‘A MAN WHO DARES TO WASTE ONE HOUR OF TIME HAS NOT DISCOVERED THE VALUE OF LIFE’

Charles Darwin

Throughout the19th century there was a transformation in thought that still reverberates today. The workings of nature and the variety of life were re-imagined in ways that underlie all modern biology. The wider implications of these ideas still provoke controversy.

One man, and one book, came to symbolise the new biology of evolution. Charles Darwin, born in 1809, was 50 when he published perhaps the most famous scientific work ever written. Therefore, 2009 marks both the bicentenary of his birth and 150 years since the first appearance of *On the Origin of Species by Means of Natural Selection*.

This exhibition explores the origins of Darwin’s book, outlines his central ideas, and explains how they remain at the core of contemporary research in biology and medicine.

1

WHO WAS DARWIN?

Charles Darwin was the son of a prosperous country doctor in Shrewsbury, in the largely rural English county of Shropshire. As a boy he loved the countryside and its creatures but had trouble settling on a career. He abandoned medical school in Edinburgh, and was sent to Cambridge University to prepare for life as a vicar.

At university Darwin met some of the most brilliant naturalists of the day and in 1831 he acquired a berth on the naval survey vessel *HMS Beagle* for a world voyage. During the five-year journey Darwin kept a scientific field journal, covering biology, geology and anthropology, with detailed notes and observations on the indigenous animals, plants, birds and insects of the places he visited – Brazil, Chile, Peru, the Galapagos Archipelago, Tahiti, New Zealand and Australia, among others.

Back in London, and later at his new home at Down House in Kent, he gradually came to understand how individual species could change; how evolution could work – although it took him over 20 years to feel ready to publish his ideas.

For the rest of his life he continued working – to defend his theory and to understand its implications, and he published further books – on orchids, earthworms and the expression of emotions, among others.

Darwin became a reclusive, semi-invalid in middle age and died in 1882, but there was one constant throughout his life – a boundless curiosity about the natural world.

Ink and watercolour drawing of Charles Darwin in 1840 by George Richmond.

John Stevens Henslow, Professor of Botany at Cambridge University, 1825–61. Henslow recommended Darwin for the job as naturalist on *HMS Beagle*.

Exquisite adaptations

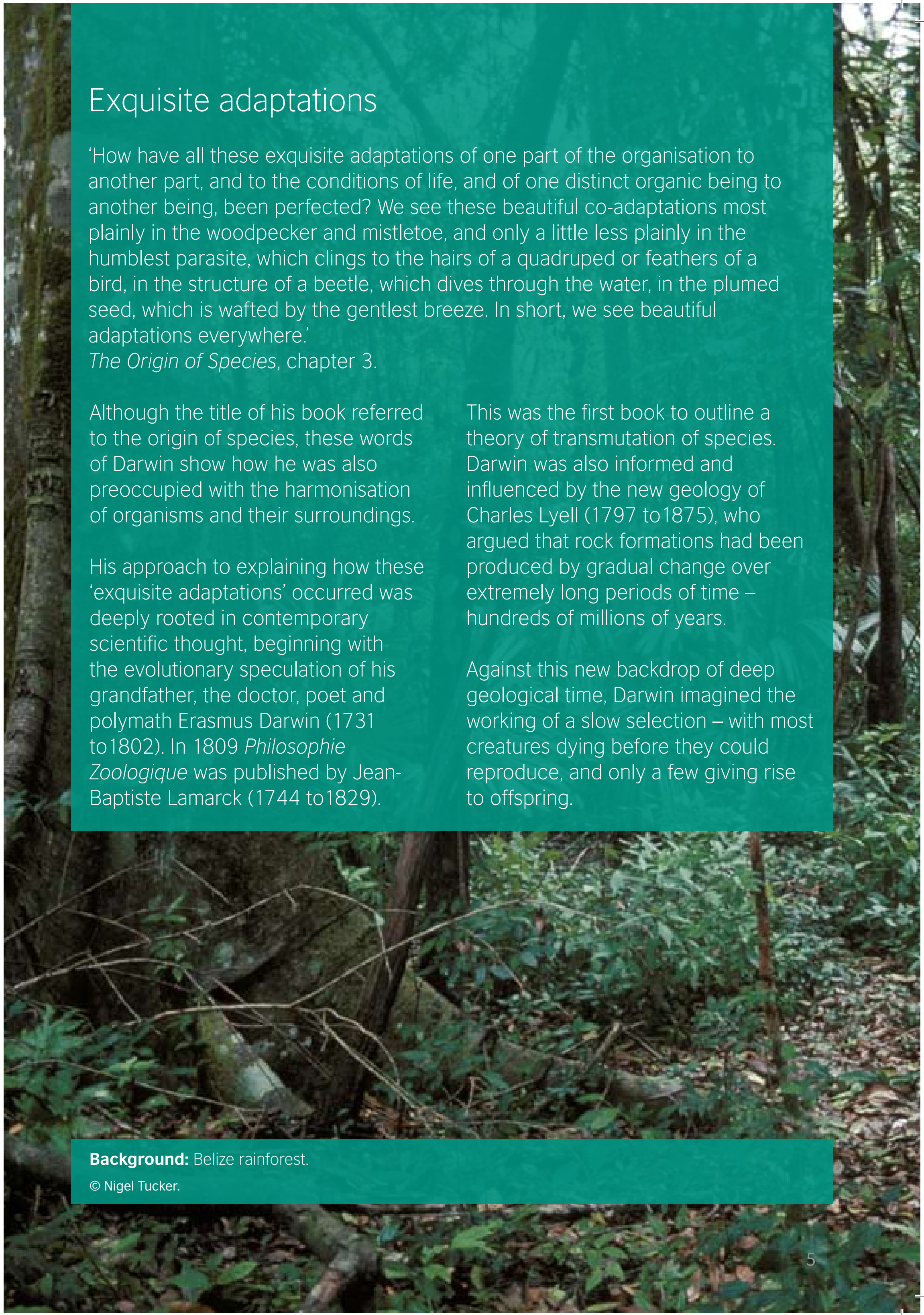
'How have all these exquisite adaptations of one part of the organisation to another part, and to the conditions of life, and of one distinct organic being to another being, been perfected? We see these beautiful co-adaptations most plainly in the woodpecker and mistletoe, and only a little less plainly in the humblest parasite, which clings to the hairs of a quadruped or feathers of a bird, in the structure of a beetle, which dives through the water, in the plumed seed, which is wafted by the gentlest breeze. In short, we see beautiful adaptations everywhere.'
The Origin of Species, chapter 3.

Although the title of his book referred to the origin of species, these words of Darwin show how he was also preoccupied with the harmonisation of organisms and their surroundings.

His approach to explaining how these 'exquisite adaptations' occurred was deeply rooted in contemporary scientific thought, beginning with the evolutionary speculation of his grandfather, the doctor, poet and polymath Erasmus Darwin (1731 to1802). In 1809 *Philosophie Zoologique* was published by Jean-Baptiste Lamarck (1744 to1829).

This was the first book to outline a theory of transmutation of species. Darwin was also informed and influenced by the new geology of Charles Lyell (1797 to1875), who argued that rock formations had been produced by gradual change over extremely long periods of time – hundreds of millions of years.

Against this new backdrop of deep geological time, Darwin imagined the working of a slow selection – with most creatures dying before they could reproduce, and only a few giving rise to offspring.



Background: Belize rainforest.

Map of Darwin's voyage on *HMS Beagle*.

2

GLOBAL NETWORKS

Darwin did not travel again after his *Beagle* voyage. However, throughout his life, he was a prolific letter-writer. It was his way of cementing scientific friendships, pursuing collaboration and gathering observations.

Preoccupied with 'the species question' Darwin was convinced that different species could start by one earlier variety changing into another – by transmutation. But how?

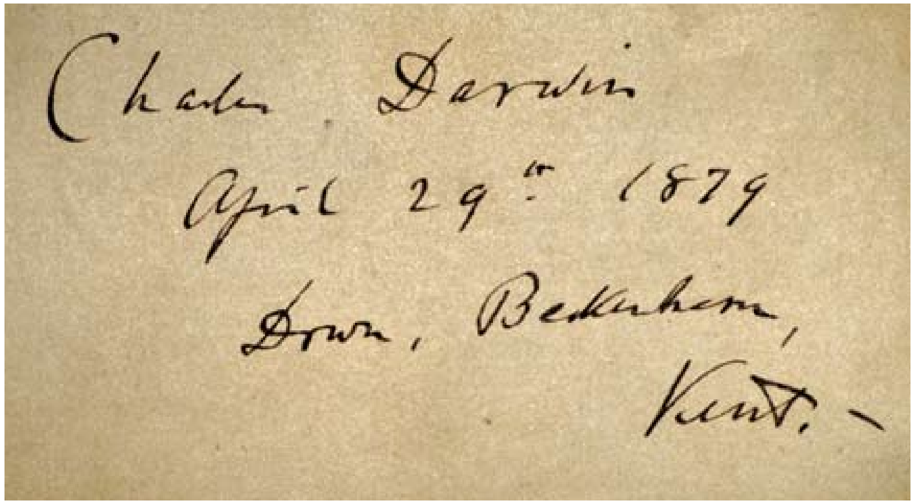
He studied specimens, the exhibits in museums and zoos, and the work of animal and plant breeders. And he read – geology, natural history, and philosophy.

