths. And digging sticks, used to unearth tubers and bulbs, do not fossilise. An alternative way of tracking dietary changes is to look at the genes involved in digestion.

"Humans can hold a pencil but we can't hang from the limb of a tree like a chimpanzee"

A digestive enzyme called salivary amylase plays a key role in breaking down starch into simple sugars so it can be absorbed in the gut. Humans have much higher levels of amylase in their saliva than chimpanzees, and recently it was discovered how this came about.

While chimps have only two copies of the salivary amylase gene (one on each of the relevant chromosome pair), humans have an average of six, with some people having as many as 15. DNA copying errors during the production of sperm and eggs must have led to the gene being repeatedly duplicated.

To find out when the duplications happened, the gene was sequenced in people from several countries, as well as in chimps and bonobos. "We were hoping to find a signature of selection about 2 million years ago," says Nathaniel Dominy, a biological anthropologist now at Dartmouth College in Hanover, New Hampshire, who led the work. That is around the time our brains underwent significant growth, and one theory is that it was fuelled by a switch to a starchier diet.

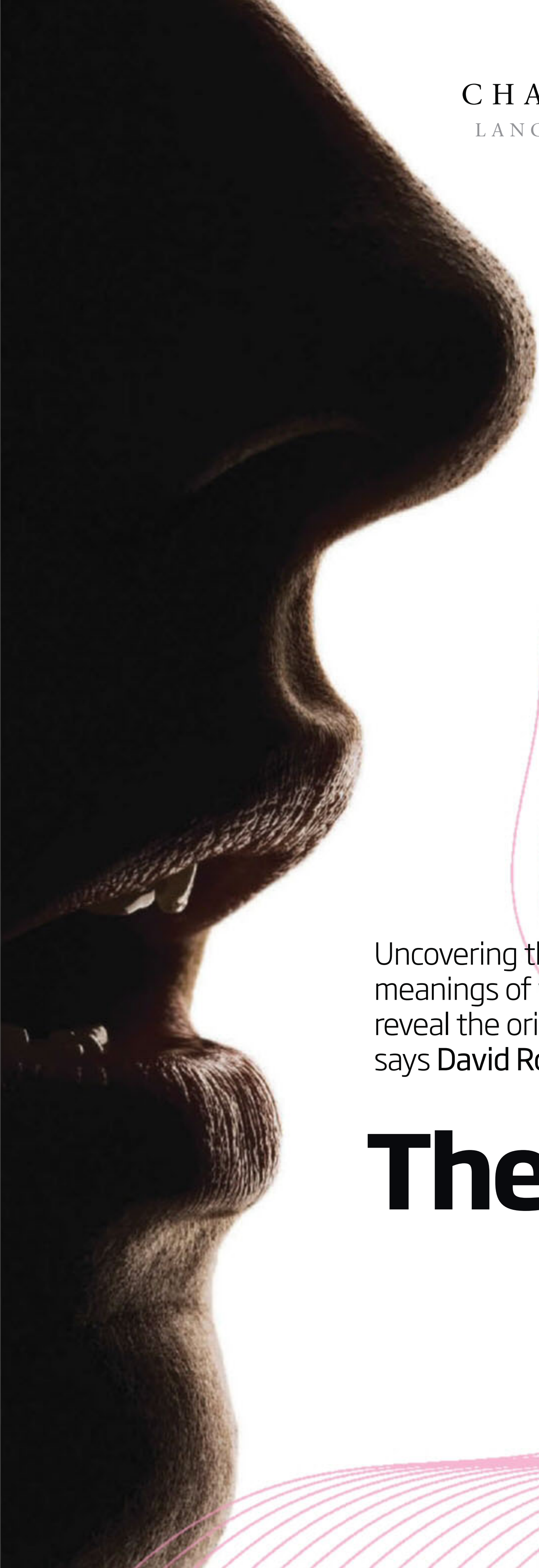
But the team found the gene duplications had happened more recently – sometime between 100,000 years ago and the present day. The biggest change in that period was the dawn of agriculture, so Dominy thinks the duplications happened when we started farming cereals. "Agriculture was a signal event in human evolution," he says. "We think amylase contributed to it."

It was the advent of agriculture that allowed us to live in larger settlements, which led to innovation, the cultural explosion and, ultimately, modern life. If we consider all the mutations that led to these pivotal points in our evolution, human origins begin to look like a trail of unfeasibly unlikely coincidences. But that is only because we do not see the harmful mutations that were weeded out, points out John Hawks at the University of Wisconsin-Madison. "What we're left with is the ones that were advantageous." It is only from today's viewpoint that the mutations that give us our current physical form appear to be the "right" ones to have.

"It's hindsight," says Hawks. "When we look back at the whole process, it looks like a stunning series of accidents." ■

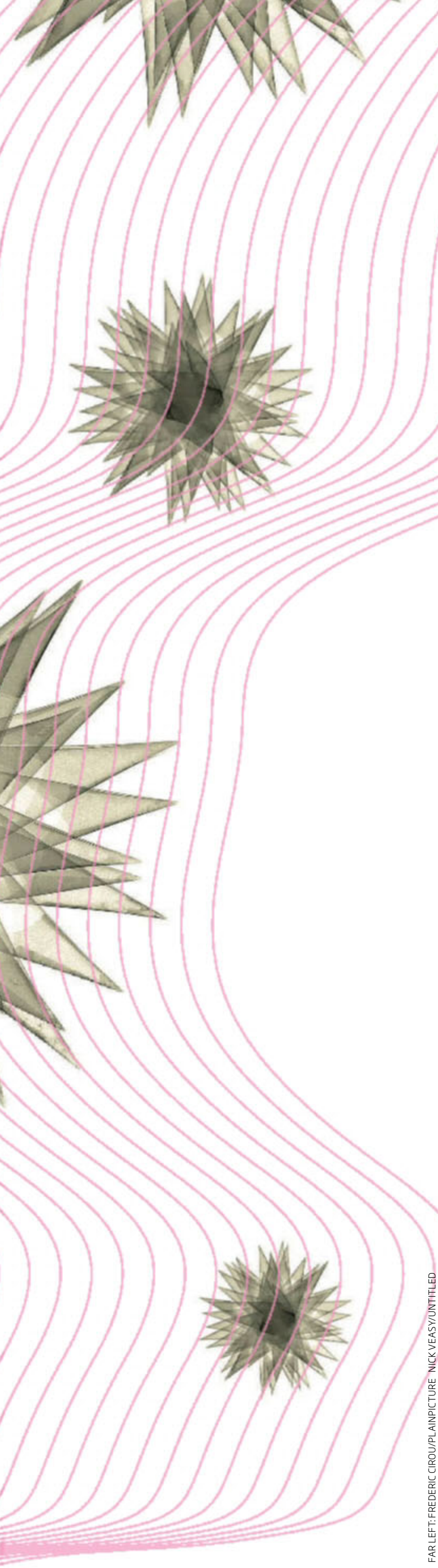
CHAPTER FIVE

LANGUAGE ORIGINS



Uncovering the hidden meanings of words could reveal the origins of language, says David Robson

The first words



FAR LEFT: FREDERIC CIROU/PLAINPICTURE NICK VEASY/UNTITLED

Through the looking glass, Lewis Carroll's Alice stumbles upon an enormous egg-shaped figure celebrating his un-birthday. She tries to introduce herself:

"It's a stupid name enough!" Humpty Dumpty interrupted impatiently. "What does it mean?"

"Must a name mean something?" Alice asked doubtfully.

"Of course it must," Humpty Dumpty said with a short laugh: "My name means the shape I am – and a good handsome shape it is, too. With a name like yours, you might be any shape, almost."

PURE whimsy, you might think. Nearly 100 years of linguistics research has been based on the assumption that words are just collections of sounds – an agreed acoustic representation that has little to do with their actual meaning. There should be nothing in nonsense words such as "Humpty Dumpty" that would give away the character's egg-like figure, any more than someone with no knowledge of English could be expected to infer that the word "rose" represents a sweet-smelling flower.

Yet a spate of recent studies challenge this idea. They suggest that we seem instinctively to link certain sounds with particular sensory perceptions. Some words really do evoke Humpty's "handsome" rotundity. Others might bring to mind a spiky appearance, a bitter taste, or a sense of swift movement. And when you know where to look, these patterns crop up surprisingly often, allowing a monoglot English speaker to understand more Swahili or Japanese than you might imagine (see "How's your Japanese?", page 74). These cross-sensory connections may even open a window on to the first words ever uttered by our ancestors, giving us a glimpse of the earliest language and how it emerged.

More than 2000 years before Carroll suggested words might have some inherent meaning, Plato recorded a dialogue between two of Socrates's friends, Cratylus and Hermogenes. Hermogenes argued that language is arbitrary and the words people use are purely a matter of convention. Cratylus, like Humpty Dumpty, believed words inherently reflect their meaning – although he seems to have found his insights into language disillusioning: Aristotle says Cratylus eventually became so disenchanted that he gave up speaking entirely.

The Greek philosophers never resolved the issue, but two millennia later the Swiss linguist Ferdinand de Saussure seemed to have done so. In the 1910s, using an approach based in part on a comparison of different languages, he set out a strong case for the arbitrariness of language. Consider, for instance, the differences between "ox" and "boeuf", the English and French words for the same animal. With few similarities between these and other such terms, it seemed clear to Saussure that the sounds of words do not inherently reflect their meanings.

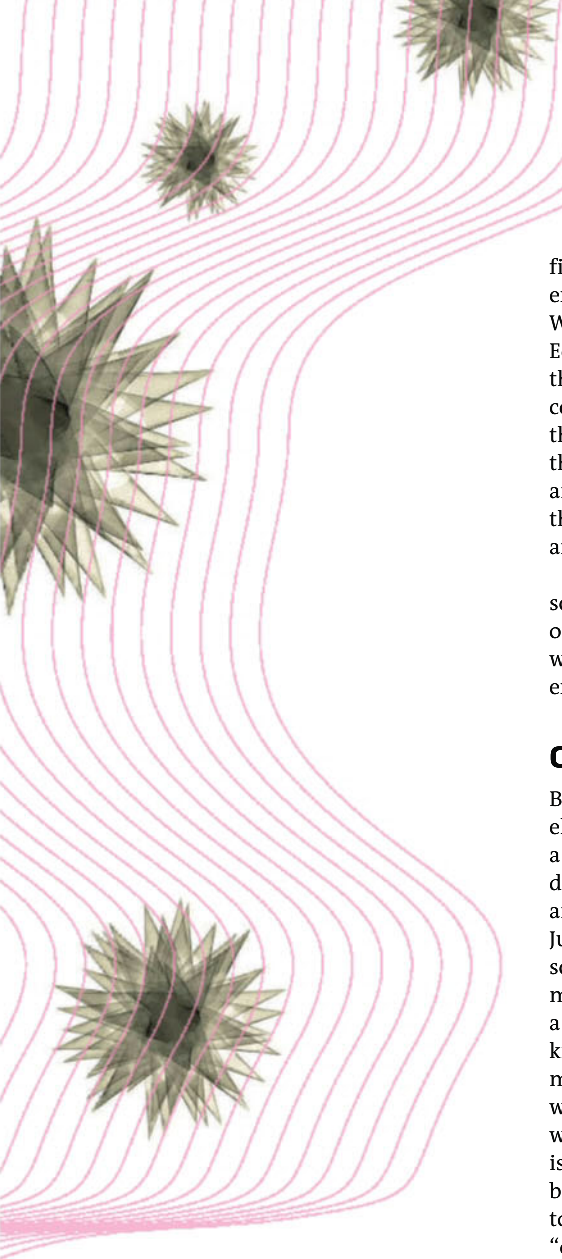
The world of linguistics was mostly convinced, but a few people still challenged the status quo. While the German psychologist Wolfgang Kohler was staying in Tenerife, he presented subjects with line drawings of two meaningless shapes – one spiky, the other curved – and asked them to label the pictures either "takete" or "baluba". Most people chose takete for the spiky shape and baluba for the curvy one. Though Kohler didn't say why this might be, the observation strongly suggested that some words really might fit the things they describe better than others. His work, first published in 1929, did not attract much attention, and though others returned to the subject every now and then, their findings were not taken seriously by the mainstream. "They were considered a curiosity and never properly explored," says Gabriella Vigliocco, professor of the psychology of language at University College London.

The turning point came in 2001, when Vilayanur S. Ramachandran and Edward Hubbard, both then at the University of California, San Diego, published their investigations into a condition known as synaesthesia, in which people seem to blend sensory experiences, including certain sounds and certain images. As many as 1 in 20 people have this condition, but Ramachandran suspected that cross-sensory connections are in fact a feature of the human brain, so that in practice we all experience synaesthesia at least to a limited extent. To explore this idea, he and Hubbard revisited Kohler's experiment to find out whether average people, and not just synaesthetes, might automatically link two different sensations.

"An astonishing 95 per cent of people labelled the spiky object as 'kiki' and the curvy one as 'bouba'"

Using similar shapes to those in the original experiment, but changing the names of the invented terms slightly, they found that an astonishing 95 per cent of people labelled the spiky object as "kiki" and the curvy one as "bouba". One possible explanation is that this might be down to the shapes of the lips as we form the vowels in these words; in "bouba" they are more curved than in "kiki".

The work turned out to be hugely influential, helping sound symbolism to ›



finally get off the ground as numerous studies explored the kiki/bouba phenomenon. Chris Westbury at the University of Alberta in Edmonton, Canada, for instance, has shown that the association may be due to the consonants as well as the vowels: in "bouba" the "b" sounds are "continuants", meaning they are produced with a continuous flow of air. This creates a smoother sound, whereas the "k" sounds in "kiki" break up the airflow and make the word more jarring.

With the renaissance of the idea that the sound of a word could be linked to some kind of inherent meaning, the obvious next step was to investigate whether sound symbolism extends beyond this one intriguing example.

Cross-sensory connections

Building on the idea that certain words might elicit cross-sensory connections in our brain, a team at the University of Edinburgh, UK, decided to explore the links between sounds and tastes. Christine Cuskley, Simon Kirby and Julia Simner dropped bitter, sweet, salty and sour drops of solution into their subjects' mouths. Then they asked them to manipulate a computer synthesiser to produce different kinds of vowel sounds that seemed to best match the taste on their tongues. The results were not random. Sweet tastes were associated with high vowel sounds, in which the tongue is placed nearer to the roof of the mouth, and back vowels, where the tongue is placed towards the throat rather than the lips. The "oo" in boot demonstrates both of these traits. Low, front vowel sounds, meanwhile – something like the "a" in "cat" has these qualities – were associated with sour tastes.

Others have been looking for evidence of sound symbolism in everyday speech. Although examples of onomatopoeia – words truly formed from a sound associated with what is named – are rare, it is possible that more subtle instances of sound symbolism have been lurking, almost literally, right under our noses. English words that begin with "sn" are often associated with our organ of olfaction: think "snout", "sniff", "snot", "snore" and "snorkel". Sceptics had argued that these "phonaesthemes" are pure coincidence, but research by Benjamin Bergen at the University of California, San Diego, suggests otherwise. He found that the brain processes meanings of pairs of phonaesthemes such as "snore" and "sniff" more quickly than other pairs related simply by their meaning (such as "cord" and "rope") or their sounds (such as "druid" and "drip"). That is exactly what you would expect if olfaction and the "sn" sound are somehow linked in the brain, says Bergen.

That's not all. At a workshop on sound symbolism in Atlanta, Georgia, in 2010, he reported that "wh" words associated with words that describe the production of noises such as "whisper", "whine" or "whirr", and those beginning with "fl" that tend to signal movement in the air, such as "fly" or "flail", also enjoyed this fast track in the brain's processing. Bergen concludes that these may all be forms of sound symbolism.

Indeed, it now looks as if sound symbolism may be present in many languages. Japanese, for example, contains a large grammatical group called "mimetic" words, which by definition are particularly evocative of sensual experiences. *Gorogoro* roughly translates as "large object rolling", while *nurunuru* is meant to evoke the feel of a slimy substance. "If you ask a speaker of Japanese, they will say they evoke an image of an expression," says Sotaro Kita at the University of Warwick, UK. He is convinced that this group of words contain some sort of sound symbolism, having discovered that both Japanese and English-speaking children learn made-up mimetic verbs more quickly when they follow the sound-meaning associations found in Japanese than when they contravene them.

Suspecting that sound symbolism might also help adults to understand a foreign tongue, Lynne Nygaard at Emory University in Atlanta presented English speakers with pairs of antonyms (such as fast/slow) recorded in 10 languages – including Albanian, Dutch, Gujarati, Mandarin and Yoruba. When given the corresponding pair of English words, and asked to match the foreign words to them, subjects performed better than they would by chance – suggesting the words' sounds must give clues to their meaning.

What could these clues be? A subsequent analysis hinted at some answers. Words that indicate general movement tend to have more vowels, for instance, and they are more likely to have glottal consonants (the "h" in "behind", for example). Sounds might also reflect the speed of movement: slow movement tends to be represented by sonorant sounds such as "l" or "w", whereas explosive obstruents produced from a blocked airway, such as "ch" or "f", are suggestive of more rapid speeds. Nygaard presented her work at the Atlanta workshop in 2010.

Bringing all the evidence together, there seems to be a strong case for saying that sound

HOW'S YOUR JAPANESE?

If certain sounds really do evoke particular meanings then, given a foreign word and two alternative translations, people should be able to get the correct meaning more often than not. That is exactly what researchers found in one experiment testing Japanese words, including those below, on non-Japanese speakers. How well do you do?

WORD	MEANING	
1. Akarui	(a) Bright	(b) Dark
2. Nureta	(a) Dry	(b) Wet
3. Omoi	(a) Light	(b) Heavy
4. Ii	(a) Bad	(b) Good
5. Neru	(a) Lie	(b) Rise
6. Suzushii	(a) Warm	(b) Cold
7. Osoi	(a) Slow	(b) Fast
8. Hashiru	(a) Walk	(b) Run

Answers:

1 (a), 2 (b), 3 (b), 4 (b), 5 (a), 6 (b), 7 (a), 8 (b)

Humpty Dumpty's name seems to evoke his handsome rotundity

BETTMANN/CORBIS

symbolism does occur in human language. However, some big questions remain. How common are words that elicit cross-sensory connections in modern languages? "Maybe they represent just small pockets of vocabulary," says Morten Christiansen at Cornell University, in Ithaca, New York.

Then there's the question of why we link certain sounds to certain shapes, flavours and styles of movement. The inherently nasal quality of the "sn" sound might explain why we sneeze and snore, but most attempts to explain many other examples are just stabs in the dark. Investigations into the cross-sensory connections of full-blown synaesthesia may well shed light on this.

Finally, is sound symbolism universal, perhaps even innate? Tests showing that the patterns are recognised by young children, and by people across cultures, suggest that is a possibility, but other studies have shown that while some sounds consistently evoke ideas about the roundness or bluntness of shapes, the link between certain sounds and flavours varies across cultures.

Nevertheless, these questions have not stopped researchers exploring the potential implications of their findings. As Kita's and Nygaard's work suggests, sound symbolism could at the very least explain why some words stick in our mind better than others – a fact confirmed in a string of studies by Susan Parault, then at the University of Maryland in College Park, which showed that children across a range of ages are better able to learn unfamiliar words if they are sound-symbolic.

Advertisers and marketing executives may begin to see dollar signs in these insights. For example, Charles Spence at the University of Oxford, who has investigated the multi-sensory experience of chocolate, hopes to help confectioners alter their brand names to reflect the taste of the products. Others have looked at whether the names of cancer drugs

"How did the genius who invented the first words get others to understand their meaning?"

might affect patients' perceptions of them.

Most intriguingly, sound symbolism might shed light on the origins of language. It appears to revive a popular 18th-century idea called the "bow-wow" theory, which proposes that humankind's first words were onomatopoeic, mimicking sounds in our ancestors' environment. The idea seems plausible until you try to explain how humans ever came to describe silent concepts – the appearance of a cave, for example. This is why it fell out of favour following Saussure's persuasive work. But later theories fail to explain how an initially dumb primate could have evolved a complex, arbitrary system of communication with no obvious stepping stones in between.

While there's good reason to believe that humans first developed the neural toolkit for language through hand gestures, for example, how did we make the transition from gesture to the spoken word? Ramachandran and Hubbard propose that sound symbolism provided the stepping stone. If the angular sounds of "kiki" seem to fit a distinctively jagged rock, for example, the word might have emerged as obvious shorthand. Sound symbolism "helped to get the first words off the ground", says Hubbard.

Bow-wow words

Not everyone is convinced. Christiansen, for instance, accepts this revised bow-wow theory is plausible. "But we can't prove it either way," he says. Others are more positive. It's very speculative, but it is a possibility, Vigliocco says. "Manual gestures seem like an obvious way [to imitate], but vocal imitation is possible as well, from imitating the shape of an object with the shape of the mouth, to imitating the size of an object by adjusting the length of the vocal tract."

The beauty of the idea, says Cuskley, is that it helps to solve one of the most exacting problems facing any evolutionary theory of language: how did the ancestral genius who invented the first words get others to understand their meanings so that language could spread? Sound symbolism would have made these first words stick in the mind, and from these simple symbolic sounds our ancestors could have started to build a larger vocabulary. Eventually, the need to describe a greater number of ideas pushed humans to develop more arbitrary terms until they finally developed the complex language systems we use today.

The implication, according to Kita, is that the sound-symbolic relations we see in today's languages may be remnants of those very first words – a kind of Rosetta stone that helps bridge the gulf to our earliest languages. That is a profound claim, since most attempts to chronicle ancient languages fail at just a few thousand years BC. These cross-sensory connections, on the other hand, give us a glimpse of tens of thousands of years ago, at humanity's dawn. "They are fossils from our ancestors' language," Kita says.

It is intriguing to think that if faced with the first humans ever to use language, we might have at least some common ground to share our thoughts. Now there's an adventure worthy of Lewis Carroll's Alice. ■

STUART KOLAKOVIC

WAR OF WORDS

If languages evolve to prevent us communicating, that might explain why there are so many, says evolutionary biologist Mark Pagel

FOR anyone interested in languages, the north-eastern coastal region of Papua New Guinea is like a well-stocked sweet shop. Korak speakers live right next to Brem speakers, who are just up the coast from Wanambre speakers, and so on. I once met a man from that area and asked him whether it is true that a different language is spoken every few kilometres. "Oh no," he replied, "they are far closer together than that."

Around the world today, some 7000 distinct languages are spoken. That's 7000 different ways of saying "good morning" or "it looks like rain" – more languages in one species of mammal than there are mammalian species. What's more, these 7000 languages probably make up just a fraction of those ever spoken in our history. To put human linguistic diversity into perspective, you could take a gorilla or chimpanzee from its troop and plop it down anywhere these species are found, and it would know how to communicate. You could repeat this with donkeys, crickets or goldfish and get the same outcome.

This highlights an intriguing paradox at the heart of human communication. If language evolved to allow us to exchange information, how come most people cannot understand what most other people are saying? This perennial question was famously addressed in the Old Testament story of the Tower of Babel, which tells of how humans developed the conceit that they could use their shared language to cooperate in the building of a tower that would take them to heaven. God, angered at this attempt to usurp his power, destroyed the tower and to ensure it would not be rebuilt he scattered the people and confused them by giving them different languages. The myth leads to the amusing irony that our separate languages exist to prevent us from communicating. The surprise is that this might not be far from the truth.

The origins of language are difficult to pin down. Anatomical evidence from fossils suggests that the ability to speak arose in our ancestors sometime between 1.6 million and 600,000 years ago. However, indisputable evidence that this speech was conveying complex ideas comes only with the cultural sophistication and symbolism associated with modern humans. They emerged in Africa perhaps 200,000 to 160,000 years ago, and by 60,000 years ago had migrated out of the continent – eventually to occupy nearly every region of the world. We should expect new languages to arise as people spread out and occupy new lands, because as soon as groups become isolated from one another their languages begin to drift apart and adapt to local needs. But the real puzzle is that the greatest diversity of human societies and languages arises not where people are most spread out, but where they are most closely packed together.

Papua New Guinea is a classic case. That relatively small land mass – only slightly larger than California – is home to between 800 and 1000 distinct languages, or around 15 per cent of all languages spoken on the planet. This linguistic diversity is not the result of migration and physical isolation of different populations. Instead, people living in close quarters seem to have chosen to separate into many distinct societies, leading lives so separate that they have become incapable of talking to one another. Why?

Thinking about this, I was struck by an uncanny parallel between linguistic and biological diversity. A well-known phenomenon in ecology called Rapoport's rule states that the greatest diversity of biological species is found near to the equator, with numbers tailing off as you approach the poles. Could this be true for languages too?

To test the idea, anthropologist Ruth Mace from University College London and I looked at the distribution of around 500 Native American tribes before the arrival of Europeans, and used this to plot the number of different language groups per unit area at each degree of latitude. It turned out that the distribution matched Rapoport's rule remarkably well (see diagram, page 78).

The congruity of biological species and cultures with distinct languages is probably not an accident. To survive the harsh polar landscape, species must range far and wide, leaving little opportunity for new ones to ›

"The more divorces a language has had, the more its vocabulary differs from its ancestral language"

STUART KOLAKOVIC

arise. The same is true of human groups in the far northern regions. They too must cover wide geographical areas to find sufficient food, and this tends to blend languages and cultures. At the other end of the spectrum, just as the bountiful, sun-drenched tropics are a cradle of biological speciation, so this rich environment has allowed humans to thrive and splinter into a profusion of societies.

Of course that still leaves the question of why people would want to form into so many distinct groups. For the myriad biological species in the tropics, there are advantages to being different in that it allows each to adapt to its own ecological niche. But humans all occupy the same niche, and splitting into distinct cultural and linguistic groups actually brings disadvantages, such as slowing the movement of ideas, technologies and people. It also makes societies more vulnerable to risks and plain bad luck. So why not have one large group with a shared language?

An answer to this question is emerging with the realisation that human history has been characterised by continual battles. Ever since our ancestors walked out of Africa, beginning around 60,000 years ago, people have been in conflict over territory and resources. In my book *Wired for Culture* I describe how, as a consequence, we have acquired a suite of traits that help our own particular group to outcompete the others. Two traits that stand out are "groupishness" – affiliating with people with whom you share a distinct identity – and xenophobia, demonising those outside your group and holding parochial views towards them. In this context, languages act as powerful social anchors of our tribal identity. How we speak is a continual auditory reminder of who we are and, equally as important, who we are not. Anyone who can speak your particular dialect is a walking, talking advertisement for the values and cultural history you share. What's more, where different groups live in close proximity, distinct languages are an effective way to prevent eavesdropping or the loss of important information to a competitor.

