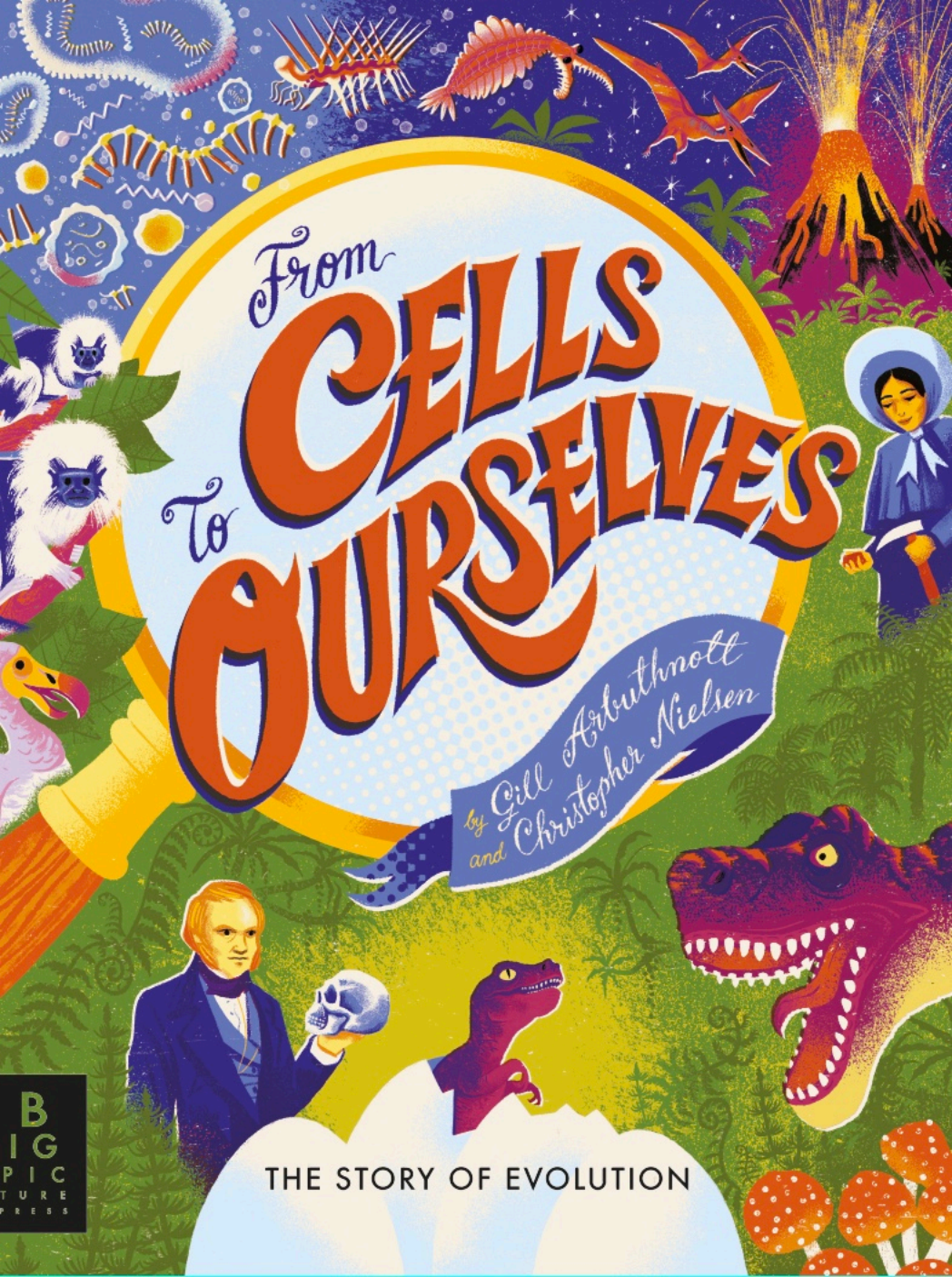
From
CELLS
to
OURSELVES
by Gill Arbuthnott and Christopher Nielsen
THE STORY OF EVOLUTION
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PRESS