As he studied, he corresponded with colleagues around the world – Brazil, India, China, North America, South America, New Zealand and Jamaica – outlining his ideas, arguing his hypothesis and requesting information and new specimens.

Once he had an outline of his theory, he consulted diplomats, army officers and colonial officials, gardeners, horse-breeders, farmers, fur-trappers and zookeepers, as well as botanists and naturalists.

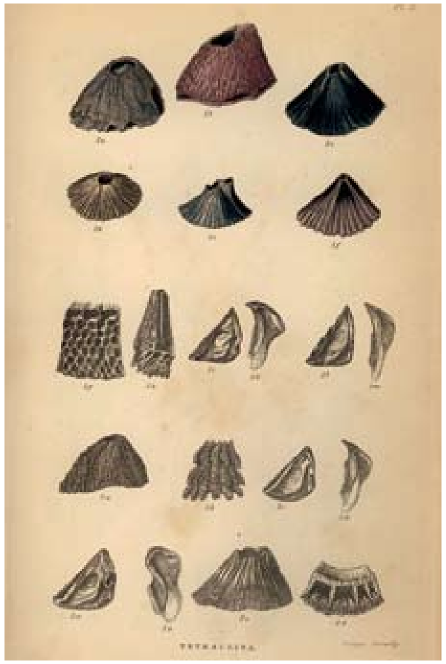
Letters also kept him in touch with the travelling naturalist Alfred Russel Wallace, who had formulated similar ideas. It was a paper from Wallace that finally induced Darwin to publish his theory.

Once *The Origin of Species by Means of Natural Selection* appeared, in 1859, the letter writing brought new information for updates of the work, and for new projects. It also helped to influence the reception of his radical ideas.



After publishing *On the Origin of Species by Means of Natural Selection* Darwin became renowned and autograph collectors wrote to request his signature.

The sand walk or 'thinking path' at Down House, photographed around 1909. Darwin walked here every day when he was at Down and used the time to contemplate his observations and to develop his theories.



Darwin spent eight years studying barnacles and made a major contribution to our understanding of them.

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Alfred Russel Wallace (1823–1913), who famously put forward similar ideas on the origin of species as Darwin. A paper by Wallace was presented alongside some of Darwin's work at the Linnean Society in 1858.

Fancy pigeon breeds similar to those studied by Darwin as he developed his theories of evolution and natural selection. Darwin compared 'artificial selection' used by breeders to that which could be seen in nature – 'natural selection'.

Darwin's study at Down House shortly after his death in 1882. Copper engraving by Acel H. Haig.

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A life in letters

'I am now employed on a large volume describing the anatomy and all the species of barnacles from all over the world. I do not know if you live near the sea, but if so I should be very glad if you would collect for me any that adhere (small or large) to the coast rocks or to shells or to corals thrown up by the gales, and send them to me.'
Darwin's letter to his former servant on *HMS Beagle*, Syms Covington, in Australia.

The Darwin Correspondence Project in Cambridge has collected 15,000 of Darwin's letters, involving around 2,000 correspondents around the world.

By the time he published *The Descent of Man, and Selection in Relation to Sex* in 1871, Darwin was writing around 1,500 letters a year. In fact, by then, much of his day revolved around reading and writing letters – he even put a mirror next to his study window so that he could see the postman walking up to the house each day.

A third of the surviving letters can now be read and searched online at www.darwinproject.ac.uk. The entire collection is also being published in book form, in a series expected to total 30 volumes when complete.

The letters reveal how substantially Darwin's success in advancing a new vision of the natural world depended on others: his wife, Emma, their ten children at home in Kent, his friends and colleagues in England and his correspondents around the world. By the end of his life, in 1882, Darwin was a member of 57 foreign learned societies – memberships he maintained without ever leaving the country after *HMS Beagle* docked in Falmouth in 1836.

One of Darwin's projects was a comprehensive study of barnacles. Begun as a diversion from his study of species, it grew into an eight-year exploration recorded in three immensely detailed books. Using his skills of persuasion, or appealing to shared curiosity, he wrote to those who had an interest in barnacles, and others who had been recommended by colleagues.

Darwin requested information, specimens – preferably live ones – and, in some cases, the loan of their entire collections. Darwin dissected and catalogued every specimen, creating the definitive work on these small crustaceans.

Background: Acorn barnacle *(Semibalanus balanoides)*.

3 DARWIN’S THEORY – INHERITANCE, VARIATION, SELECTION

One reason that Darwin’s ideas have endured is their simplicity. The theory of evolution by natural selection has just three essential parts:

- When individuals in a population reproduce, the new generation must resemble their parents.
- The resemblance between generations must be close, but not perfect, so that each generation includes new variations in characteristics.
- There must be a link between some of these new variations and the chances that an individual will be better able to survive and reproduce.

The variations, and their effects, can be very small. Repeat the cycle thousands of times, and the results can be dramatic.

In summary: all you need for evolution is inheritance, variation, and selection.

In *The Origin of Species* Darwin laid out an abundance of evidence for evolution. But there were gaps in the story. One, which is still not easily understood, was the origin of life. Another was that he had no convincing ideas about how variations in characteristics were passed down the generations.

More recent science has supplied some details about the mechanism of inheritance. Every creature can be defined by the information in its genes. These are messages written in the sequence of chemical letters in the DNA molecule.

Genes are copied and passed on to each creature’s offspring. But the process of copying can introduce small mistakes, which produce random changes in the DNA information. These are the mutations that lead to variation in the population.

Some mutations bring advantages, which make reproduction more likely in a particular environment. So, again, we have inheritance, variation and selection, but this time among molecules.

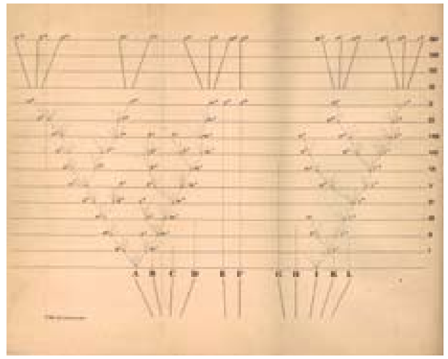
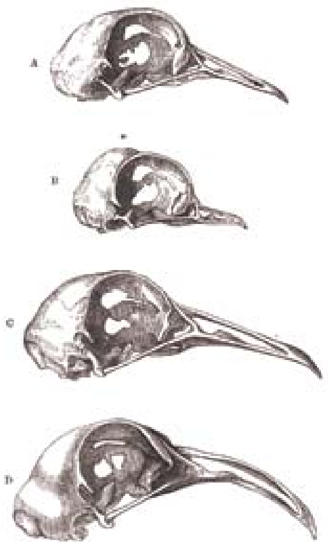


Illustration from the first edition of *On the Origin of Species by Means of Natural Selection* depicting the evidence that different species with shared characteristics can be explained through common ancestors.

Reproduced with permission from John van Wyhe, ed., The Complete Work of Charles Darwin Online (http://darwin-online.org.uk).



Diagrams of pigeon skulls showing how domestication and selection led to variations within one species.