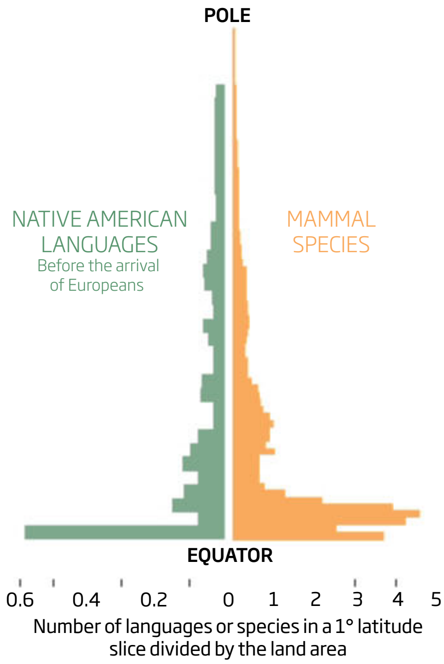
In support of this idea, I have found anthropological accounts of tribes deciding to change their language, with immediate effect, for no other reason than to distinguish themselves from neighbouring groups. For example, a group of Selepet speakers in Papua New Guinea changed its word for "no" from *bia* to *bune* to be distinct from other Selepet speakers in a nearby village. Another group reversed all its masculine and feminine nouns – the word for he became she, man became woman, mother became father, and so on. One can only sympathise with anyone who had been away hunting for a few days when the changes occurred.

The use of language as identity is not confined to Papua New Guinea. People everywhere use language to monitor who is a member of their "tribe". We have an acute, and sometimes obsessive, awareness of how those around us speak, and we continually adapt language to mark out our particular group from others. In a striking parallel to the Selepet examples, many of the peculiar spellings that differentiate American English from British – such as the tendency to drop the "u" in words like colour – arose almost overnight when Noah Webster produced the first *American Dictionary of the English Language* at the start of the 19th century. He insisted that: "As an independent nation, our honor [sic] requires us to have a system of our own, in language as well as government."

Use of language to define group identity is not a new phenomenon. To examine how languages have diversified over the course of human history, my colleagues and I drew up family trees for three large language groups – Indo-European languages, the Bantu languages of Africa, and Polynesian languages from Oceania. These "phylogenies", which trace the history of each group back to a common ancestor, reveal the number of times a contemporary language has split or "divorced" from related languages. We found that some languages have a history of many divorces, others far fewer.

Equatorial chatter

Languages seem to follow Rapoport's rule, which holds that species richness is greatest at the equator and declines towards the poles, as this chart for North America shows



SOURCE: PAGEL, M. 2009, HUMAN LANGUAGE AS A CULTURALLY TRANSMITTED REPLICATOR

When languages split, they often experience short episodes during which they change rapidly. The same thing happens during biological evolution, where it is known as punctuational evolution. So the more divorces a language has had, the more its vocabulary differs from its ancestral language. Our analysis does not say why one language splits into two. Migration and isolation of groups is one explanation, but it also seems clear that bursts of linguistic change have occurred at least in part to allow speakers to assert their own identities. There really has been a war of words going on.

So what of the future? The world we live in today is very different from the one our ancestors inhabited. For most of our history, people would have encountered only their own cultural group and immediate neighbours. Globalisation and electronic communication mean we have become far more connected and culturally homogenised, making the benefits of being understood more apparent. The result is a mass extinction of languages to rival the great biological extinctions in Earth's past.

Although contemporary languages continue to evolve and diverge from one another, the rate of loss of minority languages now greatly exceeds the emergence of new languages. About 1000 languages are in the process of dying out as the young people of small tribal societies adopt majority languages. As a percentage of the total, this rate of loss equals or exceeds the decline in biological species diversity through loss of habitat and climate change. Already a mere 10 of the Earth's 7000 languages account for about 50 per cent of the world's speakers, and most languages have very few speakers.

Still, this homogenisation of languages and cultures is happening at a far slower pace than it could, and that is because of the powerful psychological role language plays in marking out our cultural territories and identities. One consequence of this is that languages resist "contamination" from other languages, with speakers often treating the arrival of foreign words with a degree of suspicion – witness the British and French grumblings about so-called Americanisms. Another factor is the role played by nationalistic agendas in efforts to save dying languages, which can result in policies such as compulsory Welsh lessons for schoolchildren up to the age of 16 in Wales.

Linguistic creativity

This resistance to change leaves plenty of time for linguistic diversity to pop up. Various street and hip-hop dialects, for example, are central to the identity of specific groups, while mass communication allows them easily to reach their natural constituencies. Another interesting example is Globish, a pared-down form of English that uses just 1000 or so words and simplified language structures. It has spontaneously evolved among people who travel extensively, such as diplomats and international business people. Amusingly, native English speakers can be disadvantaged around Globish because they use words and grammar that others cannot understand.

In the long run, though, it seems virtually inevitable that a single language will replace all others. In evolutionary terms, when otherwise equally good solutions to a problem compete, one of them tends to win out. We see this in the near worldwide standardisation of ways of telling time, measuring weights and distance, CD and DVD formats, railway gauges, and the voltages and frequencies of electricity supplies. It may take a very long time, but languages seem destined to go the same way – all are equally good vehicles of communication, so one will eventually replace the others. Which one will it be?

Today, around 1.2 billion people – about 1 in 6 of us – speak Chinese. Next come Spanish and English with about 400 million speakers each, and Arabic, Bengali and Hindi close behind. On these counts Chinese might look like the favourite in the race to be the world's language. However, vastly more people learn English as a second language than any other. Years ago, in a remote part of Tanzania, I was stopped while attempting to speak Swahili to a local person who held up his hand and said: "My English is better than your Swahili". English is already the worldwide lingua franca, so if I had to put money on one language eventually to replace all others, this would be it.

In the ongoing war of words, casualties are inevitable. As languages become extinct, we are not simply losing different ways of saying "good morning", but the cultural diversity that has arisen around our thousands of distinct tribal societies. Each language plays a powerful role in establishing a cultural identity – it is the internal voice that carries the memories, thoughts, hopes and fears of a particular group of people. Lose the language and you lose that too.

Nevertheless, I suspect a monolinguistic future may not be as bad as doomsayers have suggested. There is a widely held belief that the language you speak determines the way you think, so that a loss of linguistic diversity is also a loss of unique styles of thought. I don't believe that. Our languages determine the words we use but they do not limit the concepts we can understand and perceive. Besides, we might draw another, more positive, moral from the story of Babel: with everyone speaking the same language, humanity can more easily cooperate to achieve something monumental. Indeed, in today's world it is the countries with the least linguistic diversity that have achieved the most prosperity. ■

CHAPTER SIX

AROUND THE WORLD

Going global

At last, the story of how our ancestors conquered the world is being told. **Dan Jones** follows the trail

LONG before the Nike logo and McDonald's golden arches straddled the planet, there was a truly global brand. Before the worldwide web, before mass production and even before the first economist, our own species, *Homo sapiens,* had penetrated every corner of the globe, succeeding in an unrivalled array of environments, from the unforgiving cold of the Arctic tundra to the blazing heat of the Australian outback and the humid forests of the Amazon. How did we achieve this global dominance? What routes did our ancestors take as they moved into lands unknown and traversed uncharted seas? When did they move and spread? How this particular naked ape became such an evolutionary success story is a question that has long intrigued us.

Now, palaeontologists, archaeologists and geneticists are finally piecing it together. As a coherent picture emerges, however, new mysteries arise. It looks likely that our species appeared far earlier than previously suspected – and remained in Africa for tens of thousands of years before going global: "All dressed up and going nowhere," as archaeologist Clive Gamble of the University of Southampton, UK, puts it. Why the delay?

Yet when our ancestors finally flocked on to the world stage, their spread was remarkably rapid. What caused them to explode out of Africa when they did? What circumstances suddenly allowed those early humans to smash down their boundaries like no species before or since?

Until quite recently, *Homo sapiens* was thought to have evolved just 100,000 years ago. Over the past two decades, however, a consensus has grown that anatomically modern humans emerged in Africa at least 160,000, and possibly 200,000, years ago. This shift in thinking began in 1987 with landmark research led by Allan Wilson of the University of California, Berkeley. Using genetic analysis to construct an evolutionary tree of mitochondrial DNA – genetic material we inherit solely from our mothers – Wilson found that we can all trace our ancestry back to a single woman who lived in east Africa some 200,000 to 150,000 years ago – the "mitochondrial Eve".

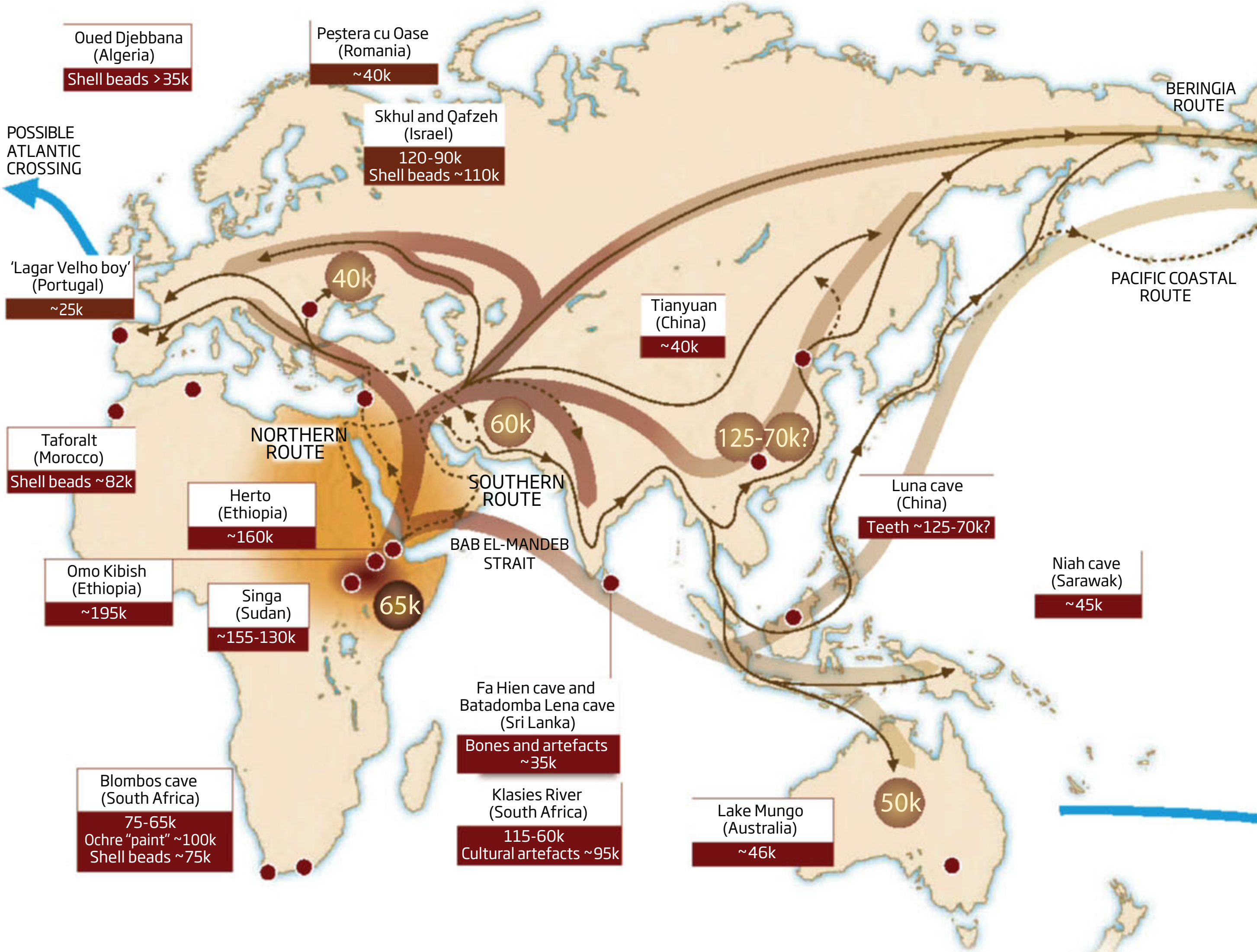
The case for such early origins has since been boosted by accumulating fossil evidence. In 2003, a team lead by palaeontologist Tim White of the University of California, Berkeley, dated fossil remains of a subspecies of *Homo sapiens* from Herto in Ethiopia at about 160,000 years old. Two years later, Ian McDougall at the Australian National University, Canberra, and colleagues pushed our origins even further back, dating fossil remains found in 1967 at Omo Kibish, Ethiopia, to as long as 195,000 years ago. Although the Omo Kibish date has been contested, few doubt that our species is much older than we once thought.

At the same time, it is becoming clear that the diaspora of *Homo sapiens* out of Africa happened more recently, and more rapidly, than has traditionally been accepted. Skeletal remains from Skhul and Qafzeh in Israel dating from 120,000 to 90,000 years ago are the oldest known traces of modern humans outside Africa. Discovered in the 1930s, these were once thought to represent the leading edge of a successful wave of colonisation that would take our newly evolved species north and west into Europe and, eventually, eastward across the globe. However, all evidence of human habitation beyond ›

SHIBUYA

THE MIGRATION OF ANATOMICALLY MODERN HUMANS

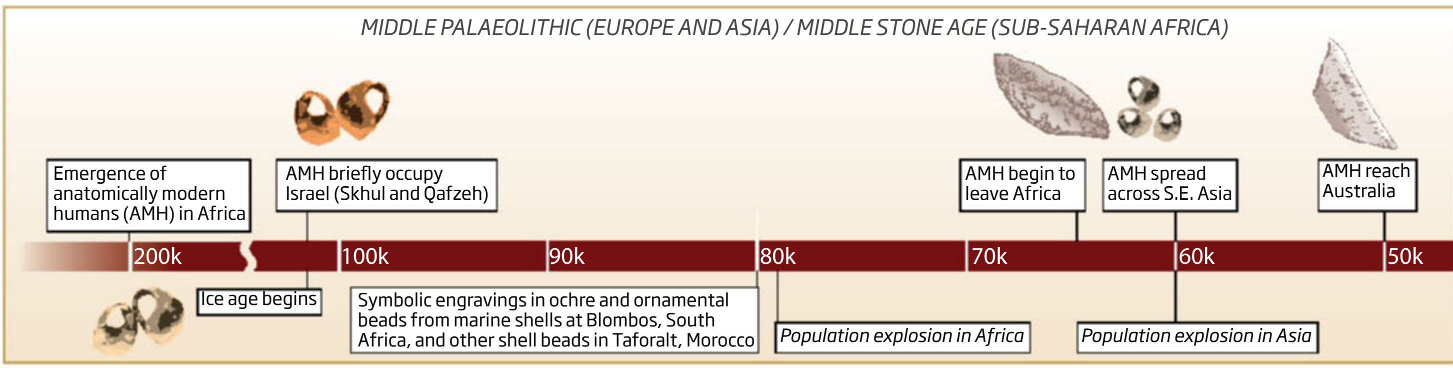
Evidence from fossils, ancient artefacts and genetic analyses combine to tell a compelling story

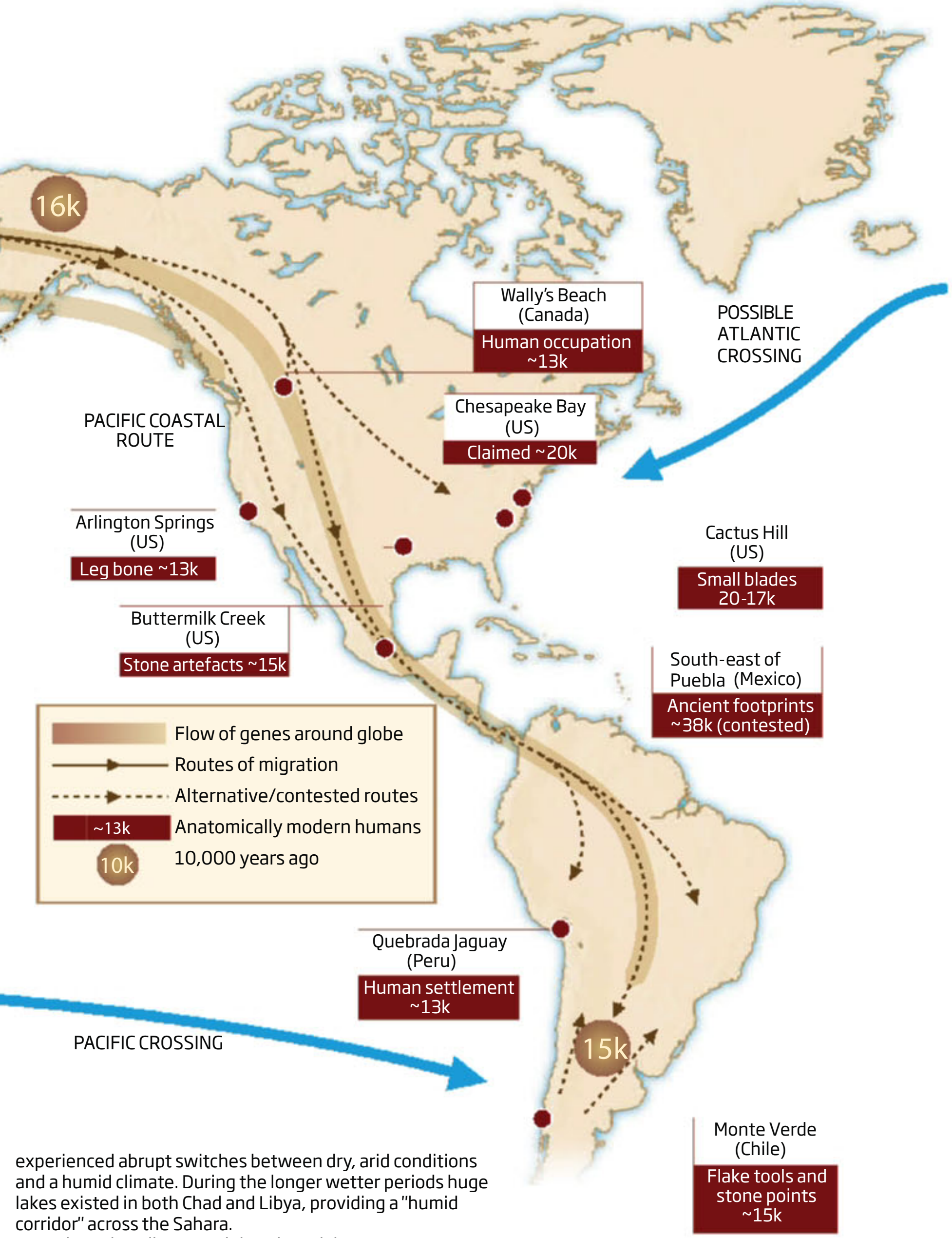


Two routes jump out as prime candidates for the human exodus out of Africa. A northern route would have taken our ancestors from eastern sub-Saharan Africa across the Sahara desert, then through Sinai and into the Levant. An alternative southern route may have charted a path from Djibouti or Eritrea in the Horn of Africa across the Bab el-Mandeb strait and into Yemen and around the Arabian peninsula. The plausibility of these two routes as gateways out of Africa has been studied as part of the UK's Natural Environment Research Council's programme "Environmental Factors in the Chronology of Human Evolution & Dispersal" (EFCHED).

During the last ice age, from about 80,000 to 11,000 years ago, sea levels dropped as the ice sheets grew, exposing land now submerged under water and connecting regions now separated by the sea. By reconstructing ancient shorelines, the EFCHED team found that the Bab el-Mandeb strait, now around 30 kilometres wide and one of the world's busiest shipping lanes, was then a narrow, shallow channel.

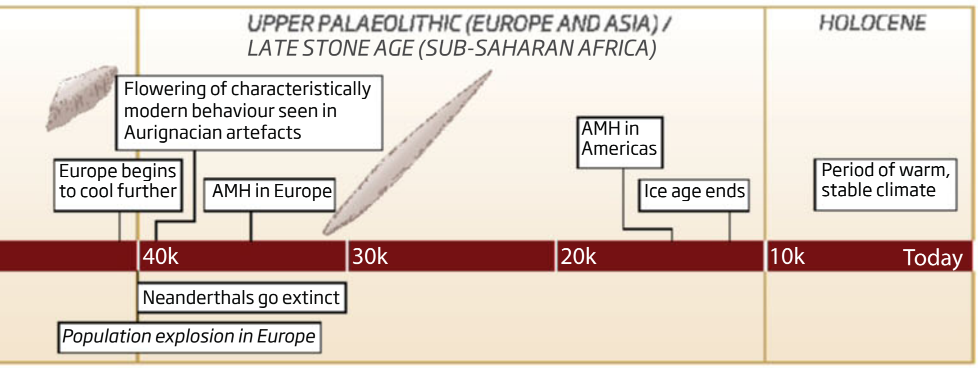
The northern route appears easier, especially given the team's finding that the Suez basin was dry during the last ice age. But crossing the Sahara desert is no small matter. EFCHED scientist Simon Armitage of Royal Holloway, University of London, has found some clues as to how this might have been possible. During the past 150,000 years, North Africa has





experienced abrupt switches between dry, arid conditions and a humid climate. During the longer wetter periods huge lakes existed in both Chad and Libya, providing a "humid corridor" across the Sahara.

Armitage has discovered that these lakes were present around 10,000 years ago, when there is abundant evidence for human occupation of the Sahara, as well as around 115,000 years ago, when our ancestors first made forays into Israel. It is unknown whether another humid corridor appeared between about 65,000 and 50,000 years ago, the most likely time frame for the human exodus. Moreover, accumulating evidence is pointing to the southern route as the most likely jumping-off point.



Africa disappears around 90,000 years ago, only to emerge again much later. The finds in Israel are widely believed to represent a precocious but short-lived surge of humanity into the wider world. Small groups may have made tentative forays out of the African homeland, but it would be tens of thousands of years before we were ready to conquer the planet.

The route that our ancestors took out of Africa is also being re-evaluated. Based on the evidence of the early occupation of the Middle East, the idea took hold that when early modern humans eventually began their global migration, they took a "northern route" through the Levant and up into Europe. Now that is being challenged. The latest discoveries point to early and widespread occupation of south-east Asia and Australasia, with migration to the north and then west into Europe happening later.

Asia first

In 2007, for example, skeletal remains found in Niah cave in Sarawak, on the island of Borneo, were dated to between 45,000 and 40,000 years old. Many researchers now believe Australia was also colonised around this time following a re-dating of skeletal remains discovered near Lake Mungo in New South Wales, which puts them at 46,000 years old. Added to these are fossils from Tianyuan cave, near Beijing, China, dated in 2007 at 40,000 years of age; reports of modern humans at Tam Pa Ling in Laos 50,000 or 60,000 years ago; and remains in the Luna cave in China's Guangxi Zhuang region, possibly of modern humans and dated at between 70,000 and 125,000 years old.

While some of our ancestors explored the far east of Asia, other groups were beginning to enter Europe. Skeletal remains from a cave in Romania called Peștera cu Oase (cave of bones) also date at about 40,000 years old. The oldest fossils in western Europe are slightly younger, between 37,000 and 36,000 years old. Only the Americas seem to have been colonised much later, towards the end of the last ice age, and probably no more than 16,000 years ago.

A similar story about human migration is also being dug from the genomes of living people. As groups of humans migrated to new areas, they carried with them rare genetic mutations from their ancestral population. ›

These "signature" mutations were then passed to the future generations that inhabited newly colonised regions, making the previously rare mutations more common in different places. Genetic mutation is an ongoing process, so further unique variations would also have sprung up as bands of humans moved from place to place, populating new lands. From the modern geographical distribution of genetic variants we can work backwards to chart possible routes of migration. Furthermore, using estimates of how frequently such mutations arise, we can work out the likely date at which specific variants appeared.

Take the genetic marker M130. Globally speaking, it is a relatively rare sequence of base pairs on the Y chromosome. It increases in frequency from 10 per cent in Malaysia to 15 per cent in New Guinea to 60 per cent in Australia, charting the eastward spread of small groups carrying the M130 mutation. Other genetic studies put approximate dates to migration patterns such as these. For example, analysis of the variation in mitochondrial DNA among Andaman islanders and people now living in the Malay Peninsula suggest that modern humans colonised this region probably 55,000, and possibly as long as 65,000, years ago. This fits broadly with genetic evidence published in 2007, revealing that aboriginal Australians are most closely related to New Guineans, and indicating that both land masses were probably settled by the same colonisation event around 50,000 years ago.

There is also genetic evidence for the later spread into Europe. Spencer Wells at the National Geographic Society in Washington DC, has charted the geographic distribution of genetic markers on the Y chromosome of men now living in Eurasia. He found that about 40,000 years ago populations started to diverge in the Middle East, some moving south into India, and others moving north through the Caucasus and then splitting into a westward arm that led across northern Europe and an eastward arm reaching across Russia and into Siberia (see map).

These later migrations would have taken people into the heart of Eurasia, but it seems likely that the first migrants skirted the coast. Where once our exodus from Africa was thought to have begun with a trek across the Sahara desert and then north through Sinai to the Levant, evidence increasingly suggests that our ancestors first left the continent from the Horn of Africa, across a then narrower Bab el-Mandeb strait, swung around the Arabian peninsula, past Iraq, and then followed the coast of Iran to the east – a single dispersal along the "southern route" (see Map).

> "This 'cultural great leap forward' equipped them to conquer the world"

As well as fitting with the genetic and fossil evidence, this coastal route makes perfect ecological sense. Early modern humans were clearly able to exploit the resources of the sea, as attested to by dumps of clam and oyster shells found in Eritrea in east Africa, dating from around 125,000 years ago, and similar marine remains in southern Africa from between 115,000 and 100,000 years ago. Sticking with what they knew, beachcombing *Homo sapiens* would have been able to move rapidly along the coastline without having to invent new ways of making a living or adapting to unfamiliar ecological conditions.

Archaeological traces of migration along the southern coastal route are patchy but consistent with this picture. Probably the earliest evidence of settlement by modern humans in south Asia comprises stone tools and human remains discovered in the Fa Hien and Batadomba Lena caves in Sri Lanka, dating from up to 35,000 years ago. What's more, it looks as if these people were equipped with the same sort of cultural repertoire as existed in Africa between 60,000 and 50,000 years ago. "The similarities between Africa and India are not coincidental, and fit in beautifully with the DNA evidence," says Paul Mellars, an archaeologist at the University of Cambridge. Although none of these artefacts is more than 35,000 years old, that may simply reflect the fact that sea levels are about 100 metres higher today than they were 50,000 years ago. Any artefacts or bones left by the first coastal migrants are now buried beneath the sea.

Yet the crucial questions remain: why did humans leave Africa when they did, and what enabled them to achieve world domination this time, where previous migrations had petered out? Richard Klein, an anthropologist at Stanford University in California, has championed the idea that fully modern behaviour appeared in a relatively sudden burst in Africa around 50,000 years ago. Such behaviours encompass the manufacture and

Ancient shell beads point to a cultural flowering some 80,000 year ago

use of complex bone and stone tools, efficient and intensive exploitation of local food resources and, perhaps most significantly, symbolic ornamentation and artistic expression. These changes were the result of a few significant genetic changes affecting cognition and intellectual capacity, Klein suggests. In particular, he speculates that *FOXP2*, a gene associated with language, may have mutated around this time, allowing for improved transmission of ideas. Klein believes that whatever the contributing factors, this "cultural great leap forward" tipped humans over into modernity and equipped them with the creativity, skills and tools needed to conquer the rest of the world.