For Marko, Yuliia and Oleh. – GA
For Bruce, a wonderful stepdad and grand-poppy. CN

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From Cells to Ourselves

Gill Arbuthnott • Christopher Nielsen

BPP

FROM THE AUTHOR

I've spent many hours watching dinosaurs terrorise humans on screen. King Kong battled a *T. rex* to save the woman he loved. Stone Age people with improbably well-groomed hair ran screaming from huge beasts in *One Million Years BC* and later, trembling children hid from velociraptors in the kitchens of *Jurassic Park*. All nonsense of course; dinosaurs had been extinct for nearly 65 million years before the first humans existed.

Dinosaurs were around for 165 million years, but it's a mere seven million since the first recognisably human ancestors appeared. Where did the dinosaurs go and where did the humans come from? It's a very long story indeed. It's the story of evolution.

Of course, it doesn't begin with humans or dinosaurs. It begins with the development of the very first cells and ends... It doesn't end. It's going on all around us right now, but usually it happens so slowly we don't notice it. Humans, just like other plants and animals, are still evolving and adapting to changing conditions.

There are winners and losers in evolution: species that can't adapt well enough go extinct. This happens all the time, but there have been five mass extinctions which wiped out 75% of the species alive at the time. It was one of these which doomed the dinosaurs and gave humans their chance. Many scientists think we are in the middle of the sixth mass extinction now, and that humans are at least partly to blame.

We are surrounded by the extraordinary evidence of how evolution shapes life, from peacocks to penguins, bats to bonobos. Humans have already driven some species to extinction, but we are the only species that can understand how precious the others are, so let's try our best to look after them. Not just the cute ones – the whole squishy, slimy, prickly, glorious variety of living things!

Gill Arbuthnott

TIMELINE

* mya = million years ago

4560 mya* Earth develops.

3800 mya Oceans develop.

3800 mya Early simple (prokaryotic) cells appear.

2700 mya Evidence for complex (eukaryotic) cells.

2400 mya Photosynthetic bacteria start producing oxygen.

2400–2100 mya Oxygen replaces methane in Earth's atmosphere.

1500 mya The first multicellular organisms (mats of algae) form.

700 mya The first animals (sponge-like) develop.

600 mya Ozone layer develops, protecting earth from UV radiation and allowing life to move onto land.

538–510 mya Cambrian explosion of marine life.

500–450 mya The first land plants appear.

500–450 mya Early vertebrates (bony fish) appear.

444 mya The first mass extinction event (Ordovician-Silurian) occurs.

420 mya Early shark-like fish develop.

385 mya Evidence for the first insects.

365–350 mya Early land vertebrates (amphibians) develop.

370–360 mya The second mass extinction events occurs (Late Devonian).

300 mya Early reptiles appear.

252 mya The third mass extinction event, 'The Great Dying', occurs (Permian-Triassic).

240–230 mya The first dinosaurs appear.

210–200 mya Early mammals appear.

210 mya The fourth mass extinction event (Late Triassic).

150 mya The earliest birds appear.

66 mya The fifth mass extinction event (the Cretaceous–Paleogene).

66 mya The 'Age of Dinosaurs' ends.

65–60 mya Early primates appear.

7 mya Early hominins appear on the human lineage.

4 mya Australopithecus appears.

2.5–2.3 mya Evolution of *Homo habilis*.

0.3–0.25 mya The first members of our species, modern humans, *Homo sapiens* appear.

In the BEGINNING

Every civilisation and religion has creation stories that try to explain the origin of the Earth and the living things that populate it. In many of these stories, a wise and powerful supreme being creates the world and everything in it from nothing. In others, a 'cosmic egg' splits open and everything emerges from that. Some stories feature a giant whose body turns into the world, while in others an animal dives to the bottom of an ancient ocean and comes up with a little piece of earth and the whole universe is created from this.

How much do we know about the true scientific origins of the Earth and how life began? Philosophers and scientists were trying to answer these questions thousands of years ago, but it was only in the 17th century that people started to understand the physical evidence that gave clues to the early history of our planet, as the science of geology began to develop. The 18th and 19th centuries saw great advances in understanding the geology of the Earth, and the discovery of radioactivity gave scientists a reliable way to measure the age of different rocks.