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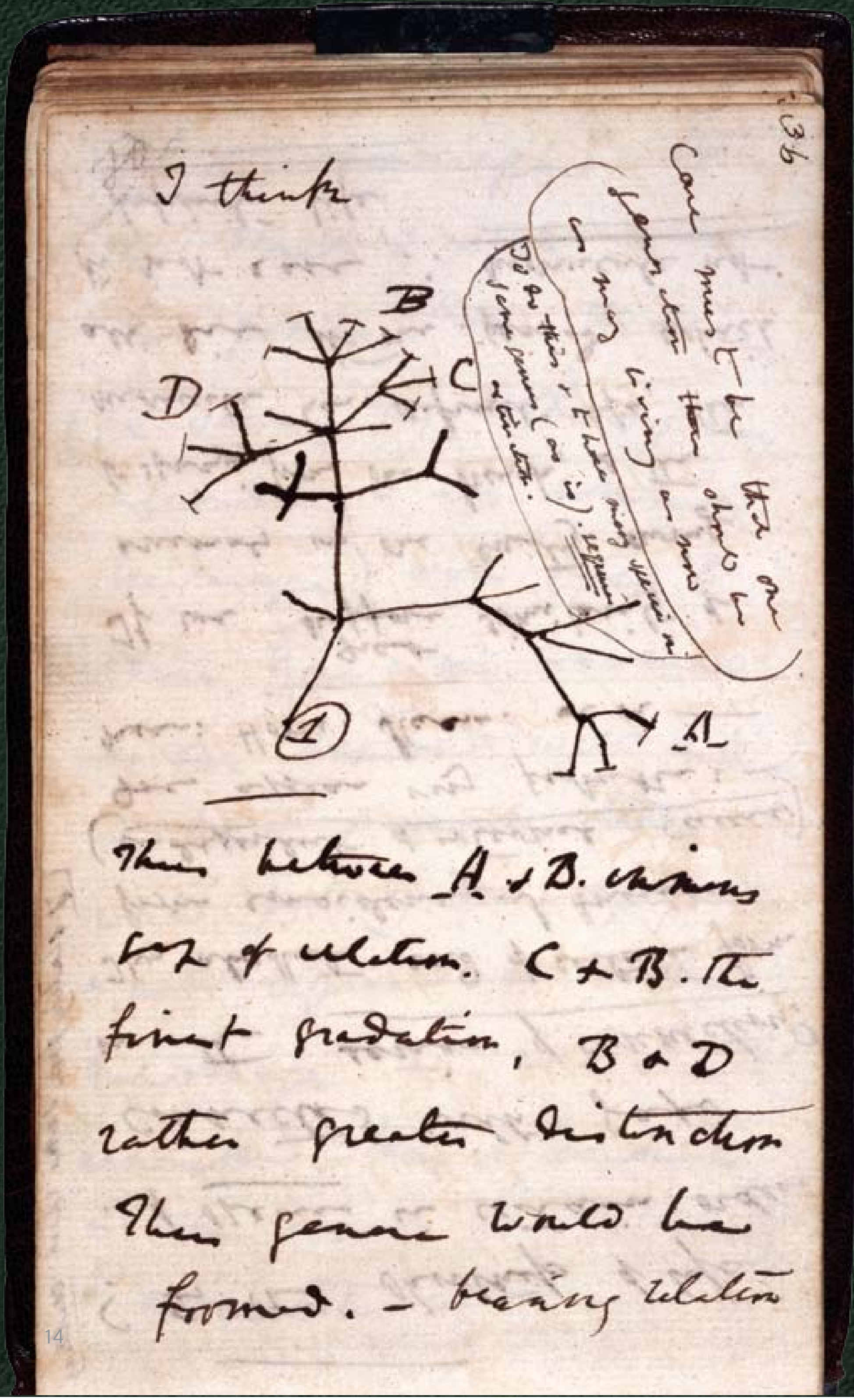


Evolution by selection

'Can we doubt (remembering that many more individuals are born than can possibly survive) that individuals having any advantage, however slight, over others, would have the best chance of surviving and procreating their kind? On the other hand, we may feel sure that any variation in the least degree injurious would be rigidly destroyed. This preservation of favourable variations and the rejection of injurious variations I call Natural Selection.'
The Origin of Species, chapter 4.

Darwin's work was concerned with the existence and evolution of living creatures. His discovery that inheritance, variation and selection can lead to change in species, however, has far wider applications.

In fact, provided a population of individual entities passes through a number of generations in some kind of cycle, evolution can occur.

Looked at this way, natural selection applies to life on Earth, as Darwin argues. Theorists and experimenters studying the origin of life assume it applies to populations of molecules in proto-living systems. Exobiologists (who study organisms that originate from outside Earth) argue that it should also apply to life anywhere in the universe, even if the molecules in play turn out to be different from those we observe on Earth.

Beyond that, entire universes might be subject to natural selection, according to cosmologist Lee Smolin. He speculates that they 'reproduce' when an existing universe collapses into a black hole, and a new one is born in which the laws of physics are subtly different.

There are also more earthbound examples of the idea of selection, such as its application to 'evolve' computer programs known as genetic algorithms and in systematic search for new molecules that may find use as drugs.

Consider how the selection theory model can be applied to our understanding of language change, cultural trends and technological developments, and one can understand why US philosopher Daniel Dennett described evolution by selection as 'the single best idea anyone has ever had'.

Opposite page: Page from Darwin's species notebooks. Written between 1837–38, his notes outline his ideas on the 'transmutation of species'.

Background: Cover from the first edition of *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life,* published by John Murray in 1859.

4

REACTIONS

Darwin's readers had strong opinions about his book in its early years – but in very different ways.

'How extremely stupid not to have thought of that!'
Thomas Huxley, naturalist

'He has opened a path of inquiry full of promise, the results of which none can foresee.'
John Stuart Mill, philosopher

'One of the most interesting parts of Mr Darwin's volume is that in which he establishes this law of natural selection; we say establishes, because – repeating, that we differ from him totally in the limits which he would assign to its action – we have no doubt of the existence or of the importance of the law itself.'
Bishop Samuel Wilberforce

'It is remarkable how Darwin rediscovers, among the beasts and the plants, the society of England with its division of labour, competition, opening of new markets, "inventions" and Malthusian "struggle for existence".'
Karl Marx, political theorist

Contemporary cartoon of Thomas Henry Huxley (1825–95).

'The most important original observations, recorded in the volume of 1859 are, in our estimation, its real gems – few indeed and far apart, and leaving the determination of the origin of species very nearly where the author found it.'
Sir Richard Owen, naturalist

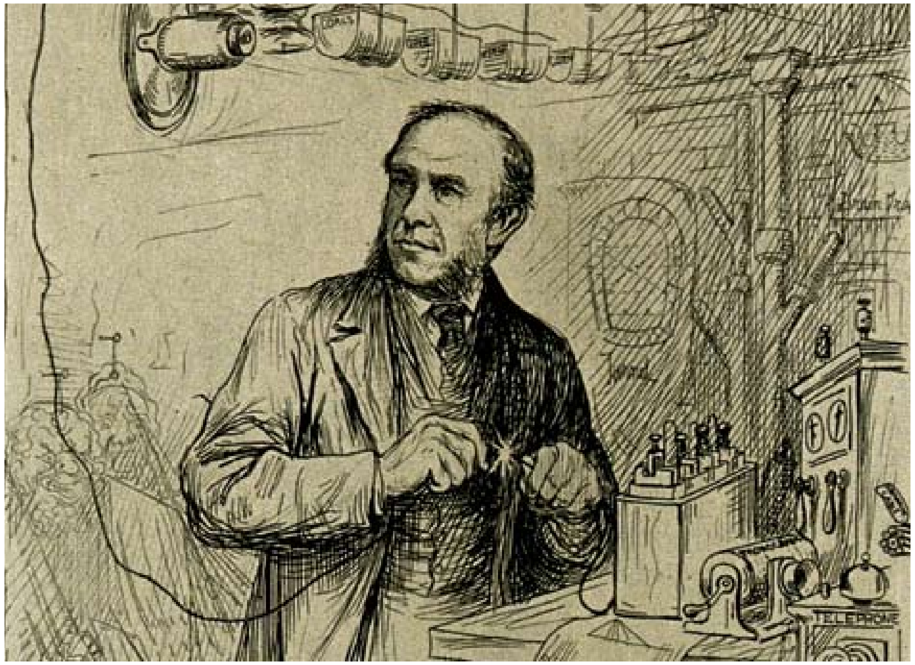
'What can we believe but that Darwin's theory is an ingenious and plausible speculation, to which future physiologists will look back with the kind of admiration we bestow on the atoms of Lucretius, or the crystal spheres of Eudoxus, containing like these some faint half-truths, marking at once the ignorance of the age and the ability of the philosopher.'
Henry Charles Fleeming Jenkin, engineer

'I have read your book with more pain than pleasure. Parts of it I admired greatly; parts I laughed at till my sides were almost sore; other parts I read with absolute sorrow, because I think them utterly false and grievously mischievous.'
Adam Sedgwick, geologist

'We had a capital meeting at Norwich, and dear old Hooker came out in great force as he always does in emergencies. The only fault was the terrible *Darwinismus,* which spread over the section and crept out when you least expected it, even in Fergusson's lecture on "Buddhist temples". You will have the rare happiness to see your ideas triumphant during your lifetime.'
Thomas Huxley, naturalist

Sir Richard Owen (1804–92).

Adam Sedgwick (1785–1873).



Henry Charles Fleeming Jenkin (1833–85).

Bishop Samuel Wilberforce (1805–73).

Lithograph of Karl Marx (1818–83).

Critics and supporters

Some people were simply unaware of Darwin's theory. When he and his fellow evolutionary theorist Alfred Russel Wallace had their first papers read at the Linnean Society in 1858, the reaction was muted. The President of the Society said later that the year had not been marked by any remarkable discoveries.

When Darwin's book was published the following year, responses were varied. Some of Darwin's strongest supporters, such as Thomas Huxley, still took issue with many details of the theory. Many accepted the idea of evolution but not the mechanism he proposed. Some thought natural selection explained some cases of adaptation, but not others. There was much speculation about the duration of natural selection, and the length of time necessary for species to change.

Some religious commentators had little difficulty with Darwin's approach to the variety of life, which could still accommodate a creator. A lawful universe was, in their view, still an orderly realm ordained by God. But some believers felt Darwin's ideas presented a challenge to concepts of morality and aspects of their interpretation of religious texts.

Some defined the theory as reinforcing support for Europeans' imperial ambitions, and for the idea that different races, or nations, competed for ascendancy. Some saw the theory as a basis for what the British philosopher Herbert Spencer called social Darwinism, in which the class structure was a result of – in his famous phrase – 'survival of the fittest'. In this view, economic competition mirrored the struggle for survival in the natural world.