By contrast, other researchers believe that the behavioural modernity that underpins the human success story evolved much earlier. They point to a growing array of artefacts such as pieces of engraved ochre, found in Blombos cave in South Africa, which probably date to around 77,000 years ago, though they may be 100,000 years old. Then there are various discoveries of ancient "beads", including pierced shells found in Morocco and dated to 82,000 years ago.

It is possible, however, that such finds might simply reflect a gradual accumulation of more modern behavioural patterns, rather than the appearance of fully modern minds. "If you look broadly at the archaeological record between 100,000 and 40,000 years ago," says anthropologist Erik Trinkaus of Washington University in St Louis, Missouri, "you find occasional artefacts, such as symbolic ornamentation, that seem to be indicative of modern behaviour, but they are extremely rare."

In 2006, Mellars proposed a model to explain the out-of-Africa diaspora that aims to tie together these controversial archaeological remains with recent genetic findings. Key to his idea are genetic studies that point to a series of population explosions, first in Africa and later in Asia and then Europe. Rapid population growth leaves a telltale signature in the number of differences in mitochondrial DNA between pairs of individuals within a specific population: as the time since the population explosion increases, so do the DNA mismatches. This analysis shows African populations were rocketing 80,000 to 60,000 years ago, neatly matching the evidence for an early flowering of behavioural modernity. "There is an extraordinary coincidence between these dates and the appearance of the first bone tools, first artistic designs such as the Blombos ochre, new forms of stone tools, and perforated shells and ornamentation," says Mellars.

Key innovations

According to his model, human behaviour was altering between 80,000 and 70,000 years ago in ways that led to major technological and social changes in south and east Africa. Key innovations, including improved weaponry for hunting, new use of starchy wild plants to eat, the expansion of trading networks, and possibly the discovery of how to catch fish, enabled modern humans to make a better living off the land and sea. Mellars says all this led to a massive and rapid population expansion, perhaps in just a small source region in Africa, between 70,000 and 60,000 years ago. This growing population, equipped with more complex technology, was finally able to push out of Africa and into southern Asia from around 65,000 years ago. What's more, the discovery of similar growth in Asian populations around 60,000 years ago ties in with evidence that humans were trekking along the southern coast of Asia at least 55,000 years ago. It is a neat story but, not surprisingly, Klein and other supporters of the human "great leap forward" dispute it.

A picture of modernity: carved ochre found in a cave in South Africa

Whether behavioural modernity and the capacity for complex culture arose gradually or in a sudden burst, questions still remain about what encouraged the great leaps in technological know-how and cultural sophistication of early modern humans. While genetic changes are likely to have been important, as Klein argues, climate may also have played a decisive role. A study of cores taken from Lake Malawi revealed that between around 150,000 and 70,000 years ago the African climate was highly variable, oscillating between periods of drought and flood, before becoming more stable and damp. "Our research suggests that the population expansion and subsequent spreading of out-of-Africa colonisers may have been aided by the newly stabilised climate," says Christopher Scholz, from Syracuse University, New York, who led the international team. The preceding era of wild climate fluctuation would have increased the pressure on our ancestors to adapt or die, plausibly driving changes in social arrangements, technology and allowing the most adaptable and successful humans to survive and proliferate. So climatic upheaval may have primed our forebears for world domination, while stability then allowed them to multiply and conquer the Earth.

The human story has always been hotly contested. Now, at last, the basic plot is finally taking shape. Although the fragmentary and ambiguous nature of the evidence means that the fine details of our species' biography are still obscure, there is every reason to expect that the synthesis of genetic and palaeontological findings will in time reveal the whole story. Then, we will be able to answer two of life's most fundamental questions: where did we come from and how did we get here? ■

Who were the first people to set foot on American soil, asks Michael Bawaya

HOW THE WEST WAS WON

NOT so long ago there was a simple and seemingly incontrovertible answer to the question of how and when the first settlers made it to the Americas. Some 13,000 years ago, a group of people from Asia walked across a land bridge that connected Siberia to Alaska and headed south.

These people, known to us as the Clovis, were accomplished tool-makers and hunters. Subsisting largely on big game killed with their trademark flint spears, they prospered and spread out across the continent.

For decades this was the received wisdom. So compelling was the Clovis First model that few archaeologists even contemplated an alternative. Some with the temerity to do so complained of a "Clovis police", intent on suppressing dissent.

No longer. Thanks to recent discoveries, the identity of the first Americans is an open question again. Clovis First is not quite dead, but most researchers now accept it is no longer a good fit for the evidence. And so the question must be asked again: when were the Americas first settled, and by whom?

The colonisation of the Americas has long fascinated and frustrated archaeologists. It was the last great human migration, the final leg of our journey out of Africa to lay claim to Earth's habitable continents. Big-game hunters from Asia were always considered likely candidates, but it wasn't until the mid-1960s that this idea was formulated into the Clovis First model, primarily by archaeologist C. Vance Haynes of the University of Arizona in Tucson.

According to Clovis First, around 13,500 years ago, near the end of the last ice age, a brief window of opportunity opened up for humans to finally enter North America. With vast amounts of water locked up in ice caps, sea level was lower than today and Siberia and Alaska were connected by a now-submerged land bridge called Beringia. As the world began to warm, the huge ice sheets that blocked entry into North America began to retreat, parting like the Red Sea to create an ice-free corridor to the east of the Rockies (see map, above). The Clovis walked right in.

The presence of distinctive stone tools throughout the US and northern Mexico supports the theory, as does the timing of an extinction that wiped out more than 30 groups of large mammals including mammoths, camels and sabre-toothed cats. This coincides neatly with the arrival of Clovis hunters, and could have been their handiwork.

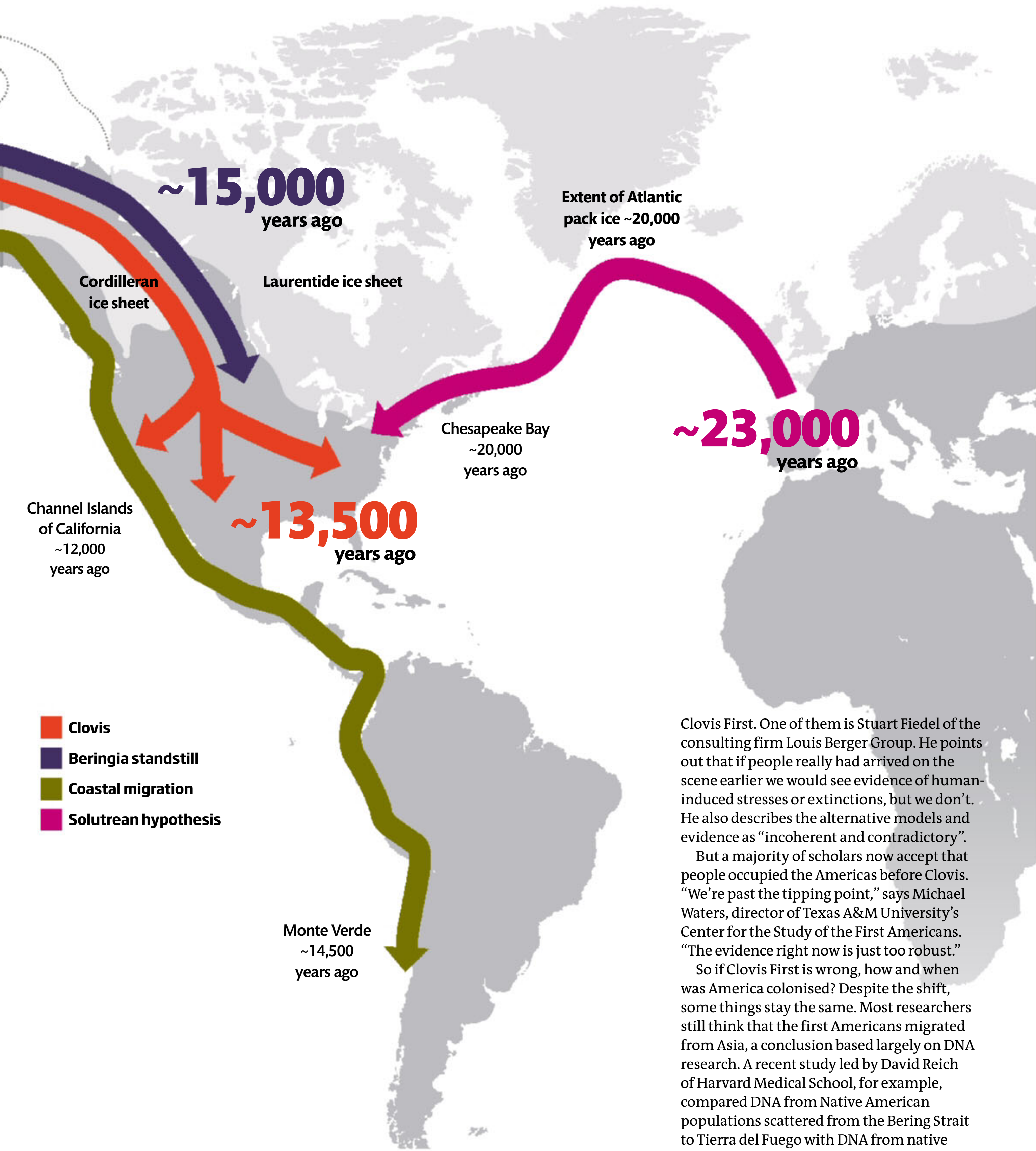
But over the years inconvenient bits of evidence have piled up. In 1997 a delegation of 12 eminent archaeologists visited Monte Verde, a site of human habitation in southern Chile that was first excavated in the 1970s and was claimed to be 14,800 years old. That, of course, contradicted Clovis First. The trip was a pivotal moment: most of the visiting archaeologists changed their minds, and prehistory started to be rewritten.

Many other pre-Clovis sites have also been found, some producing more credible evidence than others. Monte Verde is the most widely accepted; a survey of 132 archaeologists found that around two-thirds believe it is pre-Clovis.

Compare the DNA

DNA studies also contradict the old orthodoxy. By comparing the genomes of modern Asian and Native American people and estimating the amount of time it would take for the genetic differences to accumulate, geneticists estimate that people entered the Americas at least 15,000 years ago – 1500 years earlier than in the Clovis model.

There are archaeologists who still embrace



Clovis First. One of them is Stuart Fiedel of the consulting firm Louis Berger Group. He points out that if people really had arrived on the scene earlier we would see evidence of human-induced stresses or extinctions, but we don't. He also describes the alternative models and evidence as "incoherent and contradictory".

But a majority of scholars now accept that people occupied the Americas before Clovis. "We're past the tipping point," says Michael Waters, director of Texas A&M University's Center for the Study of the First Americans. "The evidence right now is just too robust."

So if Clovis First is wrong, how and when was America colonised? Despite the shift, some things stay the same. Most researchers still think that the first Americans migrated from Asia, a conclusion based largely on DNA research. A recent study led by David Reich of Harvard Medical School, for example, compared DNA from Native American populations scattered from the Bering Strait to Tierra del Fuego with DNA from native Siberians. The conclusion? The Americans are descended from Siberians who arrived in at least three waves.

That might not sound too different from Clovis First. But other research tells another ›

Clovis tools like this one can be found all over North America...

BOTTOM: DENNIS JENKINS TOP: THE TRUSTEES OF THE BRITISH MUSEUM

story. The DNA of Native Americans is sufficiently different from the Siberians' DNA to suggest that the populations went their separate ways around 30,000 years ago.

That could indicate a much earlier entry. Some archaeologists claim that they have found evidence of human habitation as far back as 50,000 years ago, but they are not widely believed.

A more likely scenario is that the settlers did not come directly from Asia, but from a population that settled in Beringia 30,000 years ago and stayed put for 15,000 years before pressing on to Alaska. This group would have become isolated from the ancestral population in north-east Asia, perhaps by ice, and built up 15,000 years' worth of genetic differences. This scenario is dubbed the "Beringia standstill".

Not everybody, however, clings to the idea that the first Americans arrived from Siberia. One of the problems thrown up by Monte Verde is its remoteness from Beringia. It is about 12,000 kilometres from the supposed entry point; even if people colonised North America 15,000 years ago, it is a stretch to imagine them reaching southern South America just 200 years later.

Enter the second alternative to Clovis First: coastal migration. Some researchers have suggested that instead of walking across Beringia, the first Americans hopped on boats and sailed along the Pacific coast.

"Perhaps the settlers did not come directly from Asia but from a population that settled in Beringia 30,000 years ago"

It is mightily difficult to test this scenario. The melting of the glaciers approximately 10,000 years ago submerged the ancient coast along with any archaeological evidence it holds. "The coastal migration theory has been marginal until relatively recently," says University of Oregon archaeologist Jon Erlandson, a leading proponent of the idea.

Nonetheless, some evidence exists. Reich's DNA study suggests that the first wave of colonists moved south along the Pacific coast. And we know that ancient East Asians were accomplished seafarers, reaching the isolated Ryukyu Islands between Japan and Taiwan roughly 35,000 years ago, and possibly up to 50,000 years ago.

There are also archaeological finds that lend credence to the idea. Erlandson has worked on the Channel Islands of California for decades and has uncovered evidence of an advanced 12,000-year-old culture there. It includes numerous barbed stone points and crescents that display remarkable workmanship. The points were conceivably used to spear fish, while the crescents were likely mounted on a shaft and thrown at birds.

Though these weapons are younger than any Clovis artefact, they are also so different that Erlandson suggests there is no connection between the two types. He and his colleagues propose that they were made by East Asian seafarers who travelled on a coastal "kelp highway" of seaweed stretching from Japan to South America.

More tentative evidence in favour of a coastal route comes from an unlikely source: human excrement. A number of human coprolites – the most ancient of which is claimed to be 14,300 years old – have turned up in the Paisley caves in Oregon, one of the claimed pre-Clovis sites. Dennis Jenkins of the University of Oregon spent six seasons excavating the caves. In 2008 he announced that the coprolites contained human DNA.

Several experts expressed doubts when Jenkins published his results in *Science*, but further DNA analysis supports the conclusion. The DNA also suggests that the people originated in Siberia or East Asia.

That in itself says nothing about coastal migration. But last year Jenkins announced another important discovery: a type of spearhead known as Western Stemmed, found in the same geological layer as a 13,200-year-old coprolite. This style of weapon was known already; the spear points are markedly different from Clovis ones and were assumed to be the handiwork of a later culture. Now it seems the technology was around at the same time as Clovis.

Who, then, made the spear points? One plausible answer is coastal migrants. The caves are quite close to rivers which feed into the Pacific. "Mariners could have easily followed these rivers inland," says Jenkins.

There is also a resemblance between Western Stemmed and a style of point known as Tanged, made in Japan about 15,000 years ago, according to Erlandson. He adds that the crescent points from the Channel Islands also resemble Western Stemmed.

Bladelets and scrapers

Support for coastal migration also comes from Waters. He is leading the excavation the Debra L. Friedkin site, a pre-Clovis site at Buttermilk Creek in central Texas, that he describes as a "game changer". Since digging began in 2006, over 15,000 artefacts have been uncovered – more than found at all other pre-Clovis sites combined – dating from 15,500 to 13,200 years ago. The great majority are offcuts from tool-making, but there are also choppers, scrapers, hand axes, blades and bladelets.

In Waters's opinion, these could be the precursors of Clovis technology. The blades, bladelets and scrapers are the types of tools they used. "You have the technology that could have become Clovis," he says.

If the dating is right, it adds further credence to a coastal migration. Waters says it is uncertain whether the ice-free corridor was open 15,000 years ago, suggesting the people who made the tools may not have entered via Beringia. "There's any number of

"We know that east Asians were accomplished seafarers, reaching isolated islands between Taiwan and Japan at least 35,000 years ago"

ways people could have come," he says – but he favours the coastal route.

Although Waters published his work in *Science*, a few archaeologists remain unconvinced the site is that old. Radiocarbon testing is generally the most accurate method for dating artefacts, but can only be used on organic material, which is absent at Buttermilk Creek. So Waters used a technology called optically stimulated luminescence.

One of the doubters is Dennis Stanford, a renowned First American expert at the National Museum of Natural History in Washington DC. He also thinks the site's "pre-Clovis" artefacts could in fact be Clovis.

Stanford has another reason for doubting Waters: he believes that he has identified the predecessors of the Clovis. Stanford and Bruce Bradley of the University of Exeter, UK, are leading advocates of the most radical alternative of all: that the first Americans came not from Asia but from Europe.

Specifically they claim that the Clovis are descended from the Solutreans, a Palaeolithic people who flourished on the Iberian peninsula approximately 24,000 to 17,500 years ago. In their book *Across Atlantic Ice*, Stanford and Bradley present a scenario in which these people reached the Americas more than 20,000 years ago, travelling by boat along the edge of sea ice that stretched across the Atlantic Ocean from the north coast of Spain to the coast of the Americas.

This is a bold – some say preposterous – hypothesis, although not a brand new one. Over the past century, other archaeologists have proposed that Europeans could have preceded Columbus by millennia, citing a similarity between Clovis and Solutrean tools (see photos left and below). Stanford and Bradley have embraced this hypothesis since the mid-1990s.

Stanford turned to Europe after spending about 30 years searching in vain for Clovis-like artefacts in Siberia. In 1996 he went to Solutré in France – the source of the term "Solutrean" – to attend an exhibition comparing Clovis and Solutrean artefacts. He eventually joined forces with Bradley, who was convinced of a Clovis-Solutrean connection.

The two argue that Solutreans were mariners and seal hunters who voyaged along the edge of the ice sheet in search of game. Some time between 23,000 and 19,000 years ago their wanderings led them to America.

Stanford also believes there were migrations from Asia, especially along the west coast of the Americas, but he maintains that the Solutreans were the precursors of Clovis.

Their hypothesis is buttressed by the recent discovery of two sites along Chesapeake Bay in Maryland, Miles Point and Oyster Cove, with Solutrean-style artefacts. Both sites have been dated at more than 20,000 years old. The pair also note that distinctively Solutrean-like artefacts have been recovered from two other claimed pre-Clovis sites in the eastern US, Meadowcroft Rockshelter in Pennsylvania and Cactus Hill in Virginia.

Stanford says *Across Atlantic Ice* has made some sceptics more amenable to his ideas. In an editorial in the *Journal of Field Archaeology*, editors Curtis Runnels and Norman Hammond of Boston University wrote that Stanford and Bradley "make a plausible case".

Open water

But others are dismissive. "It remains wild speculation," says Lawrence Straus, a Solutrean specialist at the University of New Mexico, Albuquerque, who has argued against the hypothesis for years. "I can only say that there is no evidence of the Solutrean peoples being Atlantic navigators or seal hunters."

What is more, a 2008 study by Kieran Westley, now at the University of Ulster in Coleraine, UK, and Justin Dix of the University of Southampton, UK, concluded that the ice sheet didn't stretch across the ocean for much of the year. So, contrary to Stanford and Bradley's scenario, the Solutreans would have had to navigate stretches of open water.

There is also no DNA evidence, says geneticist Ripan Malhi of the University of Illinois, Urbana-Champaign. "The final nail in the coffin will likely come when we are able to sequence DNA from ancient individuals associated with Clovis points," he said in 2013. Researchers at the Center for the Study of the First Americans have now done just that, on the skeleton of an infant from Anzick, a 12,700-year-old Clovis site in Montana. These are the only confirmed remains of a Clovis human. The infant turns out to be a direct ancestor of most peoples in Central and South America – and probably the US too – as well as a very close cousin of Canadian tribes. And his DNA shows that his ancestors crossed into the Americas from Siberia.

Nevertheless, findings such as those at Buttermilk Creek challenge Clovis First. "I think Clovis First is dead and we have to use our imaginations to come up with a new model," says Erlandson. Exactly what that is remains to be seen, but he thinks it will consist of a mixture of coastal and land migrations. People may well have walked across Beringia into the Americas – but they were not the only ones, and probably not the first. ■

THE BRIDGEMAN ART LIBRARY LTD. / ALAMY

… but do they trace their roots back to an ancient European culture?

One of the family?

Synonymous with a brutish lack of refinement, Neanderthals are ripe for rebranding. Robert Adler reports

RICHARD WILKINSON

EVER since the first fossils of a brawny, low-browed, chimp-chested hominin were unearthed in Germany in 1856, Neanderthals have stirred both fascination and disdain. German pathologist Rudolf Virchow decreed that the bones belonged to a wounded Cossack whose brow ridges reflected years of pain-driven frowns. French palaeontologist Marcellin Boule recognised the fossils as ancient, but ignored signs that the specimen he studied suffered from arthritis. It was he who reconstructed the bent-kneed, shambling brute that still lurks in the back of most people's minds. Irish geologist William King found the creature so apelike that he considered putting it into a new genus. In the end he merely relegated it to a separate species, *Homo neanderthalensis*.

Since then, hundreds of Neanderthal sites have been excavated. These show that Neanderthals occupied much of modern-day Eurasia, from the British Isles to Siberia, and from the Red Sea to the North Sea. Here they survived 200,000 years or more of climatic chaos before eventually disappearing around 40,000 years ago. The long-held view that Neanderthals were inferior to *Homo sapiens* is changing as, one by one, capabilities thought unique to us have been linked to them.

What's more, the two species clearly crossed paths, and the publication of the Neanderthal genome shows that they interbred. We share over 99 per cent of our genes with Neanderthals, and after splitting from a common ancestor between 550,000 and 765,000 years ago anatomically modern humans met and mated with Neanderthals, most likely in the Middle East around 45,000 years ago.

If our ancestors made love, not war, the same cannot be said for the researchers who study them. The new discoveries have been pounced upon by those who believe that Neanderthals thought like we did, talked like we did and enriched their world with music, decoration and symbols as we did. It has even been suggested that we are the same species. However, there are still some who vehemently argue that Neanderthal minds were no match for those of our *Homo sapiens* ancestor. Surprisingly, they too point to the latest genetic evidence to bolster this view. So, were Neanderthals once our equal, or just another failed species of hominin?

The first pieces of evidence to support the revisionist camp come from Neanderthal lifestyles, which indicate parallels with early modern humans. We know, for example, that in addition to occupying caves and overhangs, Neanderthals also constructed shelters. Holes for wooden pegs and posts that probably supported lean-tos have been found at two sites in France. Numerous hearths dating from 60,000 years ago indicate that Neanderthals also controlled fire – although they were not the first to do so. They may, however, have been the first to play music around their fires. One of the oldest known musical instruments has been attributed to Neanderthals by its discoverer Ivan Turk, although sceptics argue that the 43,000-year-old bone "flute" found at Divje Babe in Slovenia is just a cave-bear femur punctured by wild animals.

There is also evidence that Neanderthals wore clothes. And Shara Bailey at New York University thinks that, like today's traditional Inuit, they softened animal skins with their teeth. "If you get an adult skull, their incisors are often worn down to nubs, while the molars are fine. So they were probably using their front teeth to process skins," she says.

Initially seen as mere scavengers, it is now clear that Neanderthals hunted formidable prey, including rhinos and fully grown

"Although typecast as incapable of change, it now seems that Neanderthals did innovate"

mammoths. They also adapted their hunting strategies to the environment, ambushing solitary prey in forests, stalking bison and other herd animals on the steppes, and harvesting birds, rabbits and seafood at the shore.

Their toolkit, typical of the Mousterian culture, which dates from between 300,000 and 40,000 years ago, required planning, concentration and great skill to make. Meticulous preparation of a stone core was needed so that a final rap from a hammer stone would yield a predetermined flake tool. "They developed techniques that modern humans find difficult to replicate," says Thomas Wynn at the University of Colorado in Colorado Springs. They even manufactured and used compound tools made from more than one material, including hafted spears. There is also evidence, dating from 80,000 years ago, that they heated birch pitch under anaerobic conditions, creating a kind of glue with which to attach stone points to spear hafts.

In the past it was generally believed that advances in Neanderthal technology ›

WHAT DNA CAN SAY

In May 2010, a team led by Richard Green from the University of California, Santa Cruz, and Svante Pääbo from the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, reported an astonishing feat. From fossilised bone fragments of three Neanderthals who lived 40,000 years ago, they reassembled 60 per cent of the Neanderthal genome and made the first detailed genetic comparison of Neanderthals and modern humans. A complete sequence was published early in 2014.

Extrapolating from the available sequences, the team estimate that Neanderthals and modern humans are almost as closely related as any two living humans: you might share 99.9 per cent of your DNA with a randomly selected human, and 99.8 per cent with a Neanderthal. This reflects our shared common ancestors.

TWO SPECIES OR ONE?

The biggest surprise, however, was that people of non-African ancestry are more similar to Neanderthals than Africans are, leading the researchers to conclude that between 1.5 and 2.1 per cent of the DNA of all non-African people comes directly from Neanderthals. The only way that non-Africans worldwide could have acquired this dose of Neanderthal DNA is if modern humans leaving Africa mated with Neanderthals before colonising the rest of the world, something the researchers think happened in the Middle East about 45,000 years ago. This was unexpected, as previous studies of Neanderthal mitochondrial and Y-chromosome DNA showed no signs of mating with modern humans.

The DNA that sets us apart from Neanderthals is also interesting. The team discovered 78 genes and 200 longer stretches of genome which modern humans all share but Neanderthals don't. These represent mutations that occurred in the human line after the split from Neanderthals. The sequences include genes affecting senses, cognition, social interaction, metabolism and immunity. "Exactly how our brain physiology and cognition are different we don't understand yet," says Green. "But now we know where to look."

No one ever expected there to be a single gene separating Neanderthals and us, yet the researchers were intrigued by *RUNX2*. A mutation in *RUNX2* causes a suite of skeletal changes, including the brow ridges and bell-shaped chest typical of Neanderthals. "It's extremely tantalising," says Pääbo. "It might be a gene that actually reflects what you see in the archaeological record."

Some had hoped the genome comparison might resolve the 150-year-old debate over whether Neanderthals and humans belong to the same species. After all, one definition of distinct species is that they cannot mate and produce fertile offspring. Pääbo won't be drawn in. "I think that when we come to such closely related groups as Neanderthals and humans, these definitions contribute more confusion than clarity," he says. "It just makes people excited for no reason."

towards the end of their era were simply copied from early modern humans, but research from 42,000-year-old Neanderthal sites in southern Italy refutes this. There, some say, Neanderthals developed an array of stone and bone tools distinct from those used by early humans living further north. Although Neanderthals have been typecast as incapable of change, some researchers now accept that they did innovate.