As more evidence has emerged, we have pieced together the story of the Earth's violent beginnings. But there are still many more questions to answer about how life on planet Earth began...

MYTHS AND LEGENDS

Many cultures have their own creation myths. Here are a few from around the world.

EGYPTIAN

In the beginning there was only watery chaos, called Nun. The sun god, Ra, emerged from this, bringing light with him. Ra created Shu, the god of air, and Tefnut, the goddess of moisture. Their children – the sky goddess Nut and the Earth god Geb– created the rest of the universe.

MAYAN

The creator gods and Gucumatz, the feathered spirit, made the world from their thoughts. They created humans so there were creatures with hearts and minds. They used clay to create a man, but he crumbled; they tried wood, but the man was heartless. Finally, they made humans from corn, and these were intelligent and empathetic.

MĀORI

Ranginui, the sky god, and Papatūānuku, the Earth goddess, held each other so tightly that no light could get between them. Their children wanted to let light into the world and eventually one of them forced the sky and earth apart. The children became gods of various parts of the Earth and created the other creatures.

YORUBA

Olódùmarè the Supreme God, sent 17 orishas (gods) to populate the Earth. The 16 male gods failed at this task, and it only succeeded when Oshun, goddess of life and fertility, sent the water she ruled to bring life to the Earth. From this, all living things were created.

CHRISTIAN AND JEWISH

God created the heavens and the Earth. He shaped the planet and gave it mountains and seas, light and darkness. In six days he created all the plants and animals and Adam and Eve, the first humans. On the seventh day, God looked at what he had made, and was pleased. He rested, and declared the day holy.

ISLAMIC

Allah created the universe and all the living and non-living things in it. He sent the angels he had created to Earth to collect seven handfuls of soil and from these, Allah made Adam, the first man. Eve, the first woman, was created from Adam by Allah.

CHINESE

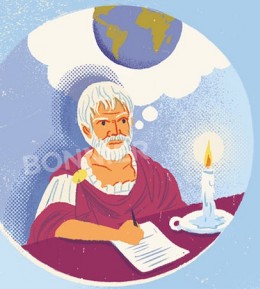
The universe was a huge chaotic egg. Inside it was the giant, Pang Gu. When he broke out, the light part of the egg rose to form the sky and the heavy part sank to form the Earth. Pang Gu stood between them to keep them apart for 18,000 years. When he died, his eyes became the sun and moon, his hair the stars, his body the mountains and his blood, water.

THE GIANT WHO FORMED THE WORLD

In Norse mythology, the giant Ymir was the first being, who formed when the ice of Niflheim met the fire of Muspelheim. He was eventually killed by the gods who were descended from him. They cut up his body and used his flesh to make the Earth. His bones became mountains, his teeth became stones, his blood became the sea. His skull formed the sky, with his brains as the clouds. His eyebrows and eyelashes became a fence surrounding Midgard, the home of humans.

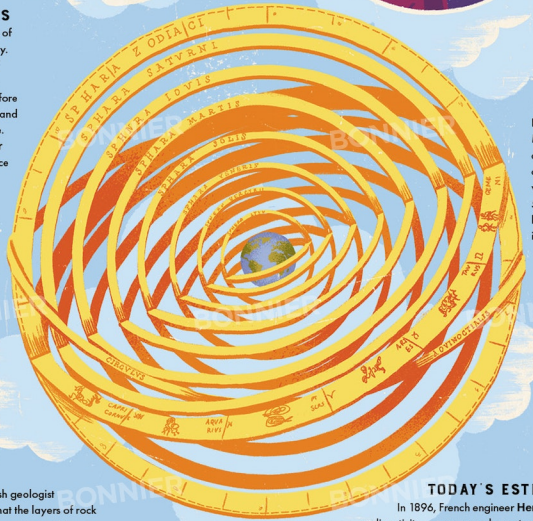
HOW OLD IS THE EARTH?

Today, we have a good understanding of the age of the Earth, and increasingly sophisticated ways of measuring it. But when people first began to wonder how old the planet was, what did they think?