However, the idea of evolution was embraced by some political radicals, who found the picture of change it offered a basis for their hopes for revolution in the social order.

All these interpretations of Darwin's and Wallace's ideas were argued over and criticised in the numerous periodicals of the time. They were often caricatured and made fun of in cartoons, humorous essays, or music hall songs.

Generally, Darwin's book, therefore, was one that people tended to read selectively – focusing on whatever ideas and conclusions they found favour with and rejecting those they had no sympathy for.

Background: Illustration of sea anemone from Ernst Haeckel's *Kunstformen der Natur,* 1899.

5

EVIDENCE FOR EVOLUTION – THEN

The Origin of Species persuaded many readers that evolution occurs because Darwin expounded the arguments for and against with such thoroughness. He also presented them with a vast amount of varying types of evidence.

Darwin laid out the enormous diversity of living things. He described the equally impressive variation within single species, brought about by people controlling the breeding of dogs, horses, pigeons or cattle. He also related the slow appearance – and disappearance – of species in the record left by fossils in the rocks.

The critical evidence came from close comparisons. Comparing fossils from different periods showed gradual change over time. Comparing body plans and bone structures of different living species showed how they were related to one another by common descent. Comparing growing embryos showed how apparently different species looked much more alike when they were at the earliest stages of development.

There was also another line of evidence, which was close to Darwin's heart because it recalled things he had seen with his own eyes on his youthful travels. The distribution of species of many kinds, in many lands, fitted his new view of the long history of the Earth and the power of variation to create slow changes in living forms.

Particularly important here was the life of islands, such as the Galapagos Archipelago. Species found in the same kind of environments on the mainland that could have flourished on islands were often absent – this suggested that the species that live on islands were not created there, but had somehow, in the past, managed to colonise the islands from the mainland.

The Madagascar star orchid *(Angraecum sesquipedale)* has a nectar tube of 25–30cm. Darwin theorised that a pollinator moth must exist with a proboscis long enough to reach the nectar. The hawk moth was identified over 40 years after Darwin's death.

Illustration of the jawbone of the ground sloth *(Mylodon darwinii)*. When he was in Brazil, Darwin discovered a fossil of the ground sloth – which became extinct about 10,000 years ago.

Rare fossil of the 'dinobird' *(Archaeopteryx lithographica)*, the earliest and most primitive form of bird known. In 1868, Thomas Huxley, 'Darwin's Bulldog', was the first to suggest that birds evolved from dinosaurs.

Illustration of a Darwin hawk moth *(Xanthopan morganii praedicta)* feeding from a Madagascar Star orchid *(Angraecum sesquipedale)*.

Pillbox containing fossils collected by Darwin during his travels on *HMS Beagle*.

A new way of looking

'Several classes of facts … seem to me to proclaim so plainly, that the innumerable species, genera, and families of organic beings, with which this world is peopled, have all descended, each within its own class or group, from common parents, and have all been modified in the course of descent.'
The Origin of Species, chapter 13.

Darwin described *The Origin of Species* as 'one long argument'. The argument was in support of the idea of descent with modification. His close study of the way breeders could modify species – such as pigeons – helped him develop his theory and he supported it with other evidence drawn from both his and other people's observations.

His experience on the *Beagle* voyage encouraged him to consider the distribution of species – what we now call biogeography. This was also a special interest of Alfred Russel Wallace, during his own journeys as a naturalist.

Darwin and Wallace were both fascinated by islands. Sometimes islands were so far from the mainland that certain groups of species were completely absent. For example, oceanic islands had no frogs, toads or newts.

'Look closer at the details,' Darwin urged, 'and see that the flora and fauna of any particular island are related to those of the nearest mainland, but are slightly different.' He even identified a relation between the depth of the sea between islands inhabited by mammals and the degree of similarity between the species on the different islands.

All this suggested that the variations in species depended on how long they had been separated. The longer they had lived apart, the greater the chance that they would have changed in ways that distinguished them from a common ancestor.

Added to this was much geological evidence and documentation, from the study of fossils, and from natural history. All were woven into a new concept: how to recognise in the living world, the traces of its long history.

Background: Close up of the centre of an ammonite.

6

EVIDENCE FOR EVOLUTION – NOW

'When we regard every production of nature as one which has had a history; when we contemplate every complex structure and instinct as the summing up of many contrivances, each useful to the possessor, nearly in the same way as when we look at any great mechanical invention as the summing up of the labour, the experience, the reason, and even the blunders of numerous workmen; when we thus view each organic being, how far more interesting, I speak from experience, will the study of natural history become!'

The Origin of Species, chapter 14.

Zebrafish *(Danio rerio)* are now also used as a model organism by geneticists to test their theories of inheritance and gene function.

Darwin gathered a mass of information to support his ideas. The types of evidence he used – from fossils to distribution of species – are all much more developed 150 years later. The proliferation of living forms in the so-called Cambrian explosion around 530 million years ago, for example, has been studied in enormous detail.

But there is even more impressive evidence for evolution from recent biological discoveries, which Darwin had no knowledge of. Much of it comes from studying deoxyribonucleic acid or DNA, the chemical at the heart of heredity, and thus the raw material for evolution.

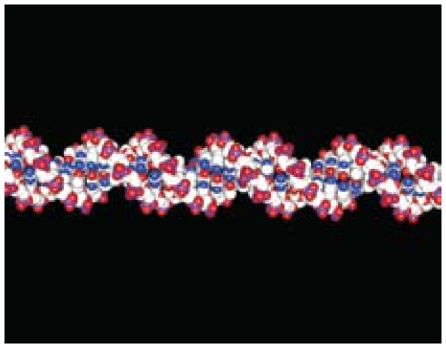
Looking closely at DNA reveals new evidence on how different species are related. Genes for basic components of cells have been preserved through time – most variations here are eliminated by natural selection as they are harmful. Sequencing the same gene in many species reveals a clear pattern of descent with modification.

The longer the time since two species had a common ancestor, the more numerous the small differences in their genes will be. So the human version of a gene will be more like the chimpanzee version than that of a mouse or a fish; the mouse version will be more like that of a rat.

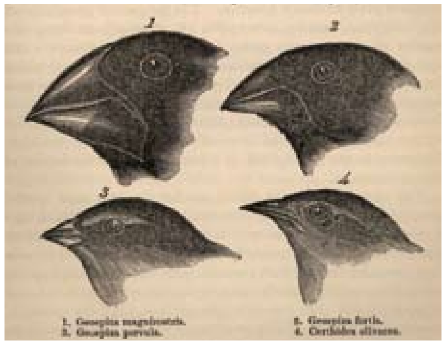
These traces of past change can now be mapped in detail; furthermore, evolution is still in evidence today.

The spread of bacteria that can resist antibiotics is a good example of evolution in action. When chemicals attack, bacteria that can survive the encounter will go on to reproduce when the other bacteria die. As bacteria reproduce quickly, and have other methods of spreading genes between them, the resistance can easily spread faster than scientists can develop new antibacterial drugs.

Wild-type fruit fly *(Drosophila melanogaster)* – this fly has been used since the early 20th century as a model experimental organism by geneticists.



Molecular model of a short string of DNA double helix generated from X-ray diffraction data.



Four species of Galapagos finch with different beaks from Darwin's *Journal of Researches* (1839).

The Galapagos finches

One does not have to study bacteria or DNA to find evidence of evolution in real time. Recent observation of the varied species of finch that Darwin observed on the Galapagos Archipelago – without realising how significant they were – have shown how strong selection can produce noticeable change in a matter of years.

The first finches arrived in the islands between two and three million years ago; those original colonists have now evolved into 14 separate species. The different species have varying environmental preferences, seek different things to eat and often have beaks of dissimilar shapes.

Such features can change in far shorter time than three million years. The Galapagos finches have been studied intensively for three decades by biologists Peter and Rosemary Grant of Princeton University.

When the Grants first did fieldwork in the Galapagos in the 1970s, there were just two species of finch on one of the islands – Daphne Major – the medium ground finch *(Geospiza fortis)* and the cactus finch *(Geospiza scandens)*. In 1977, a catastrophic drought killed many plants, leaving only a limited supply of the small seeds that the birds relied on for nourishment. In the ensuing competition for food, many of the medium ground finches died because their beaks did not have the mechanical power to crack the larger seeds that remained.

The result was that the next generation of finches on Daphne Major had larger, stronger beaks, inherited from the survivors of the drought.

A few years later, the selective effect was reversed when heavy rain encouraged growth of an unusually large population of small-seeded plants – and the birds with smaller beaks had the advantage.

Background: Eye of an adult fruit fly *(Drosophila melanogaster)* – coloured.

7

DOES EVOLUTION CHALLENGE RELIGION?

The epic sweep of the evolutionary history of life is an inspiration to many. As the British palaeontologist Simon Conway Morris put it: 'Evolution discovers the song of creation.'

Conway Morris is a scientist and a Christian, and believes that each perspective enriches the other. His commitment to Darwinism underlines his belief that there is no simple opposition between science and religion.

The idea that Darwin's theory contradicts religion arose because it was, in part, a scientific answer to some questions – such as how species appear – that had traditionally been resolved by religious explanations.