There is also broad acceptance that Neanderthals buried their dead. The earliest undisputed *Homo sapiens* burial is in Skhul cave, on Mount Carmel, Israel, around 120,000 years ago. Neanderthal burials have

"Neanderthals were people, and they probably had the same range of mental abilities we do"

been found at several sites, including La Chapelle-aux-Saints in France, where the "Old Man" was interred with coloured earth around 60,000 years ago, and Teshik-Tash in Uzbekistan, where a 9-year-old boy was buried circled by ibex horns some 70,000 years ago – although both these interpretations have been questioned. Dating from around the same time are the graves of 10 individuals found at Shanidar cave in Iraq. Ian Tattersall from the American Museum of Natural History in New York, author of *Extinct Humans*, notes that one of these burials reveals that Neanderthals took care of an injured individual for years before his death, providing "powerful, presumptive evidence

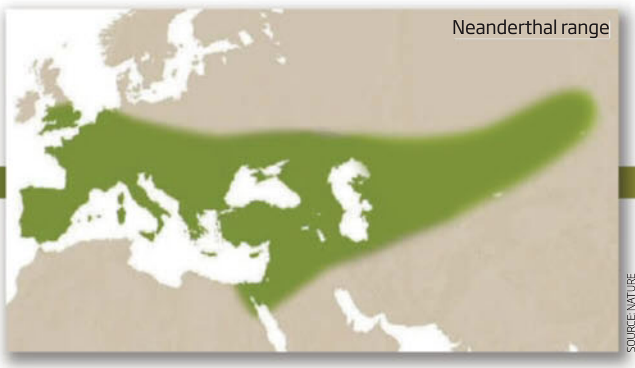
Three hundred thousand years of progress

Neanderthals developed many technologies and cultural practices to rival those of their *Homo sapiens* contemporaries

Neanderthals begin to spread through modern-day Europe and Asia

Stone tools created by striking planned flakes from prepared cores – the Levallois technique

300 Thousands of years ago



Use of fire and hearths. Possible building of lean-tos inside caves

180 170 160

for empathy and caring within the social group, and possibly for complex social roles".

Shanidar is also the location of the famous "flower burial". The high concentration of pollen from medicinal plants in this grave is sometimes cited as evidence of shamanism and ritualistic funerary practices by Neanderthals. Although this interpretation has been disputed, the case for Neanderthals' capacity for symbolic thought has been bolstered by another discovery. João Zilhão, then at the University of Bristol, UK, and Francesco d'Errico at the Institute of Prehistory and Quaternary Geology in Talence, France, found perforated seashells, red and yellow pigments, and shells encrusted with a mixture of several pigments in two caves in Spain, one 60 kilometres from the sea. This, they claim, shows that Neanderthals adorned themselves with symbolic artefacts and, since these finds date back 50,000 years, before modern humans arrived in the area, they also represent independent Neanderthal innovations.

Admittedly there is no evidence that Neanderthals produced cave paintings. Instead, says Zilhão, they may have created more ephemeral artworks, using pigments to decorate their bodies and convey symbolic information about group membership.

Symbolic thought is often associated with another characteristically human trait: language. So is there any evidence that Neanderthals could speak? Ralph Holloway at Columbia University in New York believes so. He has studied hundreds of brain casts from fossilised Neanderthal skulls and found that, even accounting for their big bodies, their brain size is within a few per cent of the

Neanderthal burials suggest they had concerns beyond the here and now

THE NATURAL HISTORY MUSEUM, LONDON

modern human brain and, despite their sloping brows, they had frontal lobes and speech areas like ours.

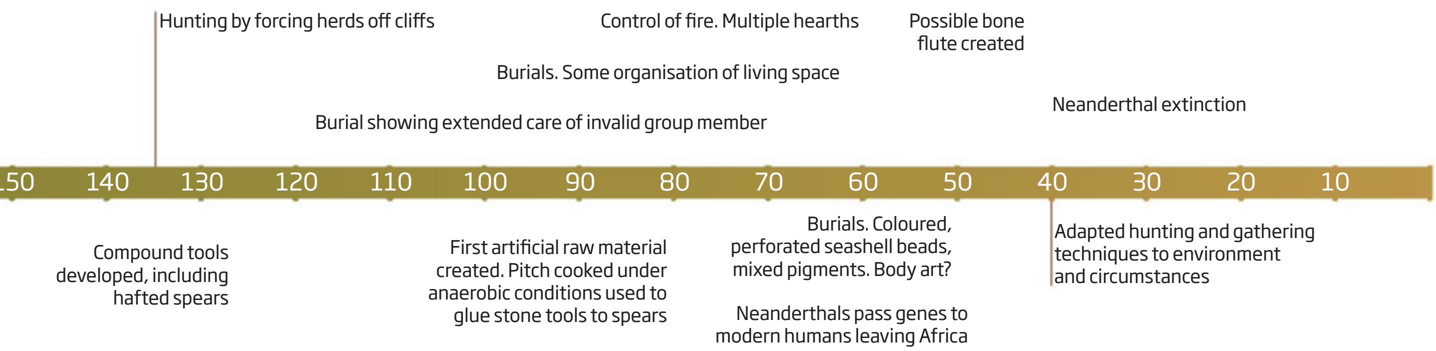
As well as these physical clues, genetic tests reveal that Neanderthals had a version of a gene called *FOXP2* that is associated with language in humans. Meanwhile, fossils from Kebara cave in Israel show that the Neanderthal hyoid, a U-shaped bone in the neck that anchors key speech muscles, matched ours. "I'm certain that they had language," says Holloway.

Philip Lieberman, a linguist at Brown University in Providence, Rhode Island, agrees that Neanderthals had speech. However, he argues that before around 50,000 years ago, neither Neanderthals nor modern humans could produce the full range of sounds we can today. Having studied skulls ranging from 1.6-million-year-old *Homo erectus* through to 10,000-year-old *Homo sapiens*, Lieberman concludes that neither species was capable of the vowel sounds in "see", "do" and "ma". Computer simulations by Robert McCarthy, then at Florida Atlantic University in Boca Raton, support this (newscientist.com/article/dn13672).

Given this accruing evidence, Eric Trinkaus at Washington University in St Louis, Missouri, sums up the case for the revisionists: "If you look at the archaeological record of Neanderthals in Europe and modern humans in Africa or the Near East at the same time period, with rare exceptions they are remarkably similar," he says. "Neanderthals were people, and they probably had the same range of mental abilities we do."

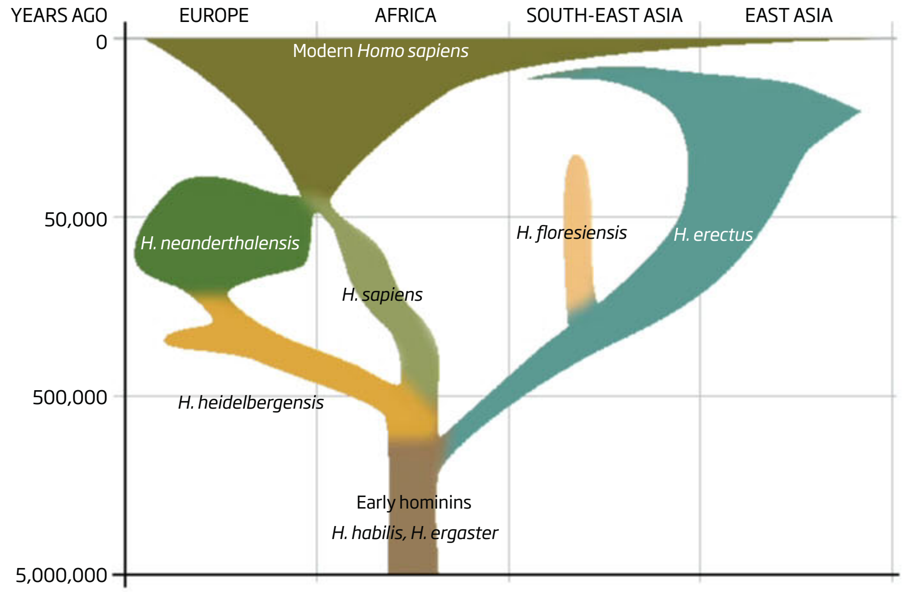
Case closed? You might think so, but there are still some researchers who disagree with this wholesale reappraisal. "Neanderthals and modern humans separated 500,000 years ago and evolved separately in Europe and Africa. Cumulatively, that represents a million years of evolution," says Paul Mellars at the University of Cambridge. "It would be staggering if there were not changes in their brains as well as anatomically." He thinks that cognitive differences between the two species were biologically based and substantial.

The publication of the Neanderthal genome lends some support to this argument. Although the difference between the genomes of today's humans and those of Neanderthals is less than 1 per cent, that could equate to mutations in hundreds of genes. ›



SLEEPING WITH THE OTHER

Comparison of the Neanderthal and human genomes suggests that the two met and mated around 45,000 years ago



Pinpointing these variations is slow work, but among those identified so far, several are in genes that underlie brain functioning and cognition, including social and interpersonal skills.

Further support comes from a study by Philipp Gunz and colleagues at the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany. Their comparison of a virtual reconstruction of the brain case of a Neanderthal newborn and those of modern human infants indicates that the brains were similar at birth but developed differently during the first year of life, a critical period for cognitive development.

Neanderthals may have other cognitive shortcomings, according to some well-respected researchers. Lewis Binford at Southern Methodist University in Dallas, Texas, argued that their lifestyles showed little forward planning. Wynn believes that they had less working memory capacity than modern humans, limiting how much information they could process at a given time. "That's one of the things that could account for their lack of innovation," he says. Steven Mithen at the University of Reading, UK, grants Neanderthals modern capacities in knowledge of the natural world, manipulating materials and social interaction. However, he thinks they lacked the "cognitive fluidity" and "capacity for metaphor" to link these domains, leaving them unable to produce complex symbolic objects. Mellars, too, is not convinced that they were capable of the symbolic thought Zilhão infers from the shell artefacts from Spain. "I think the views of Zilhão are profoundly mistaken. If those are the best things the Neanderthals did in 250,000 years over the whole of Europe, God help them."

Yet for most of this period early modern humans were not that innovative either. Even Mellars accepts that there are few differences between their accomplishments and those of Neanderthals up until about 50,000 years ago. At this point, however, early modern humans pulled away, undergoing a "big bang" of symbolic activity typified by carved statuettes, elaborate burials, an abundance of personal decorations and, eventually, elaborate cave paintings. Mellars argues that by the time modern humans entered Europe, they had better technology, better social organisation and better brains. "The Neanderthals were playing against a better team," he says.

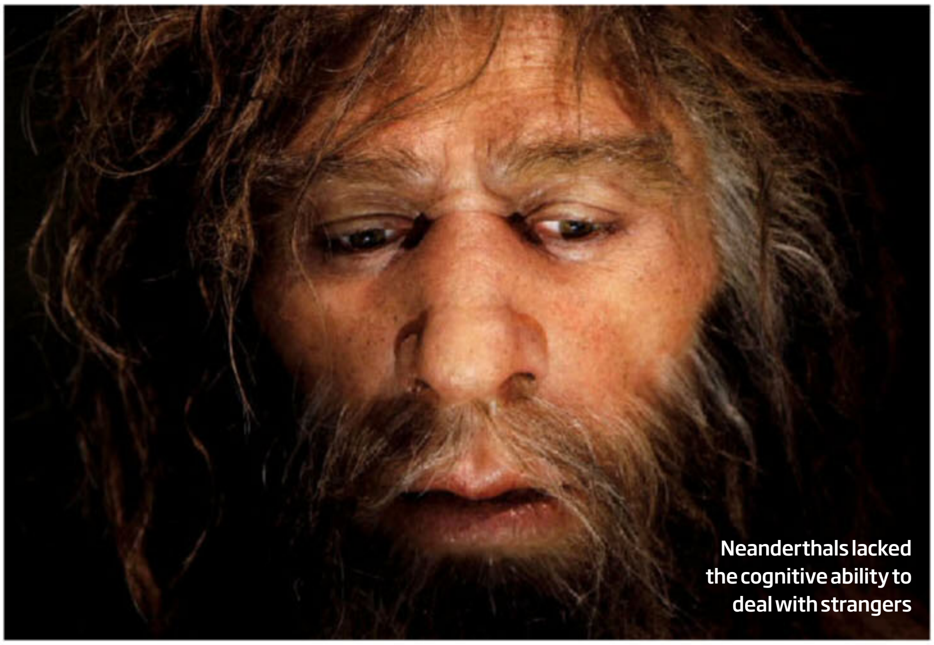
Anthropologist Richard Klein at Stanford University in California agrees. Like Mellars, he thinks significant genetic changes underlie the cognitive and symbolic flowering that occurs in modern humans. "Some people think it's almost racist to suggest that Neanderthals or earlier humans differed from us genetically," he says. "I've been accused of Neanderthal-bashing, as if I were trying to keep them out of Harvard." Yet Klein is standing his ground. "Those genes which are uniquely modern could help explain why Neanderthals aren't around anymore."

That, for traditionalists, is the crux of this debate: Neanderthals became extinct, while we are still very much extant. But here the revisionists seem to have the last laugh. Neanderthals may no longer be with us in the flesh, but their genes live on, accounting for as much as 2.1 per cent of the genome of anyone of non-African ancestry (see "What DNA can say", page 92).

This is even more remarkable given the size of Neanderthal populations: the limited variation in their mitochondrial DNA indicates a sustained breeding population of just 3500 individuals (newscientist.com/article/dn17477). As Zilhão points out, the genetic reservoir of modern humans in Africa was many times greater than that of the Neanderthals. "What happens when you mix one litre of white paint with 100 litres of black paint? You get 101 litres of black paint," he says. "That's just what the geneticists found." ■

ROADS TO EXTINCTION

Everyone, it seems, has a different idea about why Neanderthals became extinct. Those who see them as an inferior species suspect that smarter, more talkative, more social and adaptable early modern humans were to blame, outcompeting Neanderthals in terms of resource use, organisation and reproductive success. Meanwhile, those who believe that Neanderthals were just as smart as early humans typically look to climate change, natural catastrophes and cumulative cultural differences to explain the extinction. In his 2009 book *The Humans Who Went Extinct*, for example, Clive Finlayson of the Gibraltar Museum argues that the Neanderthals' stocky build and close-in hunting style limited them to a shrinking environment and made them increasingly vulnerable to a deteriorating climate, inbreeding, disease and competition. Chris Stringer at the Natural History Museum in London thinks the last Neanderthals were just unlucky. "It was one of the most unstable periods in terms of Earth's climate. They had to cope with those changes and they had a competing species alongside them," he says. "It was a kind of double whammy."


Neanderthals lacked the cognitive ability to deal with strangers

Inside the Neanderthal mind

What made them laugh? Or cry? Did they love one another? **Thomas Wynn** and **Frederick L. Coolidge** reveal the inner lives of our extinct cousins

A NEANDERTHAL walks into a bar and says... well, not a lot, probably. Certainly he or she could never have delivered a full-blown joke. Jokes hinge on surprise juxtapositions of unexpected or impossible events. Cognitively, they require an advanced theory of mind to put oneself in the position of the actors in the joke, and sufficient working memory to hold relevant information in mind and use it.

So does that mean our Neanderthal had no sense of humour? No: humans also recognise physical humour. So while verbal jokes would have been lost on them, they could have sat down and enjoyed slapstick.

Humour is just one aspect of Neanderthal life we have been plotting for some years in our mission to make sense of their cognitive life. So what was it like to be a Neanderthal?

Skeletal evidence shows that Neanderthals led very strenuous lives, preoccupied with hunting large mammals at close quarters. Based on their choice of stone for tools, we know they almost never ventured outside small home territories that were rarely over 1000 square kilometres.

This evidence is quite revealing. Hunting resulted in frequent injuries, and the victims were often nursed back to health. But few would have survived serious lower body injuries, since individuals who could not walk might have been abandoned. So it looks as if Neanderthals had empathy for group members, but also that they made pragmatic decisions when necessary.

Looking at how Neanderthals manufactured and used tools shows that they organised their technical activities much as artisans organise production. Like blacksmiths, they relied on "expert" cognition, a form of observational learning and practice acquired through apprenticeship that relies heavily on long-term memory.

"We could have interacted with them, but would have noticed big differences"

But they were not innovators. Although Neanderthals invented the practice of hafting stone points on to spears, this was one of very few innovations over several hundred thousand years. Invention relies on thinking by analogy and a good amount of working memory, implying they may have had a reduced capacity in these respects.

As for their social lives, the size and distribution of Neanderthal sites shows that they spent their lives mostly in small groups of five to 10. Several such groups came together briefly after successful hunts, but they seldom made contact with people outside those groupings.

Many Neanderthal sites have rare pieces of stone from more distant sources, but not enough to indicate trade or regular contact with other communities. A more likely scenario is that adolescents carried the stone with them when they left home and attached themselves to a new group. The small size of Neanderthal territories would have made such "marrying out" essential.

We can assume that Neanderthals had some form of marriage because pair-bonding between males and females, and joint provisioning for offspring, had been a feature of hominin social life for over a million years. They also protected corpses by covering them with rocks or placing them in pits, suggesting intimate social and cognitive interaction.

But the Neanderthals' short lifespan – few lived past 35 – meant that other social features were absent: elders, for example, were rare.

Although Neanderthals would have had a variety of personality types, their way of life would have selected for an average profile quite different from ours. They would have been pragmatic, capable of leaving members behind, and stoical, to deal with frequent injuries. They had to be risk tolerant for hunting; they needed sympathy and empathy in their care of the injured and dead; and yet were neophobic, dogmatic and xenophobic.

So we could have recognised and interacted with Neanderthals, but we would have noticed significant differences.

In the final count, when Neanderthals and modern humans found themselves competing 30,000 years ago, those cognitive differences may well have been decisive. ■

All work and no play makes a dull child

Neanderthals had shorter childhoods than modern humans – something which profoundly influenced their minds, argues archaeologist **April Nowell**

WATCHING a group of 5-year-olds chasing each other in a park, it is easy to forget that child's play is a serious business. Through play, children figure out how to interact socially, practise problem-solving and learn to innovate, skills that will be indispensable to them as adults. But if experiences gained during play are so crucial for cognitive development, what would it mean if a species had a shorter childhood?

This is exactly the case for our closest relatives, the Neanderthals. Behaviourally they were very similar to us, with some important differences which, to paraphrase Sigmund Freud, may stem from their childhoods.

Neanderthals evolved in Europe some 250,000 years ago, spread to the Middle East and eventually went extinct about 40,000 years ago. Much like their human counterparts, they made complex tools and hunted large game. But they also ate fish, tortoise, hare and a variety of plants, adapting their diets to local conditions. They had language, created fire, at least occasionally showed compassion for others in their group and sometimes buried their dead. The single greatest difference between Neanderthals and humans that we can see in the archaeological record, however, lies in both the quantity and nature of the artefacts they imbued with an obvious symbolic dimension.

Humans today live in what we call a symbolic culture. All the objects around us have a symbolic dimension. The clothes we wear, for instance, send out signals about us that are unrelated to their practical function. We form symbolic relationships where no biological relationship exists, with a husband, sister-in-law, godchild, blood-brother, for example. Language, of course, is another key example; the relationship between the words and the objects and concepts to which they refer is largely arbitrary, and that is the essence of a symbol.

Neanderthals created few symbolic artefacts. Before about 50,000 years ago there is very little evidence of any that stand up to scientific scrutiny. A few Neanderthal sites dating from after that contain some beads, pigments, raptor talons and indirect evidence for feathers – all presumably for some kind of body decoration.

Burst of creativity

But these artefacts pale next to the record of symbolic material culture created by early humans who first evolved in Africa 200,000 years ago. Even if we focus on just the period 50,000 to 30,000 years ago, we find that early humans created bone flutes, the breathtaking paintings of the Chauvet cave in France, imaginative personal ornaments such as ivory beads carved to look like shells, and figurines incised with geometric patterns. Two examples that stand out for me are the lion-human statues from the Swabian Jura region of Germany and the painting of a bison-woman from Chauvet, both fantastical, imaginary creatures.

The ability to reproduce a three-dimensional form on a two-dimensional surface, or to "see" a figure in ivory, requires a completely different way of imagining the world. Neanderthals created nothing like these artefacts and I believe this can be explained by the games they played, or more correctly did not play, as children.

Neanderthals matured more slowly than earlier hominins such as *Homo erectus*, but more quickly than modern humans. As a result, they had a shorter childhood than us. We know this because Neanderthals occasionally buried their dead, so we have a relatively large collection of Neanderthal infants and children from which to measure their development. One study in particular was a game changer. In 2010, Tanya Smith from Harvard University and colleagues

SEBASTIEN PLAILLY/SPL

Growing up fast: young Neanderthals had no time for imaginary "what if?" games

studied Neanderthal and early human teeth, counting daily growth lines to calculate the exact age. By comparing this to the individual's patterns of growth, Smith concluded that Neanderthals grew relatively rapidly and spent less time dependent on their parents.

Why should this make a difference to the minds of Neanderthals compared to modern humans? To understand this, we need to take a closer look at childhood. In general, species like us, with longer dependency periods, tend to play more and engage in many more types of play. This influences our minds, because play is an important part of the healthy cognitive development of many animals, not just humans, and being deprived of opportunities to play can be detrimental. For example, a study on rats demonstrated that those raised normally but without access to playmates suffered from the same kinds of problems as rats with damage to their prefrontal cortex, a region of the brain involved in social behaviour, abstract thinking and reasoning. In other words, play shapes the brain. But the kind of brain we have also shapes the type of play we engage in.

Humans are unique in that we engage in fantasy play, part of a package of symbol-based cognitive abilities that includes self-awareness, language and theory of mind. Its benefits include creativity, behavioural plasticity, imagination and the ability to plan. Being able to imagine novel solutions to problems and to work out their consequences before implementing them would have been an enormous advantage for our early human ancestors – this is exactly what we are practising when we play "what if" games. From what we can tell, it is unlikely that Neanderthals were able to engage in fantasy play, and it is this level of imagination that underlies the differences in material culture between Neanderthals and early humans.

"Neanderthals' level of engagement with the world was different from ours"

We need to add one final piece to the puzzle: the Neanderthal brain. Neanderthals experienced accelerated brain growth compared to us, according to research by Simon Neubauer and Jean-Jacques Hublin from the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, who concluded that this meant the environment had less impact on the connectivity of their developing brains. Taking a modern example, accelerated brain growth in children with autism lessens their ability to read social cues and engage in fantasy play. The same may have been true for Neanderthals. This leads us to believe that their perception of the world, and their level of engagement with it, was different from ours.

I think that it was only through years of "training" their unique brains through fantasy play in childhood that modern humans were able to create fantastical symbolical artworks like the Chauvet bison-woman. The shorter Neanderthal childhood, combined with their lack of complex fantasy play, influenced the adults they became, and the artefacts they left behind. ■

How to speak Neanderthal

Traces of their words are hard to find – but that's not going to stop us from trying, say linguists **Sean Roberts**, **Dan Dediu** and **Scott Moisik**

IF YOU find yourself stuttering your way through tourist French, spare a thought for the first modern humans. Travelling from Africa to Asia and Europe about 70,000 years ago, they would have encountered Neanderthals for the first time.

What did they say? In the past, many would have answered "not a lot" since Neanderthals weren't thought to have complex speech. But recent evidence suggests they probably had languages very similar to our own. Surprisingly, we may now have the means to glimpse those utterances in the words we speak today, with huge consequences for our understanding of language evolution.

The argument that Neanderthals spoke like us comes from many discoveries. Archaeological remains show that they had a sophisticated lifestyle, with human traits like caring for the infirm and the sick, and an advanced toolkit, including bone tools and body paint – complex behaviour that should only be possible if they had language. We also have some more direct anatomical evidence: traces of nerve pathways through bones in the skull suggest Neanderthals could control their vocalisations, for instance – an adaptation necessary for language that other apes lack. It also looks as if Neanderthals had many gene variants associated with processing language.

So it seems reasonable to assume that their speech would have been similar to our own, with the differences either being down to their vocal anatomy, the way their brains were

"Can we guess what Neanderthal speech sounded like? We think there is a way"

wired, or simply cultural evolution around the time they diverged from modern humans. The question is, can we guess what it sounded like?

Unlikely as it may seem, there is a way. Here's the rationale: when two groups that speak different languages come into contact, they exchange bits and pieces of language, like words or grammatical rules. Linguists can detect traces of such interactions even after thousands of years have passed. We know that once modern humans left Africa, they lived alongside Neanderthals and sometimes bred with them. They may have shared cultures, and there is evidence that Neanderthals gave our ancestors the idea for certain tools – so it seems likely they conversed too. The task, then, is to find out whether languages differ between the populations, mostly in Africa, that never came in contact with Neanderthals, and those that would have met them.

Eroded influences

The traces will be very faint and are probably reflected in a combination of features, just as differences between human populations are usually caused by variations in hundreds of genes rather than just one or two. To complicate matters further, these exchanges happened thousands of years earlier than most historical linguists would even dream of investigating – meaning that time could have eroded away the influence. Never mind looking for a needle in a haystack, it is like searching for a small patch of straw in a barn full of hay.

We certainly aren't ready to build a Neanderthal dictionary, but we have begun to investigate whether modern linguistics could, in principle, find any remains of our relatives' speech in today's languages. Then we can focus our search on more specific features.

Our starting point was the World Atlas of Language Structures, a database that documents hundreds of languages. We used a statistical method to split these into two groups, so that languages within one group were more similar to each other than to languages in the other group. We then tested whether there was a geographical divide between them, perhaps with one group mostly containing the African languages – as you might expect from our theory. Results were mixed, but comparing the overall structures – including things like word order and gender – showed a greater difference between African and non-African languages than simply comparing the vocabulary. This suggests that some kind of Neanderthal influence might linger in the grammar of non-African languages.

Along similar lines, we applied a separate technique that uses linguistic data to predict how populations must have migrated and mixed in order to arrive at today's language diversity. The best-fitting model supported the idea of two main founding populations, one in Africa, and a second that had outside influence from the Neanderthals.

Finally, we turned to methods originally used to study the divergence of species, to map out the family trees of different languages based on their related features. The trees predict when those features first emerged, so we can then look for aspects that change slowly and could still reflect interactions thousands of years ago. We could then find out if there are different patterns in the African and non-African language families. If so, they might be evidence of Neanderthal contact.

It is very tempting to jump on initial results. For instance, the way different languages mark possession proved to be one possible candidate. In African languages, possession is marked by an inflection that depends on the class of word – words about humans would have a different rule from words about inanimate objects, for instance. Eurasian languages don't make that distinction – "my dog" follows the same rule as "my son" or "my computer" – perhaps because the Neanderthals didn't either. But this could easily be a fluke result.