ANCIENT GREEKS AND ROMANS

The Greek philosopher **Aristotle**, like most people of his time, thought that the Earth had existed eternally. Over the next centuries, people based estimates of its age on how far back their written records went. Roman poet **Lucretius** thought it began shortly before the Trojan war. Some people used family lineages and dates of reigns in religious texts to estimate the age. Famously, in the 1650s Archbishop **James Ussher** calculated that the creation of Earth had taken place at nightfall on the 23rd October, 4004 BCE.



17TH CENTURY

Around the same time, Danish geologist **Nicolas Steno** suggested that the layers of rock in the Earth's crust were a chronological history of the planet. He also proposed that fossils were the remains of living things and that some rocks formed from sediments like mud and silt. These were revolutionary ideas which would be confirmed over the next two centuries.

18TH CENTURY

In the 18th century, **James Hutton**, Scottish 'father of geology', suggested that some rocks were continuously broken down by erosion caused by ice, water and wind. At the same time, others were formed by volcanic eruption and the internal heat of the planet which solidified sediments into sedimentary rock. He realised that the accepted age of the Earth at the time (around 6,000 years) wasn't nearly long enough to allow the processes involved to produce the types of rock he saw. Hutton believed the planet must be millions of years old.

19TH CENTURY

In the 19th century, **Sir Charles Lyell's** book *Principles of Geology* backed up Hutton's conviction that the Earth must be many millions of years old. This was extremely important to the work of his friend, **Charles Darwin** (see page 55), whose theory of evolution required a very long time span in order to account for changes in species.

TODAY'S ESTIMATE

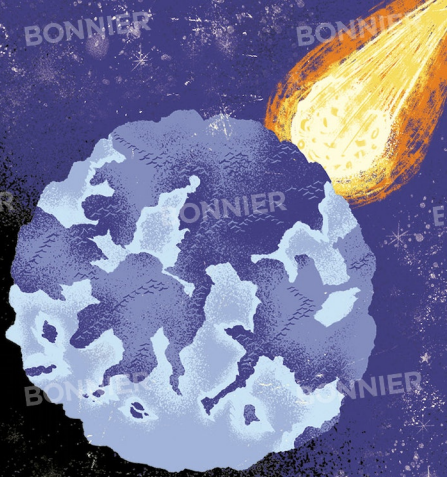
In 1896, French engineer **Henri Becquerel** discovered radioactivity – a process where atoms break down spontaneously, releasing particles or energy. In 1898, **Marie and Pierre Curie** investigated the radioactivity of uranium ore. Later, **Sir Ernest Rutherford** realised that radiactivity could be used to date rocks. Radioactive dating compares the proportions of a radioactive substance and the substance formed by its decay. Since decay happens at a constant rate, this means the age of the rock can be calculated. Using this technique, the age of the Earth has increased to today's estimate of 4.567 billion years.

HOW THE EARTH FORMED

Over 4.5 billion years ago, gravity began to pull a swirling whirlpool of dust and gas together. This process produced a solid planet – Earth – but it was very different to today's Earth. It was a sphere of molten metal and rock with a solid crust, bombarded by meteorites and split open by huge volcanic eruptions. There was no water, no atmosphere and no ozone layer to provide protection from deadly ultraviolet radiation. There was no life on this Earth: nothing could have survived.