Science and religion are both dynamic sets of ideas. Each venerates basic texts. Like all books, these can be read in different ways. The beliefs that flow from them may appear to be contradictory at times but, to some extent, this depends on how they are interpreted.

Some Victorians who read Darwin's theory, for example, were offended because it negated the role of a creator in the genesis of individual species. People who continue to believe that living organisms originate from specific acts of divine creation still, therefore, find modern versions of the theory of evolution hard to accept.

However, this is only one interpretation of a creator's role in the cosmos. Darwin's theory of species says nothing about the first appearance of life – or about the origins of the universe. It is perfectly plausible to uphold a scientific account of how natural laws allowed the universe, and life, to develop, and to believe that a deity created those laws.

Darwin's most tenacious supporter, the scientist Thomas Henry Huxley, coined the word 'agnostic'. It described his own view that, when the limits of reason are reached, an open mind about the unanswered questions is the best approach.

Even without formal religious belief, anyone who contemplates what modern science reveals about the diversity and intricacy of life is bound to feel the power of one of the universal sources of spiritual feeling – a sense of wonder.

‘Today we are faced with a challenge that calls for a shift in our thinking, so that humanity stops threatening its life-support system. We are called to assist the Earth to heal her wounds and in the process heal our own – indeed, to embrace the whole creation in all its diversity, beauty and wonder. This will happen if we see the need to revive our sense of belonging to a larger family of life, with which we have shared our evolutionary process.’

Wangari Maathai, Kenyan environmental activist, awarded the Nobel Peace Prize in 2004.

A sacred epic

Darwin saw no contradiction between his idea that all forms of life evolved from earlier species, and beliefs in a creator deity. Soon after *The Origin of Species* was published in 1859, the Anglican clergyman and novelist Charles Kingsley wrote to Darwin about the book. ‘I have gradually learned,’ he said, ‘to see it as just as noble a conception of deity to believe that he created primal forms capable of self-development … as to believe that he required a fresh act of intervention. I question whether the former be not the loftier thought.’

Darwin admired this sentiment and, with Kingsley’s agreement, included it in later editions of *The Origin of Species.*

Since then, some adherents of all religions have continued to take inspiration from the richness of the natural world, which remains, for them, as wondrous after Darwin as it was before.

As Simon Conway Morris said: ’Animals that are the end result of many billions of years of prior stellar and biological evolution may be the only way to allow at least one species to begin its encounter with God.’

Others, such as the US evangelist Michael Dowd, have preached that evolution is a sacred epic, revealing a story of complexity that unfolds over 14 billion years.

Darwin’s notion of modification with descent is supported by the fine detail of similarity between many genes shared by all species, which has been confirmed by the human genome project. This emphasis on the unity of creation is a further inspiration to many.

8
HOW DO NEW SPECIES APPEAR?

Plate showing four forms of *Heliconius numata*, two forms of *Heliconius melpomene*, and the two corresponding mimicking forms of *Heliconius erato* highlighting the diversity of patterns and mimicry in *Heliconius* butterflies.

Darwin offered a theory to explain how one species can change into another. That is what evolution means. Accepting his theory meant overturning the older view of species as distinct kinds, which stay the same for ever. Although it convinced biologists around the world it also prompted questions that are still being debated.

One such question, vital for biologists, was how exactly does change within a population lead to recognisably different species?

A possible reason is separation. When, for example, part of the population is segregated – by, say, a mountain range, river or sea channel – and if the barrier is maintained for a sufficient length of time, the two populations will change enough to become unable to interbreed. That is often taken as an unassailable condition for two collections of similar creatures to be classed as separate species. However, it is not the only one, and it does not always apply.

Another possibility, which has received more attention in the last two or three decades, is that sub-populations, which are not physically separate, can find other ways of moving apart biologically. Genetic changes create small differences in behaviour – such as eating habits, or mating preferences – which can gradually increase. Over time, these lead to divergent ways of life without physical separation.

Professor Jim Mallet of University College London has been exploring how this can work in a series of closely related species of tropical *Heliconius* butterflies. Butterfly wing colours and patterns change easily. That itself does not lead to new species. Some of the butterflies exude chemicals with a taste that is repugnant to butterfly-eating birds. He also discovered that male butterflies have a strong preference for females whose wings match their own. As these characteristics interact, new species emerge, and they no longer interbreed.

Left: Illustration of a Galapagos mockingbird *(Mimus melatonis)*. Variations between the mockingbirds on the Galapagos Archipelago first aroused Darwin's attention to the distribution of species on the islands.

Reproduced with permission from John van Wyhe, ed., The Complete Work of Charles Darwin Online (http://darwin-online.org.uk).

Below: The Galapagos Archipelago.

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Two sides of a coin

'It is important to remember that naturalists have no golden rule by which to distinguish species and varieties; they grant some little variability to each species, but when they meet with a somewhat greater amount of difference between any two forms, they rank as species.'
The Origin of Species, chapter 9.

The latest views on how new species arise are consistent with Darwin's, argues Professor Jim Mallet. In the second half of the 20th century, most biologists believed that different species were cleanly separated and differed sharply from their evolutionary relatives. This made it harder to see how they came into being, unless there was a long-term physical separation imposed by mountains or seas. Scientists call this *allopatric* speciation.

Mallet believes that differences between species are continuous with variations within a species. This was also how Darwin described the situation in *The Origin of Species*. He was influenced by his studies of artificially bred varieties, such as pigeons. A more familiar example would be dogs, which human breeders have fashioned into many different types. Technically, all remain the same species – though a Chihuahua might have a problem mating with a Great Dane.

This kind of variation could be the start of a long-term process. A species under natural selection, as opposed to human influence, can develop a range of types, perhaps showing different ecological adaptations. Some of the types then acquire differences, which become so well established that they can be classed as separate species, even though they can still produce hybrid offspring occasionally. Eventually, they may turn into creatures that are related, with a shared ancestor but that no longer cross, in line with the commonly used strict definition of species.

All of this can happen while the different varieties live alongside one another in the same geographic region. The technical term for this is *sympatric* speciation. This process suggests how species are still changing all around us. As Mallet puts it: 'Speciation is easy.'

The work is also important in probing the roots of biodiversity, and for planning conservation efforts. Speciation and extinction are two sides of a coin.

Background: Wing scale detail from purple emperor butterfly *(Apatura iris)*.

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9
EVOLVING HUMANS

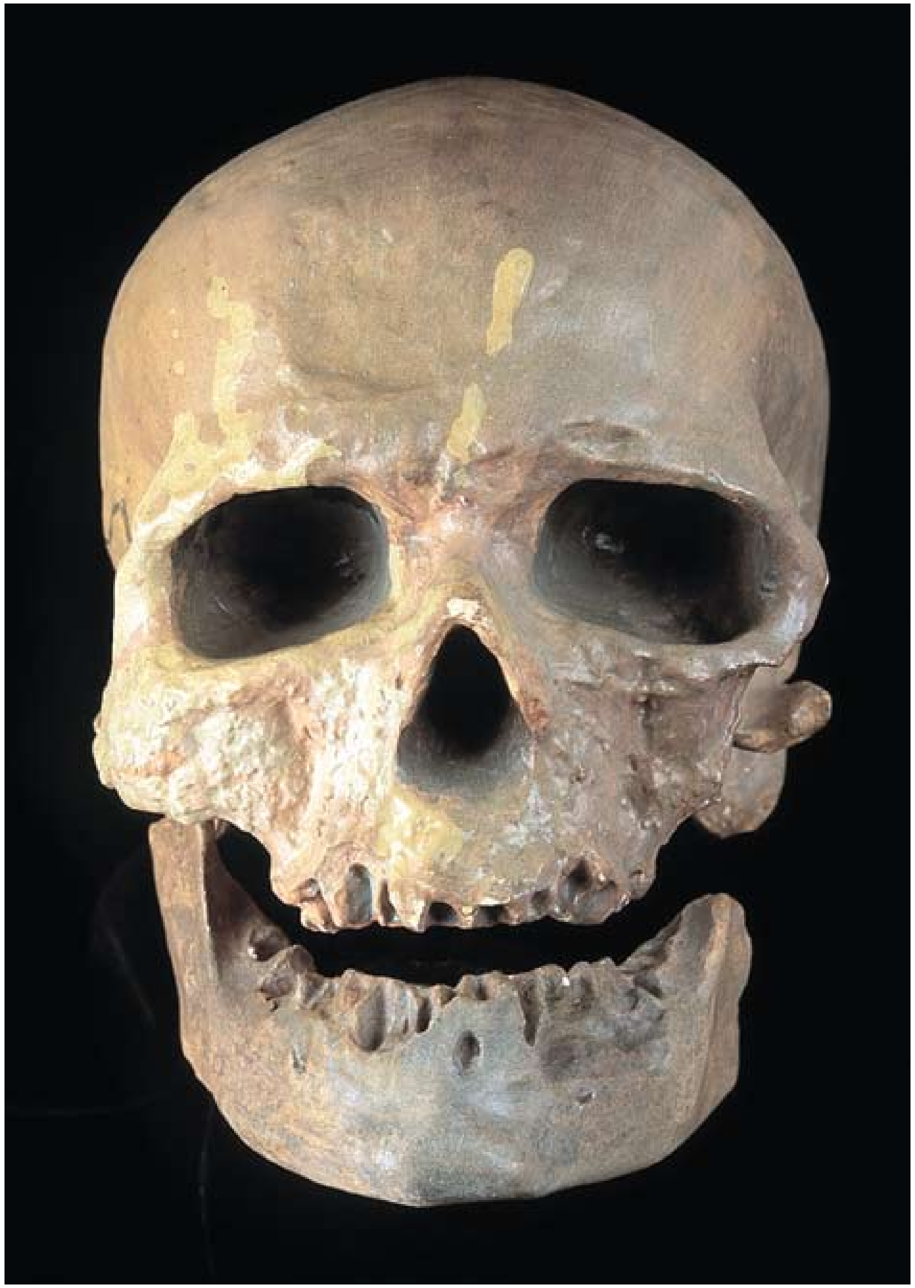
Darwin's theory of common descent had a startling implication: 'Humans are not separate from the rest of nature. Yet we are also clearly different from other creatures. Evolutionary theory is a product of human culture, which is itself a mark of that difference.'