However, rather than a single feature, we expected there to be a more general "fingerprint" left on the languages touched by Neanderthal interactions. So we trained a machine-learning algorithm to rank how well different combinations of features could predict whether a language came from Africa, or elsewhere. African and non-African languages could be distinguished with over 90 per cent accuracy, but only by using a large number of features. This makes it difficult to say what caused this difference, but it's possible that something, such as conversations with Neanderthals, pushed the evolution of European and Asian languages in a different direction to those in Africa.

Race against time

Before celebrating these results, we must make sure the statistics don't pick up on other confounding factors. For instance, we are missing information on many of the world's languages, especially those with few speakers. Since the choice of data isn't random, any patterns that seem to emerge could be influenced by biases in the selection.

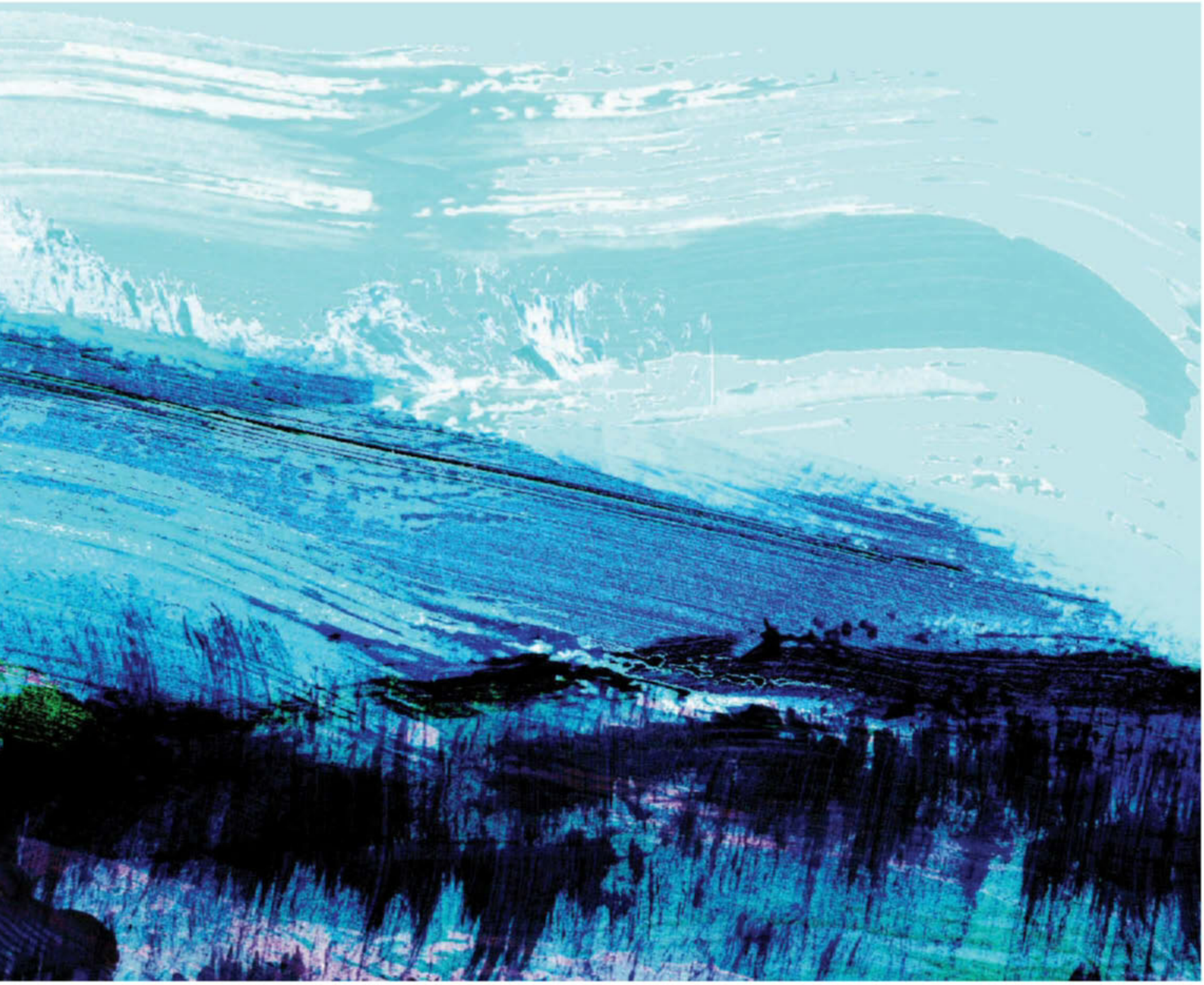
But the crucial point is that the methods seem to offer a way to test these ideas, and we won't even need a time machine to get the extra data we need; the secrets may be hidden in undocumented languages. Several large-scale language databases are already being put together, although we must act quickly given the saddening rate at which languages are dying. If that helps amplify the faint echoes of our cousin's voices, we will then be able to pick apart more specific features of their speech.

That could have important implications. The traditional view, championed by Noam Chomsky among others, is that the variation we see in world languages is constrained by our innate biases. But if these variations are, at least partly, the result of two different trajectories, one of which reflects Neanderthal biases as well as our own, we may be able to find new insights into the way genes and cultures interact to shape the words we speak.

The prospect may seem audacious, but 10 years ago, probing the Neanderthal genome was also a distant dream. Stranger things have certainly happened in science. ■

The others

We shared the planet with them for most of our existence, yet until recently we didn't even know they existed. Who were the Denisovans, asks Michael Marshall



SIMON PEMBERTON

THERE was very little to go on – just the tiniest fragment of a finger bone. What's more, it was clear that whoever it had once belonged to was long dead. This was the coldest of cold cases. Yet, there was also a suspicion that the remains, discovered in a cave high up in the Altai Mountains of southern Siberia, had a story to tell. So Michael Shunkov from the Russian Academy of Science bagged and labelled the shard, and sent it off for analysis.

At his lab in the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany, Svante Pääbo was just about to finish the first sequencing of a Neanderthal genome when the package arrived. He was perfectly placed to confirm Shunkov's suspicion. By comparing ancient DNA from the bone fragment with his sequence, Pääbo would surely show that it belonged to a Neanderthal. But they were all in for a surprise. The Siberian genome was quite unlike the Neanderthal's. And it didn't match that of any modern human. It was something completely new. Here was evidence that a previously unimagined species of humans had existed some 50,000 to 30,000 years ago – around the time when our own ancestors were painting their masterpieces in the Chauvet cave in France. "It was really amazing," says Pääbo.

Six years on, the new species has a moniker – Denisovan, after the cave where its remains were discovered. Our picture of these mysterious people is still being painstakingly pieced together. That first sliver of bone, together with a couple of teeth, is all we have to go on – there is still no body – but what these meagre remains have revealed is remarkable. The more we find out, the more we are forced to reconsider our own species. Far from being confined to Siberia, the Denisovans were more widespread than the Neanderthals with whom early *Homo sapiens* also shared the world. And they are not merely a historical curiosity – their genes live on today in some of us. The Denisovans challenge our conceptions of what it means to be human (see "Humanity in 96 genes", page 103).

The Denisova cave is named after a hermit called Denis who lived there in the 18th century. Human habitation there stretches back much further, however, as Russian palaeontologist Nikolai Ovodov discovered in the 1970s when he visited looking for remains of cave bears, and found ancient stone tools. Excavations have since unearthed several hundred artefacts revealing a human presence, on and off, lasting at least 125,000 years. Human fossils are rare, but ›

> **"If Denisovans lived in southern Siberia, how on earth did their DNA wind up in Melanesia?"**

by 2008, when Shunkov's team discovered the Denisovan bone fragment, archaeologists were convinced that the cave had been home to Neanderthals as well as early modern humans. The surprise addition of Denisovans to that mix makes the site a treasure trove for anyone interested in human origins. But there is a problem. The main inhabitants were not our ancestors, but hyenas, cave lions and cave bears. "Hyenas dig around and make dens, so they mix everything around," says Bence Viola, also at the Max Planck Institute in Leipzig. That makes it impossible to say when each group of hominins arrived and left, whether they overlapped, or which sets of tools belonged to whom.

Nifty finger work

Fortunately there is an alternative to the traditional archaeological approach. The past decade has seen an explosion of research on ancient DNA, much of it spearheaded by Pääbo, as geneticists figure out how to read ever-older genomes. Although DNA gradually breaks down, it does so in predictable ways, so we can work back and figure out what the original sequence was. DNA preserves best in cold areas, so in that respect the Denisova cave was ideal; it took just 30 milligrams of crushed bone to reveal an entirely new species.

Once Pääbo and his colleagues had uncovered the Denisovans, their first challenge was to figure out how the group fits into the human family tree. Their initial study, published in early 2010, sequenced the mitochondrial genome, a short packet of genes held in the sausage-shaped mitochondria that power animal cells. It suggested that Denisovans were quite distant relatives of ours, the two lines having separated long before the Neanderthals branched off.

But mitochondrial DNA can be misleading because it is inherited only from one's mother. To get a better picture, they needed to sequence the genome inside a cell nucleus.

This proved surprisingly straightforward. "Unlike the Neanderthal sequence, where we had to sweat blood, the Denisovan genome was of relatively high quality," says David Reich of Harvard Medical School in Boston. Within months, he and Pääbo had a draft sequence. It showed that the Denisovans were actually a sister group to Neanderthals. Our best estimates now suggest that their common ancestor branched off from our lineage around 600,000 years ago. Then Denisovans split from Neanderthals some 200,000 years later, perhaps parting ways in the Middle East, with Neanderthals heading into Europe and Denisovans into Asia. Given how recent the Denisova cave specimen is, it's quite plausible that the Denisovans were around for some 400,000 years. Modern humans have so far only managed 200,000.

With the bone sliver proving so enlightening, the hunt was on for more remains. In 2010, DNA analysis of a forgotten tooth found in the Denisova cave in 2000 revealed it too was Denisovan. Suddenly there were two fossils.

Archaeologists love teeth because they can reveal so much about an animal's body and habits, especially its diet. The specimen, a third molar – a wisdom tooth from the back of the mouth – should have been a vital clue, but it was singularly baffling. At almost 1.5 centimetres across, it is a whopper. That marks it as primitive: our apelike ancestors had larger teeth because they needed to grind up tough food like grasses. But by 50,000 years ago humans were eating softer foods, and their teeth had shrunk. The Denisovan tooth looks like a throwback. "It's probably the biggest in the last 2 million years," says Viola. Still, hominins with unusual teeth do sometimes crop up, and wisdom teeth are the most variable in the jaw, so this enormous gnasher could simply have been an anomaly.

Then, in August 2010, Denisova's archaeologists found another large tooth. Viola, who was present, thought it belonged to a bear but genetic analysis showed it to be Denisovan. It too was a wisdom tooth, although from a different individual, strengthening the case that the first was not unusual. "It probably means Denisovans in general had weird and big teeth," says Viola.

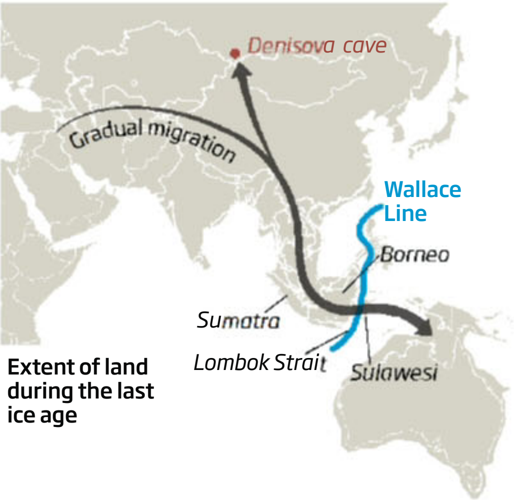
That hints at a fibrous, plant-based diet, but evidence for this idea is still lacking. Sometimes ancient teeth have the remains of food preserved on their surfaces. Not in this case – Viola has tried to recover plant microfossils and DNA, to no avail. His team has now taken moulds of both teeth and plans to reconstruct the scratches or "microwear" caused by chewing, which should provide a better idea of what the Denisovans ate.

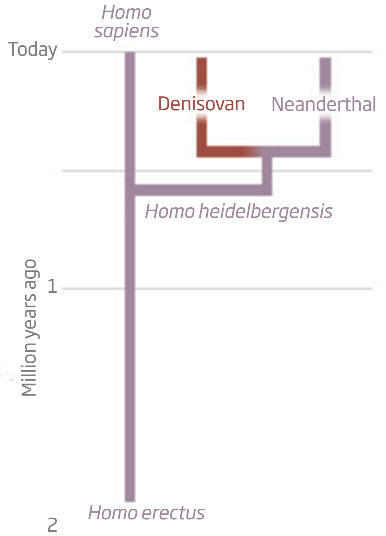
You can infer a lot about lifestyle from diet, such as whether people hunted, dug for roots and tubers, and had learned to use fire for cooking. The teeth surely have more to tell. Meanwhile, the nuclear genome has already revealed another secret about the Denisovans – one that changes everything.

When Pääbo and Reich published the first Neanderthal genome, the big news was that, on average, 1.7 per cent of the DNA in modern people other than Africans comes from Neanderthals. In other words, our ancestors interbred. Did they also interbreed with Denisovans? To find out, the geneticists

Denisovan odyssey

We know of the Denisovans through fossils in Siberia, but these ancient humans probably arose in the Middle East. They migrated south-east as well as north, and today their DNA clings on mostly in people living east of the Wallace line, suggesting that South-East Asia became their heartland





Humanity in 96 genes

The discovery that our ancestors lived alongside Denisovans and that some Denisovan genes linger on in modern humans challenges the way we see ourselves. It is now clear that modern humans are the product of a patchwork of species that evolved separately and then interbred. But studying the Denisovans should also help us answer a profound question: what makes us human?

Our closest living relatives are chimpanzees. We have evolved a great deal since the time of our common ancestor over six million years ago, but we do not know which genetic changes happened when we were still apelike, and which pushed us over the threshold into becoming fully human. To find out, we need to see how we differ from extinct species of hominins that existed as we were taking those steps in our evolution. "Neanderthals and Denisovans together are our closest evolutionary relatives," says Svante Pääbo at the Max Planck Institute for Evolutionary Anthropology in Leipzig, Germany. "They are the ones we need to look at."

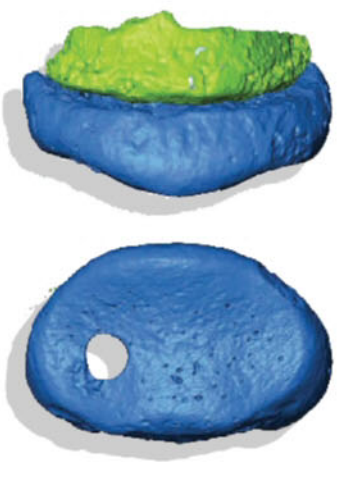
A CRIB CARD FOR HUMANITY

By comparing human, Neanderthal, Denisovan and chimp DNA, Pääbo has found 96 functional mutations – ones that alter the protein produced by a gene – that are unique to modern humans. In most cases we do not know what they do, but three are involved in cell division in the brain, suggesting they may have played a role in boosting our brainpower. In effect, Pääbo has identified a crib list of genes that were crucial in the very last stage of our evolution. And as we come to understand what differences they make to our psychology, physiology and biochemistry, we will get new insights into our evolution.

If the unexpected discovery of the Denisovans tells us anything, it's that there is still a lot to learn about human evolution. Despite decades of research, we had missed an entire species that lived relatively recently and was geographically widespread. Given that, it is a safe bet that we can expect plenty more surprises in the years to come.

A Neanderthal toe bone (above) reveals interbreeding with Denisovans

Two outsize teeth scraps of bone are all we possess of the Denisovans



BENCE VIOLA, MAX-PLANCK-INSTITUTE OF EVOLUTIONARY ANTHROPOLOGY

looked at the few parts of the genome that vary from person to person, searching for individuals who carry Denisovan versions of these sections. Most of the people they sampled had no sign of Denisovan DNA, even if they were from mainland Asia, where our ancestors might have been expected to run into Denisovans. However, as part of the Neanderthal study, the researchers had sequenced the genome of someone from Papua New Guinea. "That was a fortuitous choice," says Reich. "When you analysed the Papuan sequence, bang: you got this huge signal." More comparisons showed that other Melanesian people also carried Denisovan DNA, with an average 4.8 per cent of their genome coming from Denisovans.

Clearly interbreeding did occur. But if Denisovans lived in southern Siberia, how on earth did their DNA wind up in Melanesia, thousands of kilometres away across open sea? The most obvious explanation is also the most startling: Denisovans ranged over a vast swathe of mainland Asia and also crossed the sea to Indonesia or the Philippines. That means they had a bigger range than the Neanderthals. Alternatively, perhaps they interbred with modern humans on mainland Asia, and the descendants of such encounters later moved south-east, leaving no trace on the mainland. That would mean the Denisovans weren't as widespread as all that.

To figure out which was correct, Reich teamed up with Mark Stoneking at the Max Planck Institute in Leipzig to sequence the genomes of indigenous peoples from Asia, Indonesia, the Philippines, Polynesia, Australia and Papua New Guinea. They reasoned that if the interbreeding had happened on mainland Asia before people populated the islands, then people on all those islands should carry some Denisovan genes. But if Denisovans had reached the islands and interbred with humans already there, some isolated populations might be Denisovan-free. They found the latter pattern. "Island South-East Asia 45,000 years ago was a patchwork of populations, with and without Denisovan ancestry," says Reich. "That means it's unlikely the admixture happened on the mainland."

So the genetics is telling us that the Denisovans mated with early modern humans somewhere in what is now South-East Asia. If that is true, these people were formidable colonisers. From their origins at the split with Neanderthals, they appear to have made it out of the Middle East, spreading both north into Siberia and east to Indonesia and on to Melanesia. On their way, they would have › had to cross one of the greatest natural barriers on Earth: the Wallace line. It runs through the Lombok Strait, a deep sea channel separating the Indonesian islands of Bali and Lombok, and is traversed by a powerful current.

It is tempting to conclude that the Denisovans must have been skilled seafarers, perhaps piloting dugout canoes, but the crossings may have been accidental, says Chris Stringer of the Natural History Museum in London. He points to the Asian tsunami of 2004. "People were found on rafts of vegetation after a week at sea, 150 kilometres from where they started." Stringer proposes that some Denisovans lived in mangrove swamps close to the shore where seafood was plentiful, but where they were also vulnerable to tsunamis – which could have carried them together with buoyant swamp plants out to sea and, by chance, to another island. "OK, they've got to do it several times to go from Sulawesi to Flores. But given hundreds of thousands of years, it's possible." Only if Denisovans clearly moved rapidly from island to island is there any reason to suppose they used watercraft, he says.

During the last ice age, between 110,000 and 12,000 years ago, South-East Asia would have been an especially good place to live. Instead of lush forests, there were open grassy spaces. The ice at the poles locked up lots of water, lowering sea levels by tens of metres. As a result, Sumatra and Borneo were part of the mainland (see diagram, page 102). "At times of low sea level there was a whole continent exposed in South-East Asia which, when the conditions were relatively cool, would have been dry and ideal for hunter-gatherers," says Stringer. He thinks we have had the story of the Denisovans backwards: they may be named for a cave in Siberia, but that was not their usual abode. "South-East Asia was their centre, and they pulsed," he says. "When conditions were good they expanded north, and when conditions were bad those populations would have died out or disappeared."

The remains at Denisova are so sparse because Denisovans were hardly ever there. "Siberia may be the outer limit of their range." Indeed, the DNA in modern Melanesians, although clearly Denisovan, is different from the Siberian samples, suggesting that the northerners were outliers. What's more, a higher-quality version of the Denisovan genome published in 2012 reveals variants of genes that, in humans, are associated with dark skin, brown hair and brown eyes – consistent with the features of Melanesians today.


RIA NOVOSTI/SCIENCE PHOTO LIBRARY

Denisova cave in Siberia is a treasure trove for hominin-hunters

If the Denisovans' heartland was in South-East Asia, then that is where we should look for fossils. It may not even be necessary to dig for new evidence; many hominin specimens from this region have never been analysed. Good Denisovan fossils could be sitting in museum drawers, mislabelled as other species. But proving this will be a challenge because DNA breaks down quickly in a hot, humid climate. Still, Pääbo is setting up a new lab in Beijing, China, where researchers will attempt to extract ancient DNA from Asian fossils.

"There is still no body. Denisovans are a genome in search of a fossil"

"Our big hope is China," says Viola. However, he is also looking in colder countries including Uzbekistan and Kyrgyzstan.

So far, all these leads have drawn a blank. One problem, of course, is that we won't know what a Denisovan looks like until we find one. In theory, the genome could provide clues, but in practice even simple things like height are controlled by hundreds of genes. One clue has come from a surprising source. In late 2013, Pääbo's team obtained DNA from a specimen of *Homo heidelbergensis* found in a cave in northern Spain. At 400,000 years old, it is the oldest hominin genome ever read, and it was similar to that of Denisovans. As well as supporting the idea that *Homo heidelbergensis* was the common ancestor of Denisovans and Neanderthals, this specimen, and those found with it, may hint at the stature of their descendants. "These are big and robust guys, with body mass estimates around 100 kilograms," says Viola, which suggests that Denisovans were also large.

We don't know when the Denisovans became extinct, but some 400,000 years of evolution, as well as breeding with humans, may have changed their physical appearance. To confuse things further, it turns out that they also interbred with Neanderthals long after the split from their possible common ancestor *Homo heidelbergensis*. Pääbo and Reich recently compared DNA from a Neanderthal toe bone, found in the Denisova cave, with DNA from other Neanderthals, Denisovans and modern humans. At least 0.5 per cent of the Denisovan genome came from Neanderthals. The Denisovans also interbred with an unknown group, perhaps the last remnants of *Homo heidelbergensis*.

The revelations are likely to keep coming. Earlier this year, it emerged that the genes we inherited from Neanderthals affect skin and hair, and make people more vulnerable to certain diseases including type 2 diabetes. Now Reich's team is busy sequencing the genomes of more Melanesian people to figure out precisely which of their genes come from Denisovans. As well as indicating what these do today, it may reveal some of the ways in which the Denisovans were adapted to their Asian environment, including the local diseases to which they had developed resistance.

That first finger-bone fragment has divulged a wealth of genetic information, but there are key questions it cannot address. For instance, were Denisovans relatively simple-minded like their *Homo heidelbergensis* ancestors, or did they have the higher mental abilities of Neanderthals and early modern humans? DNA analysis cannot answer that, because we don't understand the genetic changes that made modern humans. But a skull with a big or small braincase would tell us. So the biggest challenge remains the same: to find a body. "Denisovans are a genome in search of a fossil," says Reich. ■

Raised by wolves

Our long affair with animals has been a driving force in human evolution, argues Pat Shipman

TRAVEL almost anywhere in the world and you will see something so common that it may not even catch your attention. Wherever there are people, there are animals: animals being walked, herded, fed, watered, bathed, brushed or cuddled. Many, such as dogs, cats and sheep, are domesticated, but you will also find people living alongside wild and exotic creatures such as monkeys, wolves and binturongs. Close contact with animals is not confined to one particular culture, geographic region or ethnic group. It is a universal human trait, which suggests that our desire to be with animals is deeply embedded and very ancient.

On the face of it this makes little sense. In the wild, no other mammal adopts individuals from another species; badgers do not tend hares, deer do not nurture baby squirrels, lions do not care for giraffes. And there is a good reason why. Since the ultimate prize in evolution is perpetuating your genes in your offspring and their offspring, caring for an individual from another species is counterproductive and detrimental to your success. Every mouthful of food you give it, every bit of energy you expend keeping it warm (or cool) and safe, is food and energy that does not go to your own kin. Even if pets offer unconditional love, friendship, physical affection and joy, that cannot explain why or how our bond with other species arose in the first place. Who would bring a ferocious predator such a wolf into their home in the hope that thousands of years later it would become a loving family pet?

"The human-animal link makes sense of three of the most important leaps in our development"

FERDINANDO SCIANNA/MAGNUM PHOTOS

I am fascinated by this puzzle and, as a palaeoanthropologist, I have tried to understand it by looking to the deep past for the origins of our intimate link with animals. What I found was a long trail, an evolutionary trajectory that I call the animal connection. What's more, this trail links to three of the most important developments in human evolution: toolmaking, language and domestication. If I am correct, our affinity with other species is no mere curiosity. Instead, the animal connection is a hugely significant force that has shaped us and been instrumental in our global spread and success in the world.

The trail begins at least 2.6 million years ago. That is when the first flaked stone tools appear in the archaeological record, at Gona in the Afar region of Ethiopia. Inventing stone tools is no trivial task. It requires the major intellectual breakthrough of understanding that the apparent properties of an object can be altered. But the prize was great. Those earliest flakes are found in conjunction with fossilised animal bones, some of which bear cut marks. It would appear that from the start, our ancestors were using tools to gain access to animal carcasses. Up until then, they had been largely vegetarian, upright apes. Now, instead of evolving the features that make carnivores effective hunters – such as swift locomotion, grasping claws, sharp teeth, great bodily strength and improved senses for hunting – our ancestors created their own adaptation by learning how to turn heavy, blunt stones into small, sharp items equivalent to razor blades and knives.
In other words, early humans devised an evolutionary shortcut to becoming a predator.

That had many consequences. On the

plus side, eating more highly nutritious meat and fat was a prerequisite to the increase in relative brain size that marks the human lineage. Since meat tends to come in larger packages than leaves, fruits or roots, meat-eaters can spend less time finding and eating food and more on activities such as learning, social interaction, observation of others and inventing more tools. On the minus side, though, preying on animals put our ancestors into direct competition with the other predators that shared their ecosystem. To get the upper hand, they needed more than just tools and that, I believe, is where the animal connection comes in.

Carnivore competition

Two and a half million years ago, there were 11 true carnivores in Africa. These were the ancestors of today's lions, cheetahs, leopards and three types of hyena, together with five now extinct species: a long-legged hyena, a wolf-like canid, two sabretooth cats and a "false" sabretooth cat. All but three of these outweighed early humans, so hanging around dead animals would have been a very risky business. The new predator on the savannah would have encountered ferocious competition for prizes such as freshly killed antelope. Still, by 1.7 million years ago, two carnivore species were extinct – perhaps because of the intense competition – and our ancestor had increased enough in size that it outweighed all but four of the remaining carnivores.

Why did our lineage survive when true carnivores were going extinct? Working in social groups certainly helped, but hyenas

"Domestication emerged as a natural progression of our close association with other species"

and lions do the same. Having tools enabled early humans to remove a piece of a dead carcass quickly and take it to safety, too. But I suspect that, above all, the behavioural adaptation that made it possible for our ancestors to compete successfully with true carnivores was the ability to pay very close attention to the habits of both potential prey and potential competitors. Knowledge was power, so we acquired a deep understanding of the minds of other animals.