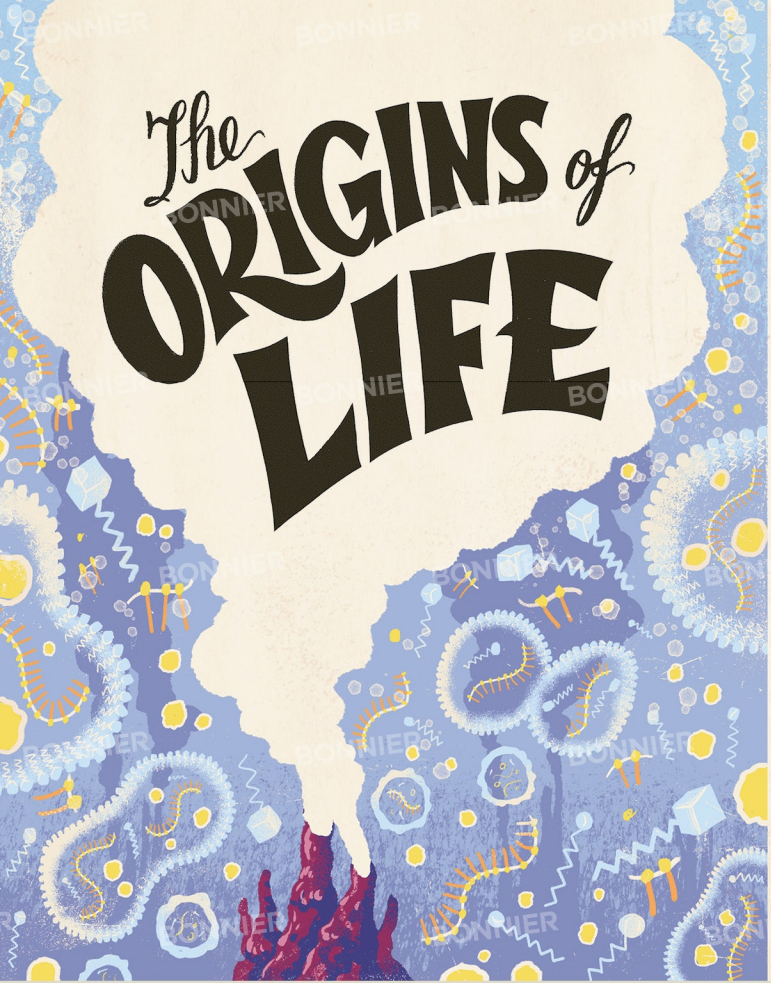
COOLING THINGS DOWN

It took 500 million years for things to cool down enough for water to exist as a liquid. Some of it probably came from water present in the rocks that formed the planet. It may also have come from asteroid or comet strikes – the minerals that make up asteroids contain a lot of water and although comets look fiery, they are more like huge dirty snowballs. The rest may have come from water in grains of space dust. The water helped the cooling of the Earth, and gases from eruptions formed an atmosphere. The densest elements sank towards the centre of the Earth, producing a solid crust and a molten core. At some point, a body the size of Mars crashed into the planet, blasting material from the Earth into space to form the Moon.



FORMING SUPERCONTINENTS

Temperatures still rose to 1600°C at times and there were frequent eruptions and earthquakes, but there must also have been oceans and rivers to provide the mud, sand and silt that were converted to the sedimentary rocks formed during this period. The continental plates on the planet's surface floated on the molten layer beneath, forming huge supercontinents, which slowly broke apart and reformed. The last supercontinent, Pangaea, broke up around 200 million years ago – its remains gradually created today's continents.



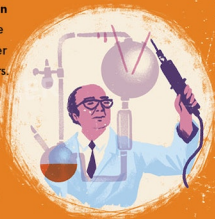
We think that life began about 3,800 million years ago. But where? And how? In the ancient world, philosophers were already considering the origins of life. Greek philosopher Anaximander proposed that life originated in water and simple forms developed before complex ones. Epicurus thought life might exist on other planets as well as on Earth, while the Roman philosopher Lucretius described a form of evolution, but assumed it had happened only in the past, then stopped.

Until the 17th century, most people accepted that simple animals and plants developed from rotting or dead matter by a process called spontaneous generation (see pages 26–27). In the 19th century, Darwin had speculated, *"But if (and oh what a big if!) we could conceive in some warm little pond with all sorts of ammonia and phosphoric salts – light, heat, electricity etcetera present, that a protein compound was chemically formed, ready to undergo still more complex changes..."*

In the mid-20th century, scientists began to experiment with simple chemicals to try to make some of the complex compounds only found in living things and found it was surprisingly easy to do so. But it's a huge leap from mixing chemicals in a flask to the development of the first cells, and we still don't know exactly how or where that happened.

HOW DID LIFE BEGIN?