Explaining the emergence of human consciousness and culture still challenges researchers in many fields. We can now compare the complete gene sequences of humans and our closest living relatives, the chimpanzees. This offers clues to which changes in DNA were crucial in producing prominent human traits. Our enlarged brains, upright walking, and use of language must have begun with genetic mutations, and these are still being unravelled.

These genetic studies combine with analysis of other traces from the past to build up a picture of more recent developments in human culture – such as tool-making.

Detailed examination of stone tools from many ancient sites can be used to map a new kind of gradual change – cultural evolution. Robert Foley, Director of the Leverhulme Centre for Human Evolutionary Studies, University of Cambridge, emphasises that changes in tools can be seen in two ways. First, they may be a record of development and migration of groups, which used different techniques to sculpt their flints. Second, the differences may have more to do with responses of groups with similar skills to different environments, or to the kind of rocks they could obtain. 'Both history and ecology are important, as is the case with most evolutionary problems,' he says.

Then comes a more speculative part of the story – determining what the use of these techniques suggests about the different tool-users' thought processes and systems of planning, co-operation and communication.



Frontal view of a cast of a skull belonging to *Homo sapiens Le Vieillard*, adult male about 45 years of age.

Left: Flint hand axe from the late Palaeolithic period, England.

Below: Left to right: *Australopithecus africanus; Homo rudolfensis; Homo erectus; Homo heidelbergensis; Homo neanderthalensis;* and *Homo sapiens*. Arranged in chronological order these specimens (casts) illustrate human evolution.

The past in the present

The emergence of modern humans is a long story that begins in our proto-human past. It can be told only from traces that survive in the present. Human and chimp DNA, for example, show two possible outcomes from the last common ancestor of the two species, which lived between four and six million years ago. But this does not reveal when gene changes between the two present-day species happened, or in what order. As in the comparative anatomy of bones, which was becoming a more precise study in Darwin's day, there is abundant scope for argument.

The same is true of samples of Neanderthal DNA, which allow comparison with a much closer relative of modern *Homo sapiens* – and are taken from bones that are 45,000 years old. However, to go further back, scientists need data from material that endures longer than DNA.

Fossil bones remain an important element. They have been used to reconstruct a human lineage in which the ancestors of modern humans diverged from our extinct relatives – the australopithecines – about two million years ago.

Over roughly the same period, many stone tools have survived. These can be studied as a record of cultural, rather than biological evolution. Over time, these tools became more varied, more complex, and needed more complicated preparation. Comparing tools from different sites, and tools that can be dated to different times, reveals how early humans' cultural capacities developed.

The challenge then is to bring fossil and DNA evidence together to give a more complete account of how the diverse strands of evolution worked together – as brain, hands and tools helped primate bands turn into human societies.

Background: A chimpanzee using a grass stem as a tool to fish for termites.

10 HOW DID MUSIC EVOLVE?

Wherever people are found, there is music, but how did music-making evolve? Darwin raised the question, but found no answer. The difficulty was in determining what advantage is offered to the music-maker by the making of music.

Bells on a classical Indian dancer's ankles.

Speech and music both involve sound. Which came first – music or language – remains unclear. Scientists can study changes in the vocal tract as early humans developed, but the sounds they made leave no trace. Studies of modern brains show that some regions are involved in both understanding language and interpreting music. Yet there are people who are both tone deaf and non-stop talkers.

Some Darwinian theorists, such as the Harvard psychologist Steven Pinker, have suggested that music is an accident, not an adaptation. It satisfies our ears in the same way that a slice of cake appeals to our taste buds.

Others, following Darwin himself, think sexual selection is important. Geoffrey Miller of the University of New Mexico argues that music is driven by mate choice. Simply put, musical performance is rather like the courtship display seen in many other species.

Steven Mithen of the University of Reading, England, has recently advanced a different view. Drawing on archaeology, fossil evidence, and studies of brains, genes, language and music in many cultures, he suggests that music and language both emerged from a common precursor – a quasi-musical use of sound – which our ancestors used for communicating. These complex calls could have found uses as infant lullabies or as part of group celebration. He also suggests that the groups that developed this use of sound had more offspring and more descendants, which is why music-making survives today. However, this route to reproductive success is more complex than simple mate choice.

Above left: Musician from Benin with flute and small percussion instrument.

Above: Marine band playing bagpipes.

Left: Girls playing a Chinese drum.

Below: Women playing the traditional Japanese instrument, the kato.

Humans and music

In his book *The Descent of Man, and Selection in Relation to Sex* (1871) Darwin considered the elements that set humans apart from other creatures – language, for example, and the ability to create culture. He was convinced that these qualities had evolved in the same way as any other characteristic. Music, however, was perplexing. 'As neither the enjoyment nor the capacity of producing musical notes are faculties of the least use to man … they must be ranked among the most mysterious with which he is endowed,' he wrote.

Darwin argued that music arose through sexual selection – as did the sounds made by other species he wrote about, such as frogs, toads, tortoises, alligators, birds, mice and gibbons. Humans, however, do more than just sing (or hum, chant or whistle). We also have a sense of rhythm – expressed in drumming or dancing – that is not found in other creatures.

Steven Mithen's story of the evolution of human music – described in his book *The Singing Neanderthals: The Origins of Music, Language, Mind and Body* – brings all these things together. He speculates that our primate ancestors evolved complex vocal calls that were a little like singing. They would be accompanied with gestures, which became more elaborate when hands were freed by walking upright.

The result, he suggests, was a communication system that preceded language and music. It used emotion, conveyed by varying pitch, just as parents now use wordless sounds to communicate with babies.

All of this helped bind groups together, and perhaps cemented co-operation, therefore increasing survival rates. From this early communication emerged the universal use of music and dance in ritual and celebration, which still appear to reinforce group ties in modern human societies.

Background: Sheet music score.

11
HOW DO GENOMES EVOLVE?

Genetic change is the motor of evolution. A single change in a gene's DNA sequence might be of no consequence or it might be damaging, leading to a defective protein molecule; occasionally, it might be advantageous.

In the 21st century, the story is becoming more complex. Biologists are now looking at entire genomes – the complete library of DNA in each cell of an organism.

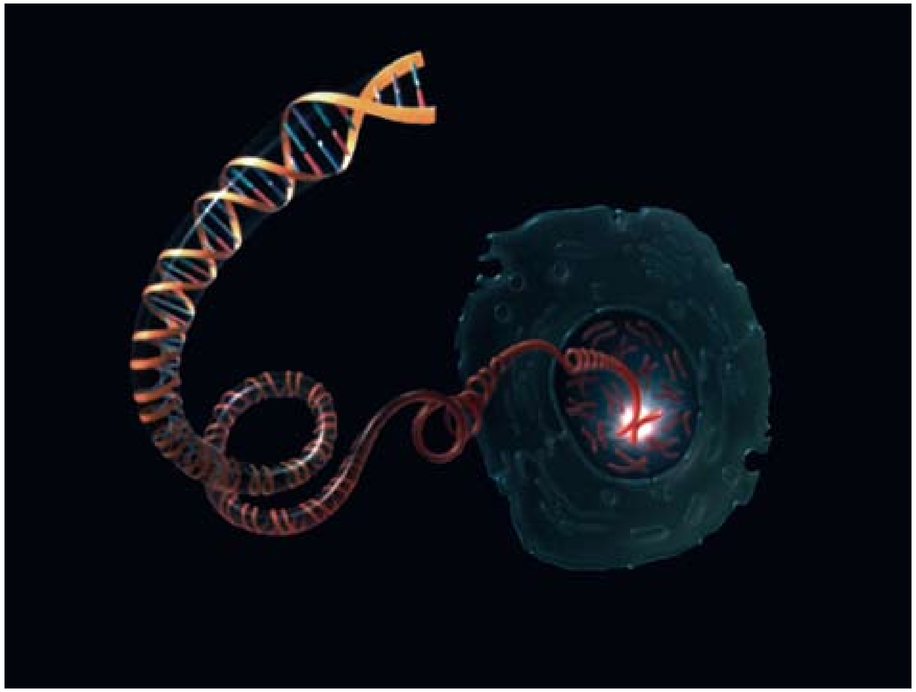
The human genome, for example, has 3,400,000,000 DNA 'letters', known as bases and labelled chemically C, A, T, or G. However, the 25,000 or so human genes take up less than two per cent of this massive total. So, what is the rest of that DNA doing?