Another significant consequence of becoming more predatory was a pressing need to live at lower densities. Prey species are common and often live in large herds. Predators are not, and do not, because they require large territories in which to hunt or they soon exhaust their food supply. The record of the geographic distribution of our ancestors provides more support for my idea that the animal connection has shaped our evolution. From the first appearance of our lineage 6 or 7 million years ago until perhaps 2 million years ago, all hominins were in Africa and nowhere else. Then early humans underwent a dramatic territorial expansion, forced by the demands of their new way of living. They spread out of Africa into Eurasia with remarkable speed, arriving as far east as Indonesia and probably China by about 1.8 million years ago. This was no intentional migration but simply a gradual expansion into new hunting grounds. First, an insight into the minds of other species had secured our success as predators, now that success had driven our expansion across Eurasia.

Throughout the period of these enormous changes in the lifestyle and ecology of our ancestors, gathering, recording and sharing knowledge became more and more advantageous. And the most crucial topic about which our ancestors amassed and exchanged information was animals.

How do I know this? No words or language remain from that time, so I cannot look for them. I can, however, look for symbols – since words are essentially symbolic – and that takes me to the wealth of prehistoric art that appears in Europe, Asia, Africa and Australia, starting about 50,000 years ago. Prehistoric art allows us to eavesdrop on the conversations of our ancestors and see the topic of discussion: animals, their colours, shapes, habits, postures, locomotion and social habits. This focus is even more striking when you consider what else might

MIKKEL OSTERGAARD/PANOS PICTURES

have been depicted. Pictures of people, social interactions and ceremonies are rare. Plants, water sources and geographic features are even scarcer, though they must have been key to survival. There are no images showing how to build shelters, make fires or create tools. Animal information mattered more than all of these.

The overwhelming predominance of animals in prehistoric art suggests that the animal connection – the evolutionary advantages of observing animals and collecting, compiling and sharing information about them – was a strong impetus to a second important development in human evolution: the development of language and enhanced communication. Of course, more was involved than simply coining words. Famously, vervet monkeys have different cries for eagles, leopards and snakes, but they cannot discuss dangerous-things-that-were-here-yesterday or ask "what ate my sibling?" or wonder if that danger might appear again tomorrow. They communicate with each other and share information, but they do not have language. The magical property of full language is that it is comprised of vocabulary and grammatical rules that can be combined and recombined in an infinite number of ways to convey fine shades of meaning.

Nobody doubts that language proved a major adaptive advantage to our ancestors in developing complex behaviours and sharing information. How it arose, however, remains a mystery. I believe I am the first to propose a continuity between the strong human-animal link that appeared 2.6 million years ago and the origin of language. The complexity and importance of animal-related information spurred early humans to move beyond what their primate cousins could achieve.

As our ancestors became ever more intimately involved with animals, the third and final product of the animal connection appeared. Domestication has long been linked with farming and the keeping of stock animals, an economic and social change from hunting and gathering that is often called the Neolithic revolution. Domestic animals are usually considered as commodities, "walking larders", reflecting the idea that the basis of the Neolithic revolution was a drive for greater food security.

When I looked at the origins of domestication for clues to its underlying reasons, I found some fundamental flaws in this idea. Instead, my analysis suggests that domestication emerged as a natural progression of our close association with, and understanding of, other species. In other words, it was a product of the animal connection.

Man's best friend

First, if domestication was about knowing where your next meal was coming from, then the first domesticate ought to have been a food source. It was not. According to a detailed analysis of fossil skulls carried out by Mietje Germonpré of the Royal Belgian Institute of Natural Sciences in Brussels and her colleagues, the earliest known dog skull is 32,000 years old. The results have been greeted with some surprise, since other analyses have suggested dogs were domesticated around 17,000 years ago, but even that means they predate any other domesticated animal or plant by about 5000 years (see diagram, left). Yet dogs are not a good choice if you want a food animal: they are dangerous while being domesticated, ›

Our family and other animals

Across the globe and over thousands of years, humans have domesticated scores of animal species, using a deep insight into their lives to alter aspects of their behaviour, physiology and life cycle

Dog *(Canis lupus familiaris)*
32,000 years ago
East Africa
Hunting, guarding, herding, companionship, pest control, transport

Cat *(Felis silvestris catus)*
9500 years ago
Middle East, North Africa
Pest control, companionship

Guinea pig *(Cavia porcellus)*
7000 years ago
Peru
Meat, companionship

Horse *(Equus ferus caballus)*
6000 years ago
Eurasian steppes
Transport, strength, milk, meat

Asian elephant *(Elephas maximus)*
5000 years ago
Pakistan
Strength, transportation

Yak *(Bos grunniens)*
4500 years ago
Tibet
Milk, strength, wool, meat

Budgerigar *(Melopsittacus undulatus)*
150 years ago
Australia
Companion

being derived from wolves, and worst of all, they eat meat. If the objective of domestication was to have meat to eat, you would never select an animal that eats 2 kilograms of the stuff a day.

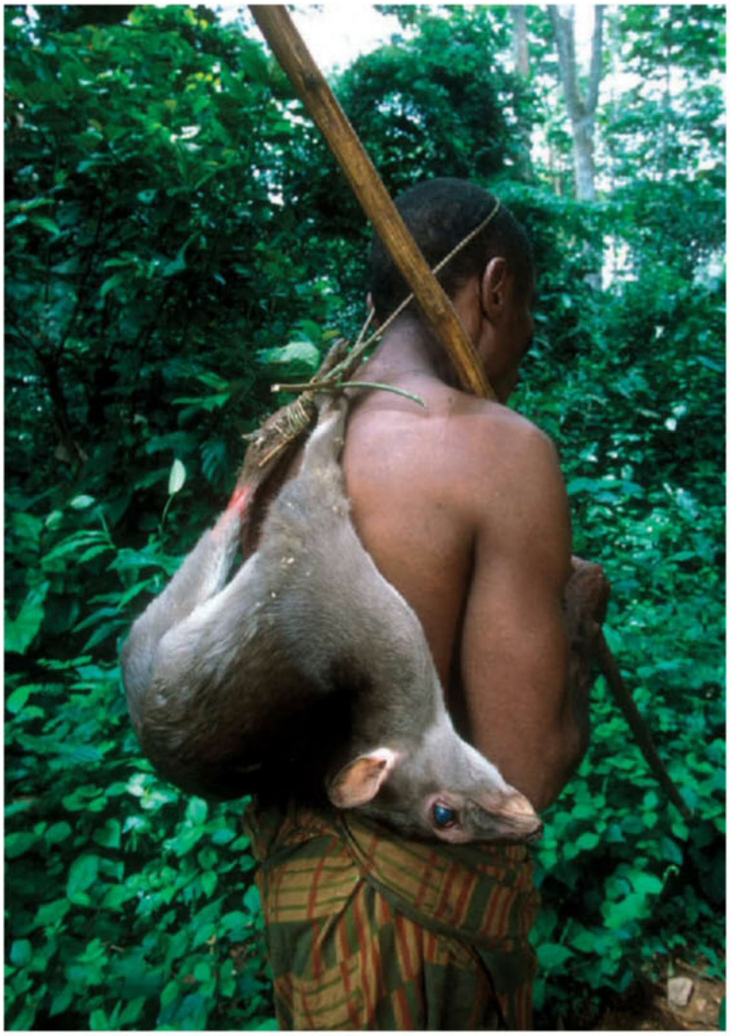
A sustainable relationship

My second objection to the idea that animals were domesticated simply for food turns on a paradox. Farming requires hungry people to set aside edible animals or seeds so as to have some to reproduce the following year. My Penn State colleague David Webster explored the idea in a paper published in 2011. He concluded that it only becomes logical not to eat all you have if the species in question is already well on the way to being domesticated, because only then are you sufficiently familiar with it to know how to benefit from taking the long view. This means for an animal species to become a walking larder, our ancestors must have already spent generations living intimately with it, exerting some degree of control over breeding. Who plans that far in advance for dinner?

Then there's the clincher. A domestic animal that is slaughtered for food yields little more meat than a wild one that has been hunted, yet requires more management and care. Such a system is not an improvement in food security.

"If our species was born of a world rich with animals, can we flourish in one where biodiversity is decimated?"

Hunting was the spur for our ancestors to acquire deep insights about other species



MARTIN HARVEY/CORBIS

Instead, I believe domestication arose for a different reason, one that offsets the costs of husbandry. All domestic animals, and even semi-domesticated ones, offer a wealth of renewable resources that provide ongoing benefits as long as they are alive. They can provide power for hauling, transport and ploughing, wool or fur for warmth and weaving, milk for food, manure for fertiliser, fuel and building material, hunting assistance, protection for the family or home, and a disposal service for refuse and ordure. Domestic animals are also a mobile source of wealth, which can literally propagate itself.

Domestication, more than ever, drew upon our understanding of animals to keep them alive and well. It must have started accidentally and been a protracted reciprocal process of increasing communication that allowed us not just to tame other species but also to permanently change their genomes by selective breeding to enhance or diminish certain traits.

The great benefit for people of this caring relationship was a continuous supply of resources that enabled them to move into previously uninhabitable parts of the world. This next milestone in human evolution would have been impossible without the sort of close observation, accumulated knowledge and improved communication skills that the animal connection started selecting for when our ancestors began hunting at least 2.6 million years ago.

What does it matter if the animal connection is a fundamental and ancient influence on our species? I think it matters a great deal. The human-animal link offers a causal connection that makes sense of three of the most important leaps in our development: the invention of stone tools, the origin of language and the domestication of animals. That makes it a sort of grand unifying theory of human evolution.

And the link is as crucial today as it ever was. The fundamental importance of our relationship with animals explains why interacting with them offers various physical and mental health benefits – and why the annual expenditure on items related to pets and wild animals is so enormous.

Finally, if being with animals has been so instrumental in making humans human, we had best pay attention to this point as we plan for the future. If our species was born of a world rich with animals, can we continue to flourish in one where we have decimated biodiversity? ■

CALL FOR ENTRIES

ConocoPhillips

University of St Andrews

THE ST ANDREWS PRIZE FOR THE ENVIRONMENT

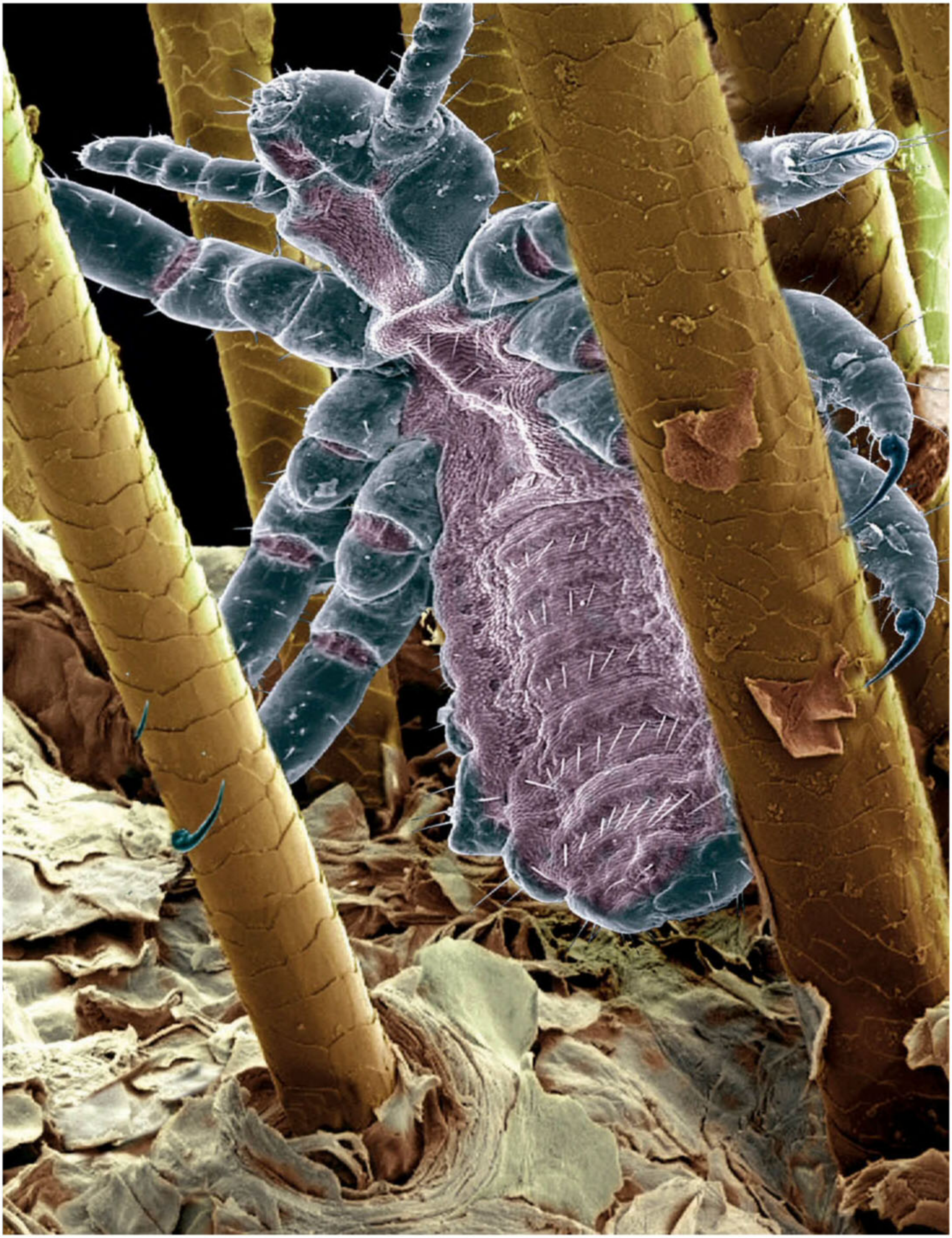
ARE YOU DOING SOMETHING SPECIAL FOR THE ENVIRONMENT?

The aim of the Prize is to promote a practical solution to an environmental problem, with particular interest in projects that can be replicated in several regions, thereby increasing overall effectiveness and help to those who need it most. The Prize is open to entrants from anywhere in the world.

THE WINNER RECEIVES $100,000 USD AND TWO RUNNERS-UP WILL EACH RECEIVE $25,000 USD

First stage submissions are required by 31 October 2014

Find out more at **www.thestandrewsprize.com**



STEVE GSCHMEISSNER/SCIENCE PHOTO LIBRARY

Of lice and men

Scratch the surface of our long relationship with parasites and you discover some unsavoury details of human evolution, says Rob Dunn

YOU have probably never heard of Henry Ewing and his adventures with lice. Yet back in the 1930s, Ewing made two key discoveries that must surely earn him the title "grandfather of lousy research".

First, in a show of commendable self-sacrifice, he pulled lice from a spider monkey and a "baboonlike monkey" at the National Zoo in Washington DC and let each suck blood from his own arm. Both promptly died, suggesting they were so exquisitely adapted to their host they could not survive on another species. Ewing worked at the US Department of Agriculture, but his second breakthrough was made while big-game hunting in Africa. It pertains to the surprising origins of the human pubic louse. More on that later, but suffice to say that the two findings stand as pillars of louse knowledge today.

We now know that there are more than 3000 species of louse, wingless insects of the order Phthiraptera. They parasitise every order of birds and almost all mammals, with the exception of cetaceans, bats, monotremes, pangolins and an odd species here and there. Ewing's belief, that the fate of each species of sucking louse is intimately bound to that of its host, is now accepted as a truism. We also know that lice occasionally jump ship to begin an association with a new host species, as the pubic louse story will show. As a result, these parasites provide invaluable insights into the evolutionary stories of their hosts – including their interactions with other louse carriers. Now a new generation of louse enthusiasts is using this knowledge to uncover fascinating, though sometimes unsavoury, details about human prehistory.

Sucking life

Most lice are scavengers, feeding on skin and other debris found on their host's body. We and other primates, however, are unfortunate enough to be afflicted by a group known as sucking lice. Once hatched, these bite into our capillaries to drink our blood, before mating and feeding again. Then they lay their eggs, also known as nits, on our hair and die. Most primates host just one species of louse, their fur forming a single habitat stretching from face to anus to toes. Orang-utans and gibbons have escaped lice altogether. But we humans, with our patchy distribution of hair and our penchant for wearing clothes, are home to three kinds of lice. On the upside, they have at least three different stories to tell about our evolution.

Let's start with the head louse (*Pediculus humanus*). Even before Ewing, it was considered the original variety, the louse that once climbed everywhere upon us like the fur lice of other primates. That being so, head lice should, of all human lice, be most closely related to those of chimpanzees (*P. schaeffi*), the two having diverged when our ancestors climbed down from the trees and went their separate way from the ancestors of chimps. Back in the 1930s, this idea was difficult to test, but modern genetic sequencing techniques have changed all that.

In 2004, David Reed at the University of Florida, Gainesville, and colleagues used DNA analysis to examine the evolutionary tree of head lice and chimp lice. Counting the number of mutations in two mitochondrial genes – which tend to mutate at a regular rate – and using these as a molecular clock, they estimated that the two species had a common ancestor around 6 million years ago.

That is exactly what you would expect if head lice evolved following the split between chimp and human ancestors, which occurred between 6 and 8 million years ago. But Reed's team made another, more surprising discovery – there is not just one type of head louse. To date they have found three › lineages, which, although they look identical, are more different from each other genetically than are chimps and humans. One is found everywhere in the world; the other two have limited distributions – the first in the Americas and Asia and the second only in Nepal and Ethiopia, at least so far. The researchers suggest that these two minor lineages derived from a louse that evolved on an ancient species of hominin in Asia and transferred onto anatomically modern humans before its original host became extinct. Then, much later, some descendants of these lousy humans migrated into America, taking one of the newer lineages with them. It is an idea that needs further testing, but if correct it would record the meeting – head to head – of our ancestors and another species of archaic human.

Whatever the origin of these lineages, their existence reflects the human story as much as it does that of lice. As our ancestors spread around the world, among the few things they carried everywhere were their head lice. Presumably as these early peoples moved into new environments their parasites evolved, adapting to different climates but also to changes in human bodies, including hair type and even immune function. With time and more research, the lice will tell.

Meanwhile, we have already unravelled another story of human evolution by looking closely at the pubic louse (*Phthirus pubis*), also known as crabs or trouser shrimps. You might suspect that it evolved from the head louse following our ancestors' loss of body fur and acquisition of coarse pubic hair, which is too thick for head lice to cling onto. But the two look nothing like each other. Head lice are dainty ballerinas on the stage of our scalp. Their pubic counterparts are wide and stumbling with large pincers, like a cross between the Hindu god Ganesh and a crab.

Until the 1930s, no one had seen another louse even remotely fitting this description. Then Ewing went hunting in Africa and, on the still warm body of a gorilla, found one. On the basis of its appearance, Ewing suggested the gorilla louse (*Phthirus gorillae*) was the closest living relative of the pubic louse. It was a lunatic idea. Lice cannot jump and they quickly dry out when separated from their moist hosts – which is, incidentally, why you are very unlikely to get crabs from a toilet seat. Ewing's idea required our ancestors to have cosied up to ancient gorillas. Surely not?

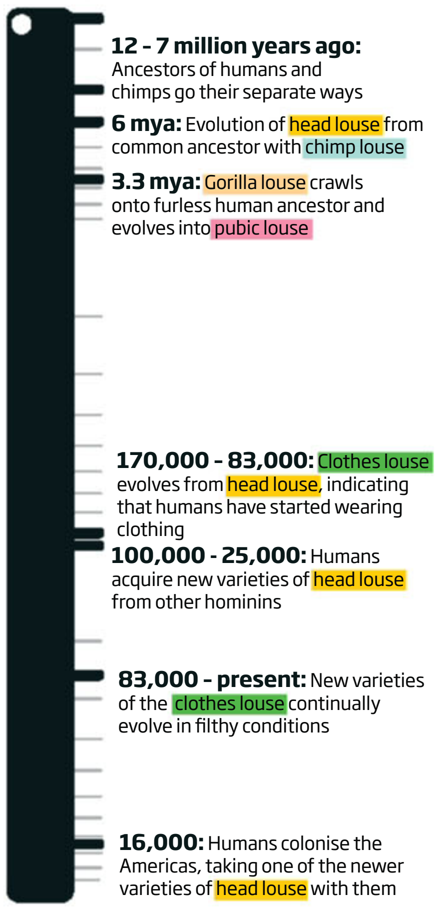
It would be a new century before Ewing's dangerous idea was vindicated. In 2006, Reed compared the genes of pubic lice and gorilla lice. Bingo! The two species were clearly sucking cousins, far more closely related to each other than to human head lice. Given how genital lice spread today, Reed's discovery sparked much media speculation about our ancestors' sexual proclivities. But perhaps the explanation is more innocent. Maybe our forebears simply ate the forebears of gorillas and their lice took the opportunity to scurry from prey to predator, hair to hair. One can hope.

The gorilla switch tells a story about the behaviour of our ancestors. It may also hold a clue about when we lost our fur. Until then "head" lice would have roamed freely across our bodies and there would have been no separate niche for pubic lice to colonise. Using mutations in junk DNA as a molecular clock, Reed's team calculated that gorilla and pubic lice went their separate ways around 3.3 million years ago. Our body hair, Reed contends, has been missing at least as long.

The third chapter in the story of lice and men came when prehistoric humans began covering their nakedness, thus providing a potential new home for a third type of louse. Clothing lice – sometimes called body lice, although this is a misnomer as they require clothing to attach to – resemble a bigger, tougher version of the head louse. There is no doubt the two are closely related and some people even believe they are the same species, just with idiosyncratic behaviours. There is

Lousy past

The evolution of the three types of human louse hold clues about developments in our past



SUZI ESZTERHAS/MINDEN PICTURES/FLPA RIGHT SUTHEP KRITSANAVARIN/ZUMA PRESS/EYEVINE

> "Given how genital lice spread today, the discovery of their similarity to gorilla lice sparked much speculation about the sexual proclivities of our ancestors"

A TRULY ANCIENT ITCH

Lice don't just hold secrets about human evolution: they can also tell us about the earliest mammals and birds. We know that both groups of animals emerged before the demise of the dinosaurs, 65 million years ago. What is not clear is whether they thrived alongside dinosaurs and suffered a mass extinction as a result of the extraterrestrial impact and volcanism that killed off their reptile neighbours, or whether most modern birds and mammals evolved later, from orders that arose during the time of the dinosaurs. The fossil record is too sparse to resolve this debate, so Vince Smith at the Natural History Museum in London and colleagues turned to lice.

Today there are thousands of species of parasitic lice. Because their fates and those of their hosts are inextricably linked, so are their histories. By comparing genetic sequences in a wide variety of lice, the researchers were able to construct a family tree establishing the ages of the major lineages. This indicated that parasitic lice emerged between 130 and 115 million years ago, earlier than previously thought, and early enough for the first lice to have clung to the first stubby feathers growing out of dinosaurs. The analysis also revealed that many lice found on modern birds and mammals can trace their lineage beyond 65 million years.

It would appear that many of today's birds and mammals – including our own forebears – are descended from groups that evolved before the dinosaurs became extinct. Our heritage is far more ancient than many had thought, or at least that is what the lice say.

Business and pleasure: nit-picking is part of life for most primates

one key difference, however. While head lice will make you itch, clothing lice carry the bacteria that cause typhus, trench fever and relapsing fever. So an infestation is not merely uncomfortable: it can kill.

These deadly parasites arose following the invention of clothing, but when was that? The archaeological record is not very helpful. The oldest hide-scrapers are half a million years old, but they might have been used for something other than making clothes. Eyed needles, for sewing, appear far more recently, 40,000 years ago. So what do the lice tell us?

The first attempt to date the origin of clothing lice using molecular clocks put it at about 100,000 years ago. More recent research by a team including Reed suggests they might have emerged somewhat earlier. Comparing the sequences of four genes in head lice and clothing lice, they calculate that a common ancestor of the two lived at least 83,000 but possibly as much as 170,000 years ago. This predates a period of global cooling in which clothes might have proved an innovation that helped early humans outcompete other hominins.

This tells us two things: our ancestors were naked for a very long time; and when they did start dressing, head lice adapted to fill the niche. The ancestry confirms what many had suspected. However, another study indicates that there is more to the story. Using a new genetic approach able to reveal differences between individual lice, a team from Reed's lab found that clothing lice have emerged not just once, but on multiple occasions throughout human history. How to explain this?

One clue comes from experiments done more than half a century ago in which hardy volunteers had head lice attached to their bodies in small pillboxes, the insides of which were woven fibre, like clothing. Amazingly, within five generations the head lice had taken on the form of clothing lice, suggesting that they are able to evolve very rapidly. These changes were associated with massive initial mortality that declined with each generation. Yet head louse generation times are so short that the whole process took just a few months. Clothing lice thrive in filthy conditions, so it is possible that they have emerged again and again whenever war, calamity and poverty have provided opportunities.

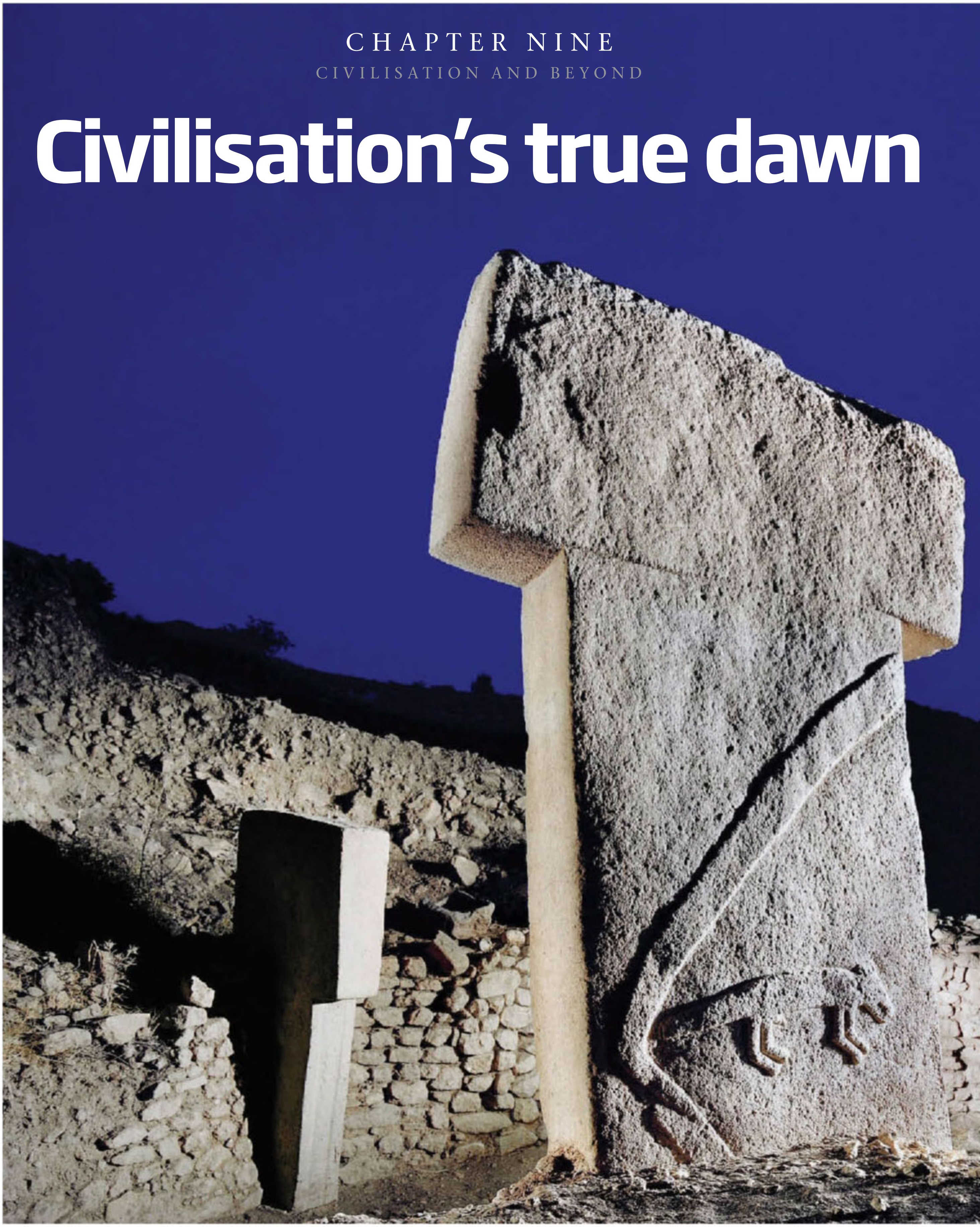
Reed points out that where people live in unhygienic conditions head lice become abundant and some might shift on to the body. Although most would not survive, a few that happen to have the right genetic make-up would evolve rapidly, giving rise to a new lineage. He believes this might also help explain why clothing lice alone carry diseases. If they only evolve under conditions that promote high densities of lice, and can reach densities much higher than head lice, these densities – rather than any attribute of the lice themselves – increase the odds that they will carry pathogens. Perhaps, then, clothing lice transmit disease because they are especially abundant, not because they are special.