In the 1920s, biochemist **Alexander Oparin** in the Soviet Union and scientist **John Burdon-Sanderson Haldane** in the UK had similar ideas about the origins of life – that simple chemicals in the hot oceans of early Earth had reacted with each other to produce compounds like amino acids (the building blocks of proteins) and sugars. These compounds, called coacervates, were the ancestors of cells.



However, there was no evidence for this. In 1953, American chemist **Stanley Miller** mixed boiling water, hydrogen, ammonia and methane, all of which were thought to be present 3,800 million years ago, and passed electricity through the mixture, to simulate lightning strikes. After a few days, amino acids had formed. This was hugely exciting: could the origins of life really be that simple?

Well, no. Even the simplest cell is enormously complicated compared to coacervates. We can't say yet how the first cells formed, but many scientists think we will understand how life began in the next few years.

...AND WHERE DID LIFE BEGIN?

The Oparin-Haldane hypothesis suggested something a bit like Darwin's 'warm little pond': an ocean so full of chemicals that it became known as 'primordial soup'.

1980s

Geologist **Mike Russell** found evidence that vents for water at less than 150°C had existed. At these lower temperatures, there was much more chance for chemicals to form and survive. But for Russell's idea to work, the water would need to be alkaline.

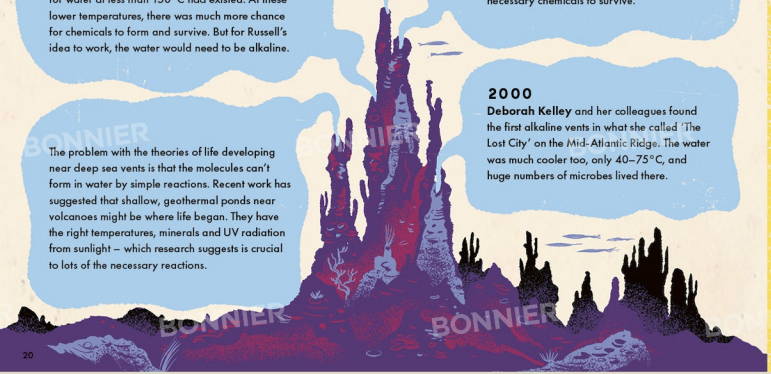
The problem with the theories of life developing near deep sea vents is that the molecules can't form in water by simple reactions. Recent work has suggested that shallow, geothermal ponds near volcanoes might be where life began. They have the right temperatures, minerals and UV radiation from sunlight – which research suggests is crucial to lots of the necessary reactions.

1977

A team led by geologist **Jack Corliss** discovered hydrothermal vents on the deep sea floor. These are areas where acidic, chemically rich water up to 400°C wells up into the ocean. They are home to shellfish, worms, crabs and bacteria. Corliss thought similar vents might have existed billions of years ago and be where life began. However, many scientists thought the water was too hot for the necessary chemicals to survive.

2000

Deborah Kelley and her colleagues found the first alkaline vents in what she called 'The Lost City' on the Mid-Atlantic Ridge. The water was much cooler too, only 40–75°C, and huge numbers of microbes lived there.



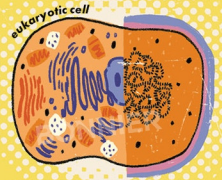
LIFE ON MARS?

A few scientists have suggested that life travelled here from another planet, carried on meteorites or comets. This idea is called 'panspermia'. It was first suggested by the Swedish Nobel Prize-winning chemist **Svants Arrhenius** in the early 20th century. The idea was quickly dismissed on the assumption that nothing living could survive a long journey through space, but bacteria are known to have survived on the outside of the International Space Station for over three years.
Recent exploration of Mars has suggested microbial life could have developed there and NASA is designing equipment to look for signs of DNA, or the closely related molecule RNA, on Mars which would confirm that there was once life there.

But even if evidence of panspermia was found, it doesn't explain how life began, it just moves the question to another planet...