It might be 'junk' – a kind of harmless molecular parasite. If so, mutations in the vast majority of the genome would go unnoticed, but we now know that large parts of these sequences are conserved. Natural selection has removed any random changes in the DNA, so it must be used for something.

While work on this continues, other studies of genomes have shed light on larger mechanisms of evolution. 'Junk' DNA can contain non-functional genes – a kind of genetic fossil – or it may contain duplicates of important genes. If there is an extra copy of such a gene, it does not matter if mutations slowly build up. This means the organism can experiment with varied forms of the gene that may, in turn, find entirely new uses. Much more rarely, copying mistakes can lead to duplication of an entire genome. This seems to have happened several times during the evolution of creatures with backbones, for example. Some researchers suggest – controversially – that such full-scale duplications are vital for the development of more complex creatures.

Mustard weed *(Arabidopsis thaliana)*, the first plant to have its genome sequenced.

Courtesy of the National Human Genome Research Institute.

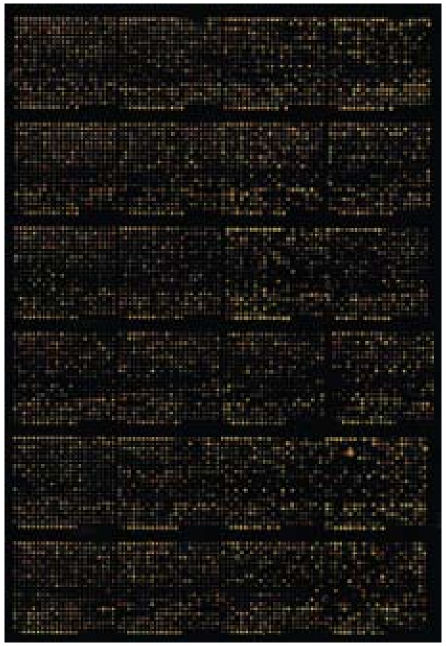


Above: Model of a strand of DNA extending from the chromosome of a cell.

Courtesy of the National Human Genome Research Institute.

Right: Microarrays showing a snapshot of all the genes active in a cell at a particular time.

Courtesy of the National Human Genome Research Institute.



Modelling the genome

Now biologists are becoming familiar with all the genes in a single organism – its genome – they would like to know how big a genome has to be. What does any organism need to stay alive? The simplest organisms ought to have the smallest possible complement of genes. One method is to take a bacterium and remove, or 'knock out' genes, one by one. If you remove a gene, and the organism survives and can reproduce, it is not essential – or so researchers argued.

However, this method can lead to errors that arise when one gene compensates for the removal of another. Remove the other gene instead, and the first makes up the deficit, but that does not mean that the function the gene allows is not essential, rather that it is so important, the organism has protected itself by building in a safety factor. This gives the false result that the loss of a particular gene – apparently – has no effect on the organism, and genes can be removed that should be included in the 'minimal genome' – the smallest set that can keep the bacteria alive.

Professor Laurence Hurst of Bath University in the UK, with collaborators in Manchester, Heidelberg, and Budapest, approached the question by developing a different technique for modelling the genome that uses data about the evolutionary history of the organism and how it interacts with its environment.

His team's approach, which was tested on two kinds of bacteria that live symbiotically inside insects, indicated that the minimal genome was almost twice as big as 'knock out studies' had indicated.

This research suggests that the content of a genome can be predicted to a large extent from knowledge of its ecology. This is likely to be important in further studies of the evolution of other organisms, and perhaps for efforts to develop bacteria with particular properties such as clearing pollutants.

Background: Growing crystals of a DNA repair protein bound to DNA.

12
INTIMATE EVOLUTION

Darwin was fascinated by examples of organisms that have adapted to each other: a flower with deep-buried nectar and a moth with a tongue long enough to reach it must have evolved together.

This kind of co-evolution is a powerful influence on many diseases – ones caused by one organism living inside another. The enduring worldwide killer malaria is an important example. Researchers hope that new insights into the evolution of malaria, and its mosquito and primate hosts, will open up new lines of attack on the disease.

A recent landmark was the completion of the genome sequence of *Plasmodium falciparum,* the malarial species most dangerous to humans.

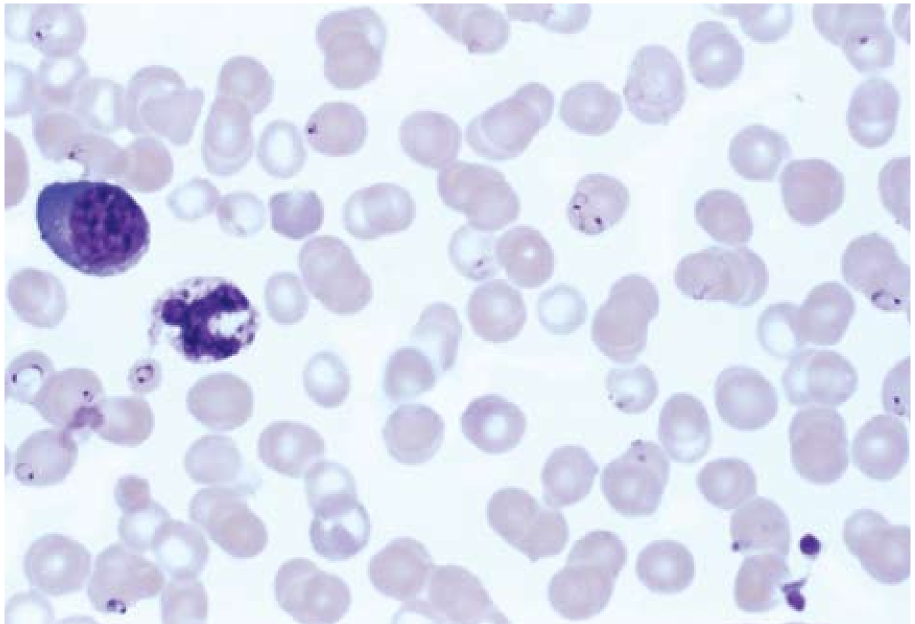
P. falciparum has some DNA sequences that are preserved almost identically in nearly all samples. Others vary much more. These variant sequences help build proteins that can be targets for the human immune system. The parasite looks as if it is evolving to evade its host's defences.

One puzzle is why malaria is so harmful. The evolutionary history indicates that some variants of the parasite have been infecting humans for millions of years, but there is evidence it has become more deadly in the last few thousand years. More research may help explain whether changes in malaria, or in its human hosts, led to this shift. There is a third player in this particular evolutionary game – the mosquito, which harbours the parasite during half of its complex life cycle. Therefore, small changes in insect behaviour, such as which animals' blood the mosquito chooses to feed on, and how often, can have a big effect on disease transmission.

Such studies will also be important for tracking the possible effects of climate change on mosquito populations, and hence on the risks of an increased spread of malaria.

A mosquito *(Anopheles stephensi)* in flight with its abdomen full of blood.

Illustration of the blood stages in the life cycle of *Plasmodium falciparum*, the parasite that causes malaria.



Above: Blood smear showing the presence of *Plasmodium falciparum* parasites in the red blood cells.

Opposite page background: Scanning electron micrograph (1990–2002h) showing oocysts of the parasite that causes rodent malaria, *Plasmodium yoelii nigeriensis*, developing on the mid-gut wall of the mosquito *(Anopheles stephensi)*.

Malaria – evolutionary complexity multiplied

Malaria is one of the world's great unsolved health problems. Hundreds of millions of people are infected with the malaria parasite through mosquito bites, and the disease causes more than a million deaths every year. Millions more are laid low by the recurrent symptoms, including fever, chills and muscle weakness.

The disease comes from a tiny parasite, which lives inside the cells of its hosts. Its life cycle is unusually complicated, involving different types of cells, and in different organisms, at different stages. From an evolutionary point of view, the three-fold co-operation – or conflict – between mosquito, human and parasite provides many places for selection to operate. Sometimes this is natural selection, as in the interaction between the human immune system and rapidly evolving genes in the parasite. This also makes it much harder to develop a vaccine against malaria. Sometimes the selective process is a response to human activities, for example, when the malaria organism develops resistance to new drugs, or – less directly – mosquitoes develop resistance to insecticide sprays.

In humans, there are a number of genetic variations, which seem to make people more resistant to malaria. The blood disorder sickle-cell anaemia arises when someone has two copies of a gene for the oxygen carrier haemoglobin, which both have a slightly altered sequence. Normally, such a change would die out. However, inheriting just one copy of the gene does not cause anaemia, but does lead to changes in red blood cells that make it harder for the malaria parasite to survive. Hence, the gene persists in areas where malaria is also common.