Since the first parasitic louse evolved over 100 million years ago, lice have tracked the division of continents and the spread of our ancestors. The three species that call us home each has its tale to tell, but we have not yet reached the end of the story. Today we use a range of pesticides to try to eradicate lice. Instead of dying out, they are evolving again. As increasing numbers become resistant to pesticides including malathion, pyrethrin and DDT, we cannot predict what forms our personal parasites will take in the coming millennia. What we can say, though, is that their future will be intimately linked with ours. The lice will continue to do what they do, clinging to their one necessity. If nothing else, they are tenacious, and it is this tenacity that produces such great stories. ■

CHAPTER NINE

CIVILISATION AND BEYOND

Civilisation's true dawn



BERTHOLD STEINHILBER/LAIF/CAMERAPRESS

What really drove our ancestors to give up a lifestyle that had served them for millennia and invent a whole new one? **David Robson** reports

Göbekli Tepe: the world's first temple in southern Anatolia

WHEN Steven Mithen's team began to dig through the desert soil, his expectations were low. "We thought it was just a big rubbish dump," he says.

Still, the prospect of rifling through trash was cause for some satisfaction. Mithen, an archaeologist at the University of Reading, UK, initially raised a few eyebrows when he told colleagues of his plans to dig for Stone Age ruins in south Jordan. "They said we'd never find anything there – it was a backwater," says Mithen. He proved them wrong by finding the remains of a primitive village. By sifting through its rubbish, he hoped to gain a glimpse of day-to-day life more than 11,000 years ago.

But as they dug through the detritus, one of his students came upon a polished, solid floor – hardly the kind of craftsmanship to waste on a communal tip. Then came a series of platforms engraved with wavy symbols. The excitement grew. "We were staggered day by day to find it getting larger, more complex, more peculiar," he says. "I'd never seen anything like it before. It was literally a moment when all your ideas change."

Mithen now compares the structure to a small amphitheatre (see picture, page 116). With benches lining one side of a roughly circular building, it looks purpose-built for celebrations or spectacles – perhaps feasting, music, rituals, or something more macabre. Pointing out a series of gullies running down through the floor, Mithen wonders whether sacrificial blood might have once flowed in front of a frenzied crowd.

Whatever happened at the place now known as Wadi Faynan, the site could transform our understanding of the past. At 11,600 years old, it predates farming – which means that people were building amphitheatres before they invented agriculture.

It wasn't supposed to be that way. Archaeologists have long been familiar with the idea of a "Neolithic revolution" during which humans abandoned the nomadic lifestyle that had served them so well for millennia and settled in permanent agrarian communities. They domesticated plants and animals and invented a new way of life. ("Neolithic" means "new stone age".)

By about 8300 years ago, people in the Levant – modern-day Syria, Lebanon, Jordan, Israel, the Palestinian territories and parts of southern Anatolia – had the full package of Neolithic technologies: settled villages with communal buildings, pottery, domesticated animals, cereals and legumes. Art, politics and astronomy also have their roots in this ›

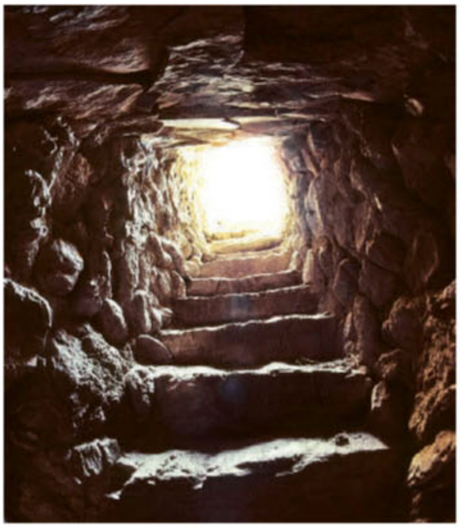
TOWER OF POWER

It has been called the world's first skyscraper. Eleven thousand years ago, a society of hunter-gatherers built an 8-metre tall tower and staircase out of stone – for no apparent reason.

Ever since it was discovered, the Tower of Jericho has puzzled archaeologists. Some have suggested that it was built as a watchtower, but there's no evidence of any invasions. Instead, the tower might have been a way for the first villagers to bond.

Roy Liran and Ran Barkai at Tel Aviv University, Israel, recently simulated the way the tower would have looked during the summer solstice. They found that the shadows of the surrounding hills would have first enveloped the tower as the sun set, creating an image full of foreboding. The eerie effect could have been used by the village chiefs, they say, to scare their brethren into working harder.

NATHAN BENN/OTTOCHROME/CORBIS



"Instead of farming, very different motivations seem to have brought people together – things like religion, culture and feasting"

time. "It's one of the most important shifts in history," says Jens Notroff at the German Archaeological Institute in Berlin.

And yet here was a settlement more than 3000 years older displaying many of those innovations, but lacking the technology that is supposed to have got the whole thing started: farming. The people who built Wadi Faynan were not nomads, but neither were they farmers. They probably relied almost exclusively on hunting and gathering.

Instead of agriculture, then, some very different motivations seem to have drawn these people together – things like religion, culture and feasting. Never mind the practical benefits of a steady food supply; the seeds of civilisation may have been sewn by something much more cerebral.

For much of the 20th century our view of the Neolithic was seen through the lens of a more recent social upheaval: the industrial revolution. The idea originated, in part, with Marxist archaeologist Vere Gordon Childe. Seeing the urban societies that had coalesced around factory towers and "dark satanic mills", Childe suspected that the first farms could have been similar hotbeds of rapid social and cultural change.

Driven to extremes

He proposed that it began in the Levant around 10,000 years ago. As the ice age ended, the region became more arid, save for smaller patches of lush land by rivers. With these limited areas to forage, nomadic hunter-gathers discovered that it was more efficient to cultivate barley and wheat in one place. A baby boom followed. As Childe put it in his 1936 book *Man Makes Himself*: "If there are more mouths to feed, there will also be more hands to till the fields… quite young toddlers can help in weeding fields and scaring off birds." And as the farmers' crops and families blossomed, so too did their crafts, including carpentry and pottery, along with greater social complexity as the groups began to organise their activities around their work. The growing communities would have also been fertile ground for more organised forms of religion to flourish.

At least, that was the theory. *Man Makes Himself* became a touchstone for many archaeologists – even as cracks began to appear in some of its assumptions. Studies of the climate, for instance, suggest the changes following the ice age were not nearly as radical as Childe believed. Without the environmental spark, there were doubts that agriculture offered any real benefits. Particularly when you only have a few bellies to fill, plundering nature's larder is just as efficient as the back-breaking business of planting, weeding, and harvesting. So why change?

By the 1990s, those cracks had turned to gaping chasms, following digs in Anatolia, Turkey. The region was already attracting attention for a site known as Nevali Çori, which was around 10,000 years old. Although it seemed to be a simple settlement of proto-farmers, the archaeologists also uncovered signs of more advanced culture, embodied in a series of communal "cult buildings" full of macabre artwork.

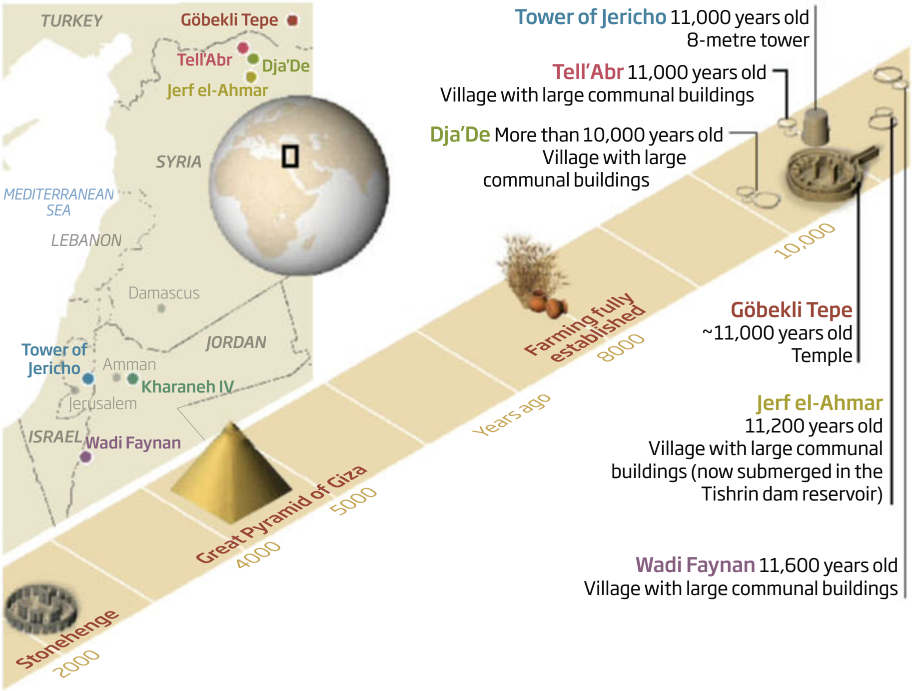
The buildings were remarkably large and complex for something so old. And what they

STEVE MITHEN

contained was even more revealing. In one sculpture, a snake writhes across a man's head; another depicts a bird of prey landing on the heads of entwined twins. The most eye-catching feature was a collection of strange, anthropomorphic T-shaped megaliths with faceless, oblong heads and human arms engraved on their sides. As people sat on benches around the walls of the buildings, these monuments must have loomed over them like sentinels.

Monumental discoveries

Recent finds in the Levant suggest that people were living in large settlements and building temples long before they invented agriculture



Lost society

Sadly, the site was submerged when the Atatürk dam was built across the Euphrates. But one of the archaeologists, Klaus Schmidt of the German Archaeological Institute, set about scouring the surrounding countryside for further clues to the origins of this lost society. During this tour he found himself on a mound called Göbekli Tepe. The grassy knoll was already popular with locals visiting its magic "wishing tree", but what really caught Schmidt's eye was a large piece of limestone that closely resembled those T-shaped megaliths from Nevali Çori.

It didn't take him long to realise he had stumbled on something even more extraordinary. Buried beneath the hill, he found three layers of remains. The oldest and most impressive was more than 11,000 years old, with a labyrinth of circular "sanctuaries" measuring up to 30 metres in diameter. Around the inner walls were magnificent, T-shaped monuments encircling two larger pillars, like worshippers surrounding their idol. "They appeared to be everywhere," says Notroff, one of Schmidt's colleagues.

Some were engraved with belts and robes, and given their monumental size – around three times the height of a modern man – and abstract appearance, Schmidt (who died in July 2014) interpreted them as representing some kind of godlike figure. Others bear grotesque carvings of wild beasts such as snakes, scorpions and hyenas. To Schmidt, the images brought to mind the horrific scenes in Dante's *Inferno*.

If Nevali Çori was a humble parish church, then this was a cathedral. Strangely, each sanctuary seems to have been dismantled and deliberately filled in sometime later, perhaps as part of a ritual. Amid the jumble of debris, Schmidt's team found many bones, including human remains. His team also found a surprisingly high number of rooks and crows – birds that are known to be drawn to corpses. For this reason, Schmidt's team believe that some of the buildings' functions may have centred on death.

We can never know what happened there, but Schmidt had some suspicions. From the outset, he was fascinated by strange door-like "porthole stones", found within the sanctuaries and often decorated with grisly images of predators and prey. Since the holes in the middle are often the size of a human body, Schmidt imagined that visitors might have crawled through to symbolise the passage into the afterlife.

It is clear that Göbekli Tepe was the creation of a sophisticated society, capable of marshalling the labour of perhaps hundreds of people. "It suggests organisation and cooperation," says Notroff. "That degree of social complexity just wasn't expected in emerging early Neolithic cultures."

Along with the complex artwork and intricate ideology, this kind of development was supposed to come long after agriculture. Yet Schmidt failed to find any signs of farming. Domesticated corn can be distinguished from its wild ancestor by its plumper ears, but there was no trace of it. Stranger still, there is no sure evidence of any kind of permanent settlement at Göbekli Tepe. According to Schmidt, it was too far away from water supplies, and he found little evidence of the hearths, firepits or tools you might expect in a dwelling.

His conclusions were radical. He proposed that Göbekli Tepe was a dedicated site of pilgrimage, perhaps the culmination of a long tradition of gatherings and celebrations. Importantly, it was ideology, rather than farming, that was pulling these people together to form a larger society.

Indeed, it may have been the need to feed people at these kinds of gatherings that eventually led to agriculture – which turns the original idea of the Neolithic revolution on its head. "Rituals and feasts may have been the impetus to motivate people to gather on certain occasions at certain places," says Notroff. "Maybe, new food sources and processing techniques were explored to feed this demand." Tellingly, genetic work pinpoints the origin of domestic wheat to a spot very close to Göbekli Tepe.

Alternatively, agriculture could have been an accidental by-product of social gatherings where large quantities of wild food plants were consumed and their seeds dropped, creating a cycle of unintentional cultivation. "My guess is that domesticated plants fall out almost by accident, due to intensive exploitation of wild plants that is demanded by the communal activities," says Mithen. Some researchers now argue that domestication of animals, particularly wild cattle, also has spiritual rather than economic roots (see "Sacred cows", page 118).

Schmidt's finds astonished archaeologists and captivated the wider world. The "first temple" soon began attracting a new swarm of pilgrims, with film-makers, archaeologists and tourists flocking to visit. "It was extraordinary," says George Willcox of the Archéorient Laboratory of the French National Centre for Scientific Research in Jalès, who has visited the site. "People just couldn't believe it was Neolithic." ›

The "amphitheatre" at Wadi Faynan: evidence of monumental architecture 11,600 years ago

SACRED COWS

By David Lewis-Williams and David Pearce

Domestication of plants in the Neolithic Middle East is often explained in economic terms, as a labour-saving device or an attempt at food conservation. In the light of new finds (see main story), this long-accepted explanation is no longer convincing.

It now appears that the human mindset began to change before the economy changed. It began with nomadic hunters and gatherers coming together for ritual purposes at places like Göbekli Tepe. As some laboured, probably seasonally, on the construction of the monuments, others gathered wild grains to feed them. Some grain dropped near the temporary settlement. By a process of repetition and gathering the nearest plants first, wheat was gradually and accidentally domesticated.

What of animals? Could "accident" have played a role there too?

We argue that the domestication of animals had its conceptual roots in hunter-gatherer societies of the Upper Palaeolithic (around 20,000 to 12,000 years ago). Cave art suggests that people at that time had settled on a bestiary of species with special significance beyond pure economics.

The core species of Upper Palaeolithic art were aurochs, horses, bison and felines. Other species, such as mammoths, were added and discarded in some areas, but there was never a time when Upper Palaeolithic cave artists painted whatever took their fancy, such as predominantly human faces trees, or hares. The image-makers focused on creatures that were believed to be spiritually powerful.

What we call "conceptual domestication" of certain – largely herd – animals was already part of people's thinking long before they began to drive and corral animals.

We still see this in modern foraging societies such as the San of southern Africa, where the social status of "ritual specialists" (similar to shamans) frequently rests on their intimate relations with powerful spirit animals. Often, these animals are big cats – the ultimate, intractable wild creatures. But this sort of relationship extends to the control of economically beneficial species, such as antelope.

The striking carvings at Göbekli Tepe suggest that around 11,000 years ago, a similar "spiritual" relationship may have existed with numerous creatures: birds, felines, foxes, aurochs and even insects.

At later sites, the relationship begins to focus on more easily corralled animals, such as pigs and sheep. However, because ritual specialists find power in wild animals rather than those that have been domesticated and thereby trivialised, this trend eventually focused on herds of wild aurochs.

Possibly, people already believed that these wild herds were under the control of ritual specialists. Actual domestication, by driving and corralling, was a logical next step, as it would have been a visible manifestation of the ritual specialists' power. People did not invent domestication of animals for economic purposes: they did so for socio-religious ones.

VINCENT J. MUSI/NGS

Passage to the afterlife? One of the "porthole stones" from Göbekli Tepe

Some researchers are dubious. The original peoples' habit of periodically burying their sanctuaries means there is always the possibility that old remains were dug up to dump on the monuments, rather than contemporary debris. That would shave hundreds or thousands of years off the age of the temple, making it much less revolutionary.

Others doubt Schmidt's claims that Göbekli Tepe was a pilgrimage site rather than a permanent settlement. "I think the evidence is weak," says Edward Banning at the University of Toronto, Canada. Take the apparent lack of a water supply. Banning points out that rivers and springs that once watered the site may have long since dried up without leaving a trace. The extravagant artwork, meanwhile, could just be house decorations. "It's quite possible to have domestic structures that are heavily invested in symbolism," he says – just look at the way people today hang crucifixes and icons in their kitchens.

Such concerns don't necessarily derail Schmidt's broader theory that culture, rather than farming, propelled our march to civilisation. "I think there is something to be said for social and ideological changes having an important role," says Banning. But it was clear that to expand the theory, archaeologists needed to look further afield.

Ideology before subsistence

Fortunately, they were on the trail almost as soon as Göbekli Tepe was discovered. A little down the Euphrates, across the border into Syria, French researchers have found a trio of early Neolithic villages called Dja'De, Tell'Abr and Jerf el-Ahmar. Although they are clearly permanent settlements rather than sites of pilgrimage, they all house large, highly decorated communal buildings that seem to have been the product of the same complex, ritualistic culture as Göbekli Tepe.

With war raging, they are now off limits – but Willcox did manage to sift through charred remains of seeds caught in cooking pots and house fires at Jerf el-Ahmar. He found that the first inhabitants were still gathering a wide variety of wild cereals and lentils. Later on, however, in the upper layers, a few species begin to dominate – ones that would later be domesticated. You also find evidence of imported crops that wouldn't naturally grow in the region. So the people of Jerf el-Ahmar were probably cultivating plants by the latter stages of its occupation. The killer point, though, is that they had begun to build their complex society long before they had domestic crops.

The "amphitheatre" at Wadi Faynan, Jordan, which Mithen first excavated in 2010, tells a similar story much further south. With a floor area of nearly 400 square metres – about the same as two tennis courts – it is one of the

"People were already experimenting with new ways of living 20,000 years ago"

ED KASHI/NGS

The Neolithic village Nevali Çori disappeared under water when the Euphrates was dammed

largest ancient structures to have been found after the Göbekli Tepe. It was also surrounded by a "honeycomb" of other rooms, which Mithen suspects may have been workshops.

Importantly, the remains are neatly layered, allowing the archaeologists to pin a firm date on the site – 11,600 years ago, right at the dawn of the Neolithic. So far, Mithen has found only wild varieties of figs, barley and pistachios in the lowest, oldest layers, suggesting the first inhabitants were hunter-gatherers.

What's most surprising is that Wadi Faynan lies hundreds of kilometres from the other sites. "It shows that a complex society was developing in the wider Levant at that time," says Mithen. Further east, too, there is monumental architecture that predates agriculture and may have had a ritualistic function (see "Tower of power", page 116). Mithen and others now think of the whole region as an area of "social experimentation".

If these finds are helping to rewrite one chapter of the Neolithic, there are still many blank pages to fill. Wadi Faynan and Göbekli Tepe must have been the product of a long journey – so when did we make those first baby steps, and why?

We may have to dig deep into the past to find out. Around the banks of the Sea of Galilee in Israel and across the border in Jordan, archaeologists have unearthed the foundations of brushwood and mud huts dating from at least 20,000 years ago. From the scattering of plant remains, it seems these sites were occupied by many people, perhaps for long periods, suggesting they were already experimenting with new ways of living at this time.

As if foreshadowing the huge gatherings at Göbekli Tepe, these places were meeting points for different bands from across the region, each of which left their mark with signature styles of stone tools. And their connections may have stretched far and wide; the Jordanian site, Kharaneh IV, has yielded a small hoard of assorted seashells originating from the Mediterranean, Red Sea and the Indian Ocean. "We knew these large-scale interaction networks were common in the Neolithic period, and now sites like these clearly demonstrate these networks were established much earlier in time," says Lisa Maher at the University of California, Berkeley, who has studied the site in Jordan.

Might these early meetings have spurred on the cultural change? "In a large group you need to establish a collective identity," explains Trevor Watkins at the University of Edinburgh, UK – otherwise the meetings are volatile and soon break up. "And the way that works is through ceremonies, rituals, and symbols." So social gatherings can fuel cultural change.

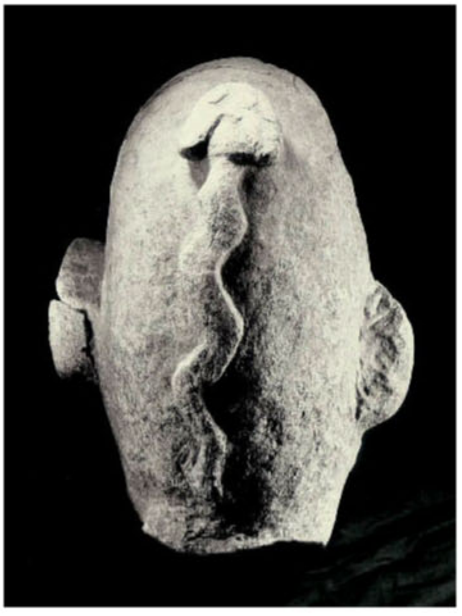
It also works the other way: culture can encourage us to seek out other people to share ideas and maintain our traditions. "It's why I live near Edinburgh," says Watkins. "We have a lot of music, theatre, writers, and from my point of view, a lot of archaeologists to talk to." There's no reason to think that the thirst to share and communicate would have been any weaker in prehistory.

So perhaps the Neolithic arose as communities and cultures evolved together through a self-perpetuating cycle. It was just luck that with a lush climate and plentiful wild foods, these emerging societies could also find a new way of exploiting the land to feed their booming populations. By around 8000 years ago, they began to explore pastures new, bringing their seeds, languages and genes to the rest of Europe and Asia.

The archaeologists have their hands full exploring the riches of their digs. Schmidt's team hasn't reached the oldest layers of Göbekli Tepe yet, so it may yet yield more secrets. "To completely understand the importance and meaning of the site, a lot more research is necessary," says Notroff. Turkish archaeologists have explored other, smaller sites nearby that might solve some of the remaining mysteries of the culture.

Mithen, meanwhile, finds the prospect of work at Wadi Faynan both "daunting and thrilling". It has already been more than a decade since he first visited. "And I know it's going to be a dominant aspect of my work for the next 10 or 20 years." As his team digs deeper, he hopes he may find some structures from even further back in time – perhaps helping to join the dots between those early mud huts and the more elaborate society that sat around the amphitheatre. "We've only scratched the surface."

Whatever they find, our views of the origin of civilisation – and of the modern world that we live in – will never be the same. ■



HEIDELBERG ACADEMY OF SCIENCES AND HUMANITIES, ROCK CARVING ARCHIVE/CORNUCOPIA

A sculpture from the 10,000-year-old settlement called Nevali Çori

Guns and steel

Could lethal weapons have been a driving factor in human evolution and the development of civilisation? Laura Spinney investigates

BEATRIZ ORDUÑA/FLICKR/GETTY

IT'S about 2 metres long, made of tough spruce wood and carved into a sharp point at one end. The widest part, and hence its centre of gravity, is in the front third, suggesting it was thrown like a javelin. At 400,000 years old, this is the world's oldest spear. And, according to a provocative theory, on its carved length rests nothing less than the foundation of human civilisation as we know it, including democracy, class divisions and the modern nation state.

At the heart of this theory is a simple idea: the invention of weapons that could kill at a distance meant that power became uncoupled from physical strength. Even the puniest subordinate could now kill an alpha male, with the right weapon and a reasonable aim. Those who wanted power were forced to obtain it by other means – persuasion, cunning, charm – and so began the drive for the cognitive attributes that make us human. "In short, 400,000 years of evolution in the presence of lethal weapons gave rise to *Homo sapiens*," says Herbert Gintis, an economist at the Central European University in Budapest, Hungary, who studies the evolution of social complexity and cooperation.

The puzzle of how humans became civilised has received new impetus from studies of the evolution of social organisation in other primates. These challenge the long-held view that political structure is a purely cultural phenomenon, suggesting that genes play a role too. If they do, the fact that we alone of all the apes have built highly complex societies becomes even more intriguing.

In May 2012, an independent institute called the Ernst Strüngmann Forum assembled a group of scientists in Frankfurt, Germany, to discuss how this complexity came about. Debate centred on the possibility that, at pivotal points in history, advances in lethal weapons technology drove human societies to evolve in new directions.

The idea that weapons have catalysed social change came to the fore three decades ago, when British anthropologist James Woodburn spent time with the Hadza hunter-gatherers of Tanzania. Their lifestyle, which has not changed in millennia, is thought to closely resemble that of our Stone Age ancestors, and Woodburn observed that they are fiercely egalitarian. Although the Hadza people include individuals who take a lead in different arenas, no one person has overriding authority. They also have mechanisms for keeping their leaders from growing too powerful – not least, the threat that a bully could be ambushed or killed in his sleep. The hunting weapon, Woodburn suggested, acts as an equaliser.