THE FIRST CELLS

The first organisms were simple, single cells called 'prokaryotes'. For about 1.5 billion years, they were the only cell type, but about 2.7 billion years ago a more complex type of cell evolved. These eukaryotic cells are the ancestors of all other living things. Eukaryotic cells contain many specialised organelles – tiny structures surrounded by membranes – which are not found in prokaryotes. It is thought that these organelles were originally independent bacteria, which evolved to live permanently inside large cells.



The first eukaryotes were single-celled organisms, but over 1.7 billion years ago they began to form multicellular organisms. The first ones were probably mats of cells similar to modern algae.

The first recognisable animals were sponges, forming at least 700 million years ago. Next came mysterious organisms called Ediacarans, which lived on the seabed. These were thought to be algae, bacteria or fungi, but researchers now think that some were early animals with guts and the ability to move.

But the big explosion in life forms was just around the corner...

THE CAMBRIAN EXPLOSION

The Cambrian explosion saw a huge increase in the variety of animal life in the seas. Fossils of many of these were found in an area called the Burgess Shale in the Canadian Rocky Mountains in 1909, and some were very odd indeed...

Some of these species – trilobites, for instance – were hugely successful for hundreds of millions of years, though they died out eventually. By the end of the Cambrian period however, most of the invertebrate groups that exist today had been established, along with the possibly the earliest types of vertebrates, such as the wormlike *Pikaia gracilens*.

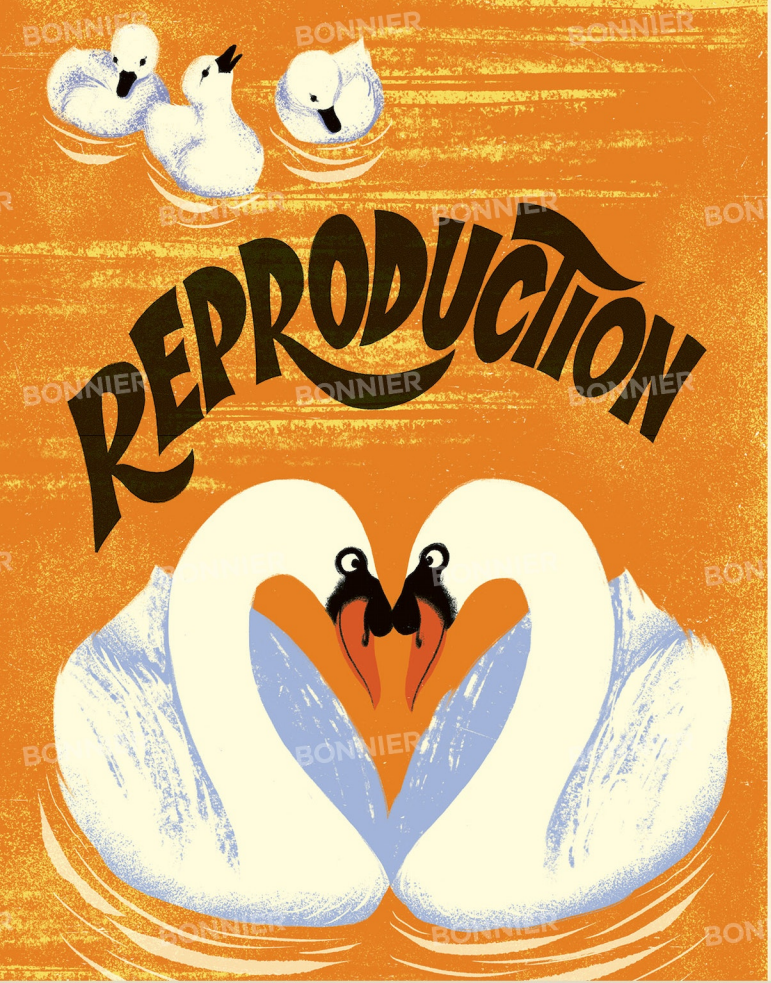
Hallucigenia walked on seven pairs of legs and was protected by seven pairs of spines on its back. It had simple eyes and a ring of teeth round its mouth. It was about 5cm long.