Recent research continues to uncover new details of the evolutionary relationships that affect how common the malaria infection is, and how harmful it is to infected people. David Conway, who heads the malaria research programme at the UK Medical Research Council's Laboratories in Gambia, is unravelling the way the human immune system deals with the parasite, and how it fights back.

Other work could open up new routes to controlling the disease. Dr Steven Sinkins, from the Department of Zoology at Oxford University, is studying the evolution of interactions between mosquitoes and another insect parasite – a group of bacteria known as *Wolbachia* that affects the insects' reproduction in complex ways. One possibility is to understand *Wolbachia's* genes well enough to manipulate them to make mosquitoes sterile on demand.

13
A LARGER SYNTHESIS?

Understanding natural selection in terms of genes cemented Darwin's place at the centre of biology. The union of genetics with Darwinian evolutionary theory was famously dubbed the 'modern synthesis' in a book by Thomas Huxley's grandson, Julian, in 1942.

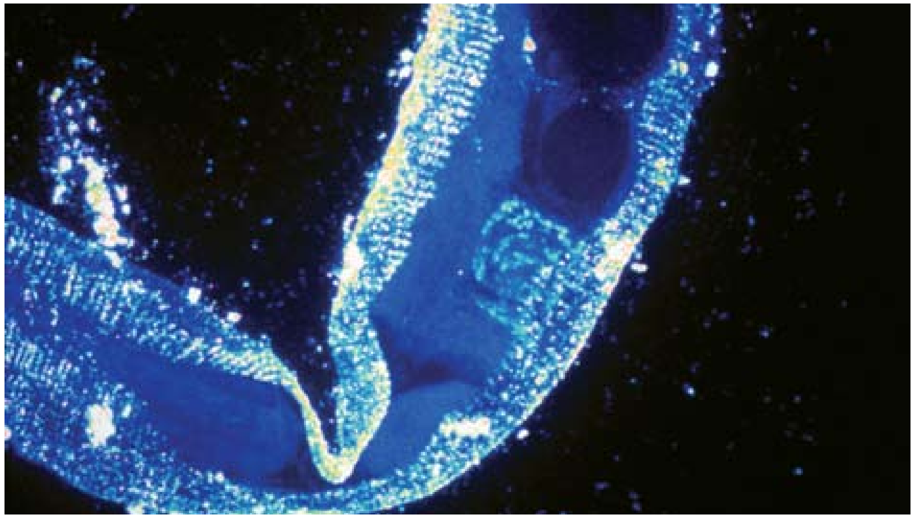
A stage 16 chick embryo showing where the Hoxa-2 gene is switched on (purple). Hoxa-2 is a transcription factor, binding to DNA and affecting the action of other genes.

The study of whole genomes, and collections of genomes, has shed new light on the mechanisms of evolution.

Recent research has focused on the DNA of complete microbial communities, rather than on individual microbes. This work highlights co-operation rather than competition. For example, the series of reactions needed to build up or break down a particular chemical can be distributed between different microbes that live together, even if they are quite different species. Only when all the microbes work together, with each species causing a particular reaction in the series, can the process be completed.

Research on the operation of genomes in individual cells also reveals unexpected levels of complexity. Many genes are marked with special 'marginal notes', left by adding or modifying chemical groups at precise locations on the outside of the molecules of DNA. These markers affect whether the genes can be switched on or off – and the complete set of markers in a cell registers its state of development.

In addition to these so-called epigenetic markers, recent research is finding many new types of the cellular messenger molecule RNA. They are read from parts of the genome whose purpose was previously unknown, and also help regulate gene action. Here is yet another level for evolutionary selection to operate – which is still being explored.



Confocal image reconstruction of the nematode worm *(Caenorhabditis elegans)*, often used for genetic studies. The confocal microscope takes a series of sections through a specimen that are reconstituted to produce a three-dimensional image.

Above: Image of hatching nematode.

Opposite page background: A frontal section of a stage 23 chick embryo head showing the distribution of transcripts of the Barx-1 gene.

DNA and transposable elements

Understanding how evolution proceeds through changes in the genetic material DNA was a significant development.

In the 21st century, scientists are learning more about how genomes can change without the actual DNA sequence – the most basic information they contain – being altered. These changes can also be passed on to a new generation. The study of heritable changes in genomes that can occur without a change in the sequence of DNA 'letters' is the modern definition of *epigenetics*.

Epigenetic changes are often due to the attachment or removal of relatively simple chemical groups. They may be used to tag particular locations on the DNA. Alternatively, they modify the special proteins that manage the packaging of the long, twisty DNA molecules in the cells of higher organisms. Altering these proteins – the histones – can affect whether a particular stretch of DNA can be read by the molecular machines that use the information it preserves.

One particularly powerful way for epigenetic changes to influence the activity of genes is when they interact with another recently discovered feature of genomes. Most complex genomes are home to bits and pieces of DNA that can jump around between parts of the genome, or even between cells. Many are remnants of viruses that infected the organism's ancestors long ago in evolution.

They still play a part in life and evolution today. Small, repeated sequences – called transposable elements – in the genomes of plants move from place to place, and switch whole genes on or off.

The twist in the story is that the mobile elements are themselves controlled by the addition of a simple chemical group – a methyl group – which inhibits their transfer from place to place. However, when plants are put under environmental stress, these methyl groups may be pulled off and the transposable elements become active.

Peter Meyer of the Centre for Plant Sciences at the University of Leeds, England, suggests that this complex system brings advantage to the plant by allowing it to adapt more swiftly to environmental change.

Understanding these mechanisms is also important when attempting to modify plants by introducing new genes. These newly inserted genes may work as researchers hoped in young plants, but become inactive as the plants age – especially if they become stressed. The plants' epigenetic controls modify the tags on the new gene, without affecting its DNA sequence, and stop it working.

14
WHY SO MANY?

Darwin's account of the origin of new species does not make it clear why there are quite so many similar ones.

In fact, natural selection might lead one to expect a 'winner takes all' competition. Each small space in an ecosystem would end up harbouring just one, amazingly well-adapted species.

However, many ecosystems are not like this. There are 300 different kinds of trees in a typical hectare of tropical forest. Even a habitat such as chalk grassland can support over 50 species per square metre. They do not seem to have adapted to different conditions but, according to Darwin, even plants are competing to survive. So how do these similar species co-exist?

The answer is that environmental differences can be subtle. Small variations in sunlight, in water, in the soil, or in how deep roots grow, can mean that similar plants experience different conditions. Also, the better the plants are suited to one precisely defined environment, the less likely they are to compete effectively with plants adapted to a slightly different one.

The renewed attention to variations in micro-environments features in the work of Professor Jonathan Silvertown of the UK-based Open University. He first showed how variations in water use help separate species in English country meadows. This established the importance of 'hydrological niches' – which differ based on how much effort it takes a plant to take up moisture from the soil, or to avoid getting waterlogged. He is now investigating some of the many thousands of species found in the Cape region of South Africa to record how his findings apply in other countries.

Chalk grassland at Cuckmere Haven, East Sussex, England.

Image reproduced with permission of Dr Fern Elsdon-Baker.

Cape Point, South Africa, where Jonathan Silvertown is conducting research.

Mimetes fimbrifolius, Western Cape, South Africa.

Image reproduced with permission of Prof. Jonathan Silvertown.

Berzelia Lanuginosa, Western Cape, South Africa.

Image reproduced with permission of Prof. Jonathan Silvertown.

DARWIN INITIATIVE

Jonathan Silvertown's research is funded by the Darwin Initiative. More information about his research is available in his book *Demons in Eden: The paradox of plant diversity*, Chicago University Press (2008). See www.demonsineden.com.

Biodiversity

There are still many evolutionary puzzles to solve, and South Africa presents a major challenge to a theory of biodiversity. It comes in the form of heather and other plants, which have evolved a richness of varieties not seen elsewhere. Heather of the genus *Erica*, for instance, is found in just a few kinds of heaths in Europe. In the Cape region of South Africa the Fynbos heathland harbours more than 800 types. How can there possibly be 800 different environments for them to have adapted to?

This question did not occur to Darwin when *HMS Beagle* stopped at Cape Town in 1836. His unusually acute powers of observation failed him; he found the treeless mountainsides rather dull, and reported that there was 'little worth seeing'.

Other plants in the region have also generated many separate species, for example the plants known as restios, of which there are 350 varieties. They differ in size, but that cannot be the only factor determining their survival.

In the UK, Jonathan Silvertown and his collaborators have shown that apparently unvarying grassland habitats have many small environmental differences, which favour different kinds of plants with varying preferences for the moisture content of the soil.

Research is continuing to test whether something similar has happened in the Cape, which would suggest that the explanation is widely applicable. If so, it would fit with a complementary theory that so many plants appeared in the region because it has been unusually climatically stable over the recent evolutionary past – the last few hundred thousand years. That would enable species to become more specialised in their habitat, without risking their survival when there were relatively small changes in temperature or rainfall.

Background: Snake's Head Fritillary *(Fritillaria meleagris)*, which grows in grasslands and river meadows in Europe.

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