Some years later, anthropologist Christopher Boehm at the University of Southern California pointed out that the social organisation of our closest primate relative, the chimpanzee, is very different. They live in hierarchical, mixed-sex groups in which the alpha male controls access to food and females. In his 2000 book, *Hierarchy in the Forest*, Boehm proposed that egalitarianism arose in early hominin societies as a result of the reversal of this strength-based dominance hierarchy – made possible, in part, by projectile weapons. However, in reviving Woodburn's idea, Boehm also emphasised the genetic heritage that we share with chimps. "We are prone to the formation of hierarchies, but also prone to form alliances in order to keep from being ruled too harshly or arbitrarily," he says. At the Strüngmann forum, Gintis argued that this inherent tension accounts for much of human history, right up to the present day.

Egalitarian tendencies

Boehm's belief that we have inclinations towards both hierarchical and egalitarian social structures is strengthened by research published in 2011 by Susanne Shultz, then at the University of Oxford, and colleagues. They looked at the social structures and genetic relatedness of 217 living primate species. Their analysis revealed a range of organisations from solitary living to complex social structures, and showed that the closer two ›

"Democratisation tends to go hand in hand with the citizens of a country gaining access to weapons, usually handguns"

species were genetically, the greater the similarity between their social structures. If our ancestors were once hierarchical like chimps, how did they develop a different political structure? Gintis sees the transition to group living as the watershed, because it allowed primates to cooperate to share large animal kills. Species of *Australopithecus* that lived 3 or 4 million years ago were probably scavengers, but they may have thrown stones to chase off predators. "We know that australopithecines aggregated stones and moved them about," he says.

At some point, hominins took up hunting and invented weapons that could kill from afar. The world's oldest spear was found by archaeologist Hartmut Thieme in an opencast mine in Germany in the 1990s, along with two others like it, as well as horse, elephant and deer remains. However, it is likely that such weapons were produced earlier than 400,000 years ago: the archaeological record is patchy and wood perishes easily. Stone spear points 500,000 years old have been found at Kathu Pan in South Africa.

Whenever it occurred, the invention of projectile weapons influenced the evolution of our ancestors. The upper body of chimps is adapted for swinging through trees. Throwing requires a different organisation of the torso, arm and hand, along with the brain circuitry that underpins coordination of arm movements, adaptations that were selected in our ancestors. Throwing skill became the defining human characteristic, evolutionary biologist Paul Bingham and psychologist Joanne Souza of Stony Brook University in New York argue in their 2009 book, *Death from a Distance and the Birth of a Humane Universe*. They place throwing on a par with the cheetah's capacity to run, and believe that it made social cooperation inevitable: once humans could kill from a distance, no individual could rule by strength alone.

Without an alpha male imposing order, our ancestors needed new behaviour to ensure social cohesion. Studies of modern egalitarian societies indicate that a key development was the emergence of strict social norms, including the punishment of "free riders". The Turkana, nomadic cattle-herders in East Africa, lack a centralised government yet can successfully raise large raiding parties of warriors who are not kin and often do not even know each other. Sarah Mathew and Robert Boyd at Arizona State University in Tempe found that the Turkana produce this cohesion, at least in part, by punishing cowardice and desertion with public floggings and fines.

Cooperate or die

So, group living begat hunting, hunting spurred the development of weapons technology, and new weapons overthrew the alpha male and led to the emergence of cooperative tendencies. It's a neat story, but are lethal weapons really necessary to explain the transition from hierarchies based on brute strength to egalitarian living?

At the forum, Carel van Schaik, who directs the University of Zurich's Anthropological Institute in Switzerland, noted that in hunter-gatherer societies, individuals are extremely reliant on one another, especially if they become ill or cannot provide food for themselves for any reason. "Because of this interdependence, you just can't afford to be too bossy," he said.

Perhaps, then, early hunter-gatherer societies had to be egalitarian simply to survive. This possibility is weakened by recent discoveries about how chimps behave in the wild. Like our ancestors, they hunt collectively,

ALAMY

share meat and care for their sick. But the one thing they do not do is wield lethal projectile weapons. Although chimps have been known to use stone tools, to crack nuts for example, they cannot throw them with any precision. And they continue to live in hierarchies dominated by beefy alpha males.

Whatever allowed our ancestors to break free of hierarchical rule, egalitarianism proved remarkably successful, lasting for hundreds of thousands of years. Then, about 10,000 years ago, there was another massive political

TO DEMOCRACY AND BEYOND

If innovations in weapons technology have driven the emergence of civilisation (see main story), the obvious question is, what next?

The past 70 years have seen the rise of the megaweapon, including nuclear, biological and now cyberweapons. According to Paul Bingham and Joanne Souza of Stony Brook University, New York, these have enforced a kind of crude democracy between nations, giving coalitions of states a credible threat to help keep "rogue" states in check. "There is no other route to global cooperation than precisely this kind of coercive equilibrium. Nor will there ever be in the future," Bingham says.

Because democratic states tend to be wealthier than authoritarian ones, they can afford more megaweapons, which explains why internationally the coercive push has been away from autocracy, towards democracy. Within a state, however, megaweapons offer no one sector of society any power over another, so they have little effect on social structure. At national level, it is individual weapons – and guns in particular – that influence the balance of power. According to Bingham and Souza, the more successfully a state's security bodies monopolise access to guns, the more authoritarian that state will be. That's why they argue that democracy begins with the democratisation of arms.

In the future, however, a new advance in weapons technology could set civilisation on a novel track. "A technology could easily arise that irremediably places democracy on the defensive," says economist Herbert Gintis at the Central European University in Budapest, Hungary.

He gives the example of an implant with the capacity to inflict pain on, or gather information about, an implanted individual. Such technology is already conceivable, he says. How it might influence the future of human social organisation is not.

With weapons to keep bullies in check, Hadza society is egalitarian

upheaval. The immediate catalyst was the invention of farming, and the increased trade it allowed. The result was a change in the way weapons were deployed. "As soon as you get accumulated wealth," says Gintis, "then individuals can monopolise that wealth and incentivise others to protect them." This led to a new kind of hierarchy dominated by a "Big Man" who did not need to be physically strong, just rich enough to pay a small cabal of armed and trusted subordinates to protect him.

In this way, human societies entered an age of rampant despotism. Those at the top exploited those lower down – making slaves of them, demanding taxes and so on. But they also protected them from outsiders, so the system was stable for as long as the threat of the enemy outweighed the inhumanity of the exploitation. Less stable, however, was the fate of despots, relying as it did on the risky strategy of buying the loyalty of others. "They didn't often die in their sleep, let's put it that way," says Gintis.

Such wealth-based hierarchies were the seeds of the modern state. And from small beginnings, these proto-states grew, spurred at least in part by another innovation in weapons technology. Horses were domesticated about 5500 years ago. Wear on their teeth shows they were probably ridden with bits in their mouths. It was not until about 1000 BC, however, that nomads on the Eurasian steppes learned how to to shoot iron-tipped arrows from small, powerful bows while mounted, according to Peter Turchin at the University of Connecticut in Storrs. The combination of horse and armed rider was, he says, arguably the first weapon of mass destruction.

The first WMD

"This technology dramatically increased the scale of warfare, making it much more offensive," Turchin told the forum. To improve their chances of survival, groups under threat coalesced into larger, more defendable societies. Turchin even suggests that today's major religions emerged at around this time, in response to the need to create social cohesion between disparate ethnic groups. "These religions allowed sociality to break through the barriers of ethnicity," he said. The nation state was born, and its weapon of choice was the cavalryman.

With so much firepower now available, you might expect this to have been a bloody phase of human civilisation. In fact, the opposite is true, says Samuel Bowles, an economist at the Santa Fe Institute. His calculations, based on archaeological and ethnographic data, suggest that even in the 20th century – the "century of total war", as it has been called – warfare accounted for about 5 per cent of mortality in Europe, just half that for Stone Age Europeans and today's egalitarian hunter-gatherer societies. Figures for deaths in war, and what conflicts count as war, are of course controversial. But the nation state proved particularly good at winning wars and protecting people, Bowles concludes, and that explains why it has been the dominant social model for the past 500 years.

If despotic, power-based hierarchies worked so well, what caused latter-day Big Men to cede some of that power in the form of democracy? Again, it was a response to new lethal weapons, says Gintis. Starting with the invention of the flintlock musket in the 17th century, handgun technology evolved until, by the early 20th century, armed foot soldiers finally had the edge over cavalry. In other words, guns had put power back into the hands of the masses. Now leaders were reliant for their protection on a sector of society that was disenfranchised and potentially disgruntled. If Gintis is correct, extending the vote to most of the population was the price the elite paid to buy their support.

This pattern continues today, says Bingham. Democratisation tends to go hand in hand with the citizens of a country gaining access to weapons, usually handguns, and thereby breaking the state's monopoly on coercive threat.

Another modern technology has also helped our anti-hierarchical tendencies get the upper hand. The challenge, just as it was millions of years ago, is to coordinate the majority, which is why real-time social media have become powerful drivers for democracy – as the Arab Spring initially promised. "Even armed merely with stones and other simple weapons, large, well-coordinated majorities have significant coercive clout," says Bingham.

The gradual elimination of despots has been one of the major political trends of the past century. So are we headed for universal democracy? Gintis believes there is no room for complacency. Torn as humans are between hierarchical and anti-hierarchical instincts, open societies will always be threatened by the forces of despotism. Boehm agrees. "It boils down to whether a government can establish fear, rather than consensus, as its basis," he says. "And with humans, this will always be up for grabs." ■

Modern makeover

Thousands of years of civilisation have resculpted the human body. Does this mean we are still evolving?

IN A basement storeroom at the University of Zurich in Switzerland, rows of cardboard boxes are stacked tidily on metal shelves. Although stamped with the logo of a banana import company, they contain, not fruit, but something more macabre.

Inside are the heads of two Egyptian mummies and bits of ancient bog bodies. More recent remains include bones from a medieval graveyard, and others from Swiss citizens who died in the early 20th century.

Some of the body parts bear marks of exotic or violent rituals: there are traces of gold leaf around one of the mummies' eyes, for example. Others show the ravages of diseases that have long since been eradicated. In this plain, windowless room lie the remains of 2000 individuals, all told.

The collection is overseen by anatomist Frank Rühli, who wants to reconstruct the people to whom they once belonged. He is discovering how the human body has changed over the last few thousand years, to chart how civilisation is resculpting our bodies. The modern Western lifestyle continues to change not only our waistline but also our height, muscles, bones, blood vessels and hormones.

Some of those transformations could be genetic in origin, examples of recent microevolution in action. But there is reason to suspect that others are temporary changes wrought throughout our lives that would melt away if we returned to a Stone Age environment. The complex interplay of nature and nurture is hard to disentangle, but the sheer breadth and scale of the changes show the ease with which the human body can adapt to new habitats over short timescales.

Discovering how those adaptations are making us more vulnerable to certain diseases and less so to others is an important facet of evolutionary or Darwinian medicine, a young specialty that views health and disease through the lens of evolutionary theory. In October 2010, the university opened a Centre for Evolutionary Medicine with Rühli at its head; the centre was made a permanent institute in 2014. Evolutionary medicine sheds light on many common ailments that have arisen because our modern Western lifestyle is so different from the one we evolved to suit, says Rühli.

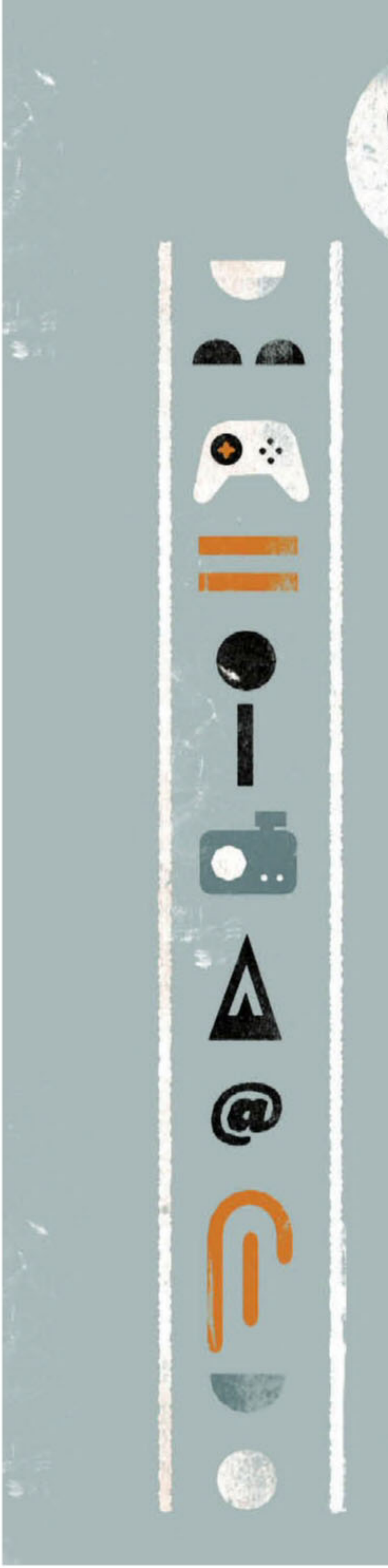
Anatomically modern humans are thought to have arrived on the scene around 200,000 years ago. They lived as hunter-gatherers in small nomadic groups until around 10,000 years ago, when the advent of farming and permanent settlements led, in fits and starts, to civilisation.

Ancient remains

The idea that evolution could have been taking place in the past few thousand years goes against all received wisdom. Weren't we taught that natural selection operates over millions of years?

Yet recent evidence indicates that we have got this wrong. A gene that gives people the ability to digest milk after infancy, for example, was recently shown to have arisen and spread with the invention of dairy herding several thousand years ago.

The genetic evidence stems from samples taken from people alive today. By looking at how a gene's sequence varies among populations, we can work out how long ago it arose and chart its spread round the globe.



BORJA BONAQUE

Arguably, information about the past can be obtained more directly from ancient human remains that have been preserved by accident or design. By comparing them with modern-day humans, we can work out just what civilisation has been doing to our bodies.

Perhaps the best-known difference is that westerners have got fatter, thanks to our calorie-rich diet and less active lifestyle. Obviously, that change would be reversed if we returned to hunting and gathering to find our food. A less well-known trend is that we have been becoming less muscular, almost certainly because we have been using our muscles less and less. Bones that no longer support large muscles can themselves become punier, so our shrinking musculature can be tracked in the fossil record. Our bones have become more spindly or "gracile", with the overall diameter shrinking as well as the dense outer cortex of the bone becoming thinner in cross-section (see diagram, page 126).

Christopher Ruff of the Johns Hopkins University School of Medicine in Baltimore, Maryland, has travelled the world to X-ray about 100 fossil leg bones going back over 3 million years. He also studied bones from three populations from the near-present: Native Americans from the American Southwest who lived about 900 years ago, and east Africans and US whites from the early to mid-20th century.

"If you returned to the Stone Age and were forced to work harder, you would probably develop stronger bones"

Ruff's team documented an average fall in bone strength of 15 per cent between 2 million and 5000 years ago. At that point, the trend accelerated, as there was another 15 per cent reduction over a mere 4000 years.

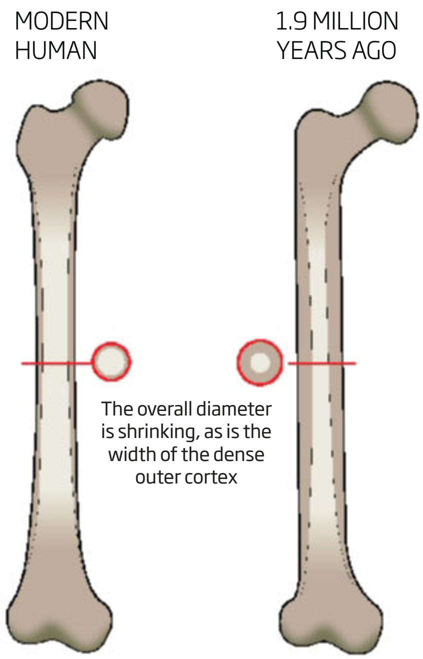
Ruff thinks gracilisation kicked in when we began to use tools that reduced physical exertion, starting with hand axes, through to ploughs and eventually cars. Our increasingly sedentary lifestyle means our survival has come to depend less and less on our strength.

How much of this process is due to genetic changes, and how much would be reversed if we returned to a Stone Age lifestyle? It's impossible to say, admits Ruff. "We don't know what genes control bone mass and there's no way we can go and sample these fossils and figure that out."

What we do know is that the body has an impressive capacity to respond to exertion over a single lifetime. Take professional ›

That shrinking feeling

Our thigh bones have become thinner and punier, with a 15 per cent loss of strength in the last 4000 years alone



tennis players: by looking at X-rays, Ruff's team has worked out that the humerus in their playing arm is more than 40 per cent stronger than the corresponding bone in the opposite arm. For comparison, non-athletes have only a 5 to 10 per cent difference. "That would suggest that if you were in the Stone Age and you were forced to travel longer distances and lift heavier things, you would probably develop stronger bones," he says.

It's an important finding, because it suggests that we retain our ancient capacity for strength – if only we work our bodies hard enough – and stronger bones mean fewer fractures. Broken hips were less common in the past, and are vanishingly rare in archaeological specimens, even accounting for the fact that lives were shorter then.

Civilisation is changing not only our physical features but also the size of our families, which alters women's hormone levels. Female hunter-gatherers would typically have had six or seven children and spent much of their adult lives pregnant or breastfeeding, both of which cut oestrogen exposure. In the west we have smaller families and it is now rare to breastfeed for more than a few months. Obesity, lack of exercise, the contraceptive pill and hormone replacement therapy also raise oestrogen levels. "For many reasons modern women are exposed to enormous amounts of oestrogen," says Israel Hershkovitz of Tel Aviv University in Israel. That is thought to be the main reason women today have a 1 in 8 chance of developing breast cancer over their lifetime.

Breast tissue does not fossilise, but there is a way that hormone levels can be tracked through history. Prolonged oestrogen exposure is thought to cause thickening of the skull on the inside, just above the eyes.

Using medical school collections, Hershkovitz's group has measured nearly 1000 skulls of women who were alive 100 years ago. The team also ran CAT scans on 400 living women and found this thickening to be 50 per cent more common than it was a century ago. Among women in their 30s, the prevalence has nearly quadrupled, from 11 to 40 per cent.

There are other physical changes that are more mysterious in origin. We seem to have acquired a new blood vessel in our arms, called the median artery. In fact, this blood vessel is present in the embryo but according to textbooks it normally dwindles and vanishes around the eighth week of pregnancy, to be replaced by the ulnar and radial arteries. An increasing number of adults now have this artery, up from 10 per cent at the beginning of the 20th century to 30 per cent at the end.

Over the same period, a section of the aorta lost a branch that is one of several supplying the thyroid gland. One of those who has helped to document these changes is Rühli's former teacher Maciej Henneberg, now an anatomist at the University of Adelaide in South Australia. They could be due to differences in the diet and lifestyle of pregnant mothers, he speculates, or perhaps a relaxing of the forces of natural selection, thanks to modern medicine and welfare systems.

Disease origins

It is these kinds of uncertainties that leave some practising doctors less than impressed with the buzz around evolutionary medicine. We cannot know if evolutionary explanations are true, since we rarely have a complete picture of the past, points out retired American family physician Harriet Hall, who blogs as The SkepDoc. "Conventional medicine has a long record of successes," she says. "Evolutionary medicine hasn't proven that it has any real value."

That's not to say that documenting trends over time isn't useful, even if it only corrects

Ancient Peruvians buried their dead in a seated position

the textbooks. If the arteries of a 20-year-old differ from those of a 90-year-old, it could affect how they should be treated medically. At the very least, surgeons need to know in order to operate safely.

Even our fingerprints have been changing over time. Henneberg's team took prints from 115 bodies donated to the University of Cape Town in South Africa. They divided them into two groups: those who were born before 1920 and those born later. There were significant differences in their patterns: simple arches, tented arches and whorls were more common in the later group, and ulnar loops less so.

Fingerprints may seem like a trivial sort of change, but one of Rühli's next projects may shed light on the origin of a serious disease. In the world's malarial zones a number of mutations have arisen that persist in the gene pool despite causing serious diseases, because they protect their carriers from malaria. One of these affects an enzyme in red blood cells called glucose-6-phosphate dehydrogenase (G6PD), and those who carry two copies of the mutation have a serious form of anaemia.

By studying ancient miners, Rühli's team hopes to narrow the window when the G6PD mutation could have arisen. On two occasions – once in 500 BC and once in AD 500 – a salt mine collapsed in what is now Iran, burying those working there and preserving their flesh. That has given us two samples from the same place preserved in the same

SIEMENS AG

way, 1000 years apart. Rühli's team is trying to get usable DNA from the salt mummies.

Sometimes these looks into the past shed light on our future risk of disease. One such case involves spina bifida, the birth defect that causes paralysis of varying severity depending on how high up the spine is affected. It happens when the embryo's neural tube, which develops into the spine and brain, fails to close up properly, leaving gaps in one or more vertebrae.

The incidence of spina bifida has been falling over the past couple of decades in most Western countries, thanks to campaigns persuading pregnant women to increase their folic acid intake. But this could be obscuring a longer-term trend in the opposite direction.

There is a much milder and commoner form, known as spina bifida occulta, where the only affected vertebrae are in the sacral region at the bottom of the back, which consists of five fused vertebrae known as S1 to S5 (see diagram, left). Most affected people have no outward sign and don't even know they have it, although there is some evidence linking the condition with back pain and some rarer health problems.

There is now an array of evidence that spina bifida occulta has become more common. Some comes from work on human remains found by Henneberg at Pompeii, the Roman city buried when Mount Vesuvius erupted in AD 79. Pompeii has provided a wealth of

"These were the last moments of real people, frozen in time"

information since excavations began in the 18th century. "You find families trapped together with the mother trying to protect the children," says Henneberg. "These were the last moments of real people, frozen in time."

Henneberg and his wife Renata, who led their Pompeii project, looked at the rate of spina bifida occulta among the Pompeians. About 10 per cent had an unclosed S1 vertebra, compared with an estimated 20 per cent of people today. Vertebrae lower down the spine are now even more likely to be open. The bottom-most one, S5, was open in about 90 per cent of Pompeians, compared with nearly 100 per cent in people alive today.

True spina bifida is so rare it is impossible to gauge its past prevalence with any accuracy. When we look at spina bifida occulta, however, the spine as a whole seems to be taking on a more open structure – although folic acid supplements and fortification may be able to counter this trend.

What's behind the change? Henneberg thinks one possible explanation is the long-term gracilisation of the skeleton. Changes to genes controlling the long bones in the legs and arms could have knock-on effects on the spine. "There's less bone everywhere in the body," he says.

A different explanation is, again, that selection pressures on humans are easing. "There's no question that it's relaxing," says Henneberg. "One hundred years ago, one-third of children died before the age of 5. Now practically everyone who's born survives."

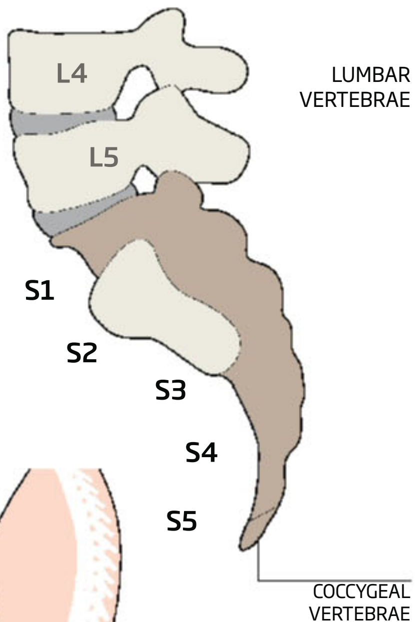
This kind of talk often comes with dire warnings about weakening the human race, and in the past has triggered eugenics movements. But today's evolutionists seem sanguine about the future.

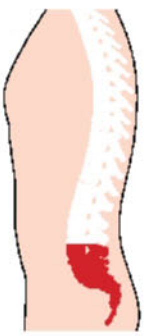
Rühli believes less selection pressure is not necessarily bad for a species' survival. "The more a [population] is under environmental pressure, the more it narrows the variability," he says. With humans today: "We see a higher degree of variability within the body. An increase in variability may be good."

Even if that means a rise in conditions like spina bifida occulta? If food or minerals become scarce in future, it might be better to have spindly bones, says Henneberg. "Who knows what the future might hold for the human race?" ■

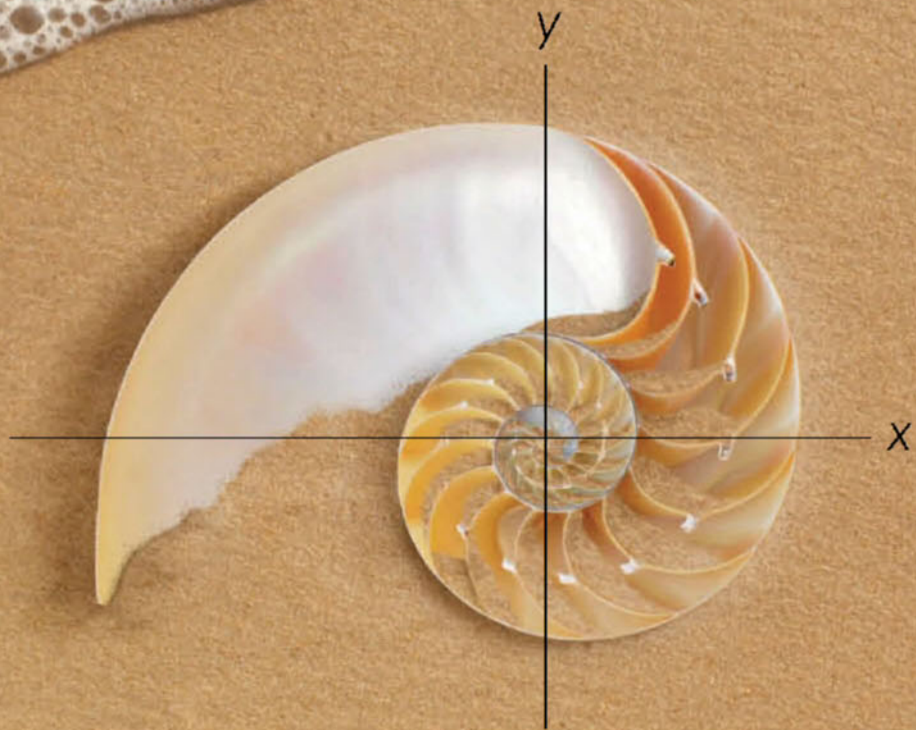
Hidden defect

Around a fifth of us may have the condition called spina bifida occulta without knowing it





The vertebrae in the lowest part of the spine, the sacrum, fail to form properly. In most cases there is no outward sign, although back problems may result


y
x