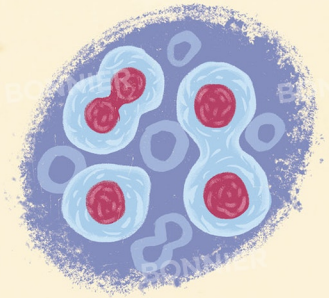
Wiwaxia was a small, (up to 5cm long) soft-bodied marine animal. Its back was protected by armour plates and spines, and it likely moved slowly along the seabed.

Opabinia had five simple eyes and a long, flexible proboscis with pincers to move food into its backward-facing mouth. Its soft, segmented body was up to 7cm long, with flaps on the sides and a fan-shaped tail.

Anomalocaris, was a large shrimp-like animal with good eyesight, spiked claws to catch its prey and teeth to break them up. It was the top predator, and could reach 1m in length.

Trilobites had a segmented body with three distinct sections, protected by a hard external skeleton. There were many species, ranging in size from a few millimetres to 60 centimetres.





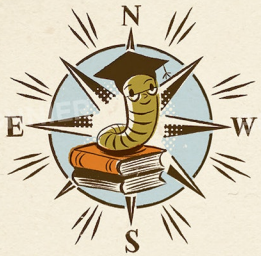
For centuries, many living things were thought to reproduce by spontaneous generation, meaning new individuals simply formed from non-living things, as if by magic. To us, this seems ridiculous, but it was only careful observations by scientists that disproved this theory. Even after it had been shown that this was not how animals reproduced, the tiny size of microbes made it difficult to study them and it was not until the 19th century that chemist Louis Pasteur proved that microbes did not spontaneously generate (see page 27).

We now understand how most living things on our planet reproduce. In some species of animals, and many species of plants, single individuals can reproduce all by themselves using a variety of types of asexual reproduction. Some single-celled organisms simply split in half, but most asexual reproduction involves more elaborate methods. Many animals and plants use sexual reproduction, which involves two individuals, usually a male and a female.

There are advantages and disadvantages to both systems and each species has evolved to use the one that works best for them. Evolution can change organisms however they reproduce, but sexual reproduction offers more opportunities for new combinations of characteristics to develop, as genetic material from two individuals is mixed.

SPONTANEOUS GENERATION
(WHERE *DID* THEY COME FROM?)

You might imagine that seeing how farm animals and pets breed would have given people an idea how other animals reproduced, but apparently not. Many species were thought to somehow create themselves from non-living matter. Here are some of the wilder ideas of where living things came from...



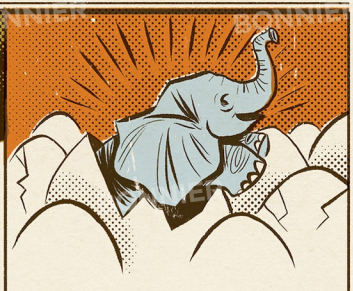
Roman architect **Vitruvius** recommended that libraries shouldn't face south or west as winds from those directions generated bookworms.

It was also accepted that anchovies were made of sea foam and swallows made of mud. In Egypt, it was thought that snakes and crocodiles sprang from the mud of the Nile river.

Barnacle geese, which were sometimes known as tree geese, get their name from the old belief that they emerged from goose barnacles (a type of shellfish) growing on wood. Some medieval churchgoers claimed that this meant that the goose counted as a type of fish, so could be eaten during Lent.

During the 16th century, **Jan Baptist van Helmont** wrote that a piece of dirty cloth and some wheat, left for 21 days, would produce mice.

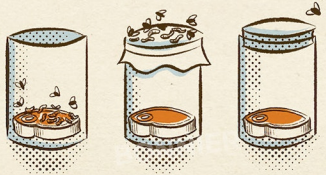
The geographer **Zeigler** of Strasbourg claimed that lemmings – small vole-like rodents – fell from the sky during stormy weather.



William Harvey suggested that all animals developed from eggs, some of which were too small to be seen, rather than spontaneously generating.

MULTIPLYING MAGGOTS NO MORE!

In the 17th century, **Francesco Redi** carried out an experiment to show that maggots did not spontaneously generate in rotting meat. He covered some jars of meat with fine gauze, and left others open. Maggots only appeared in the open jars because the gauze prevented flies laying eggs on the meat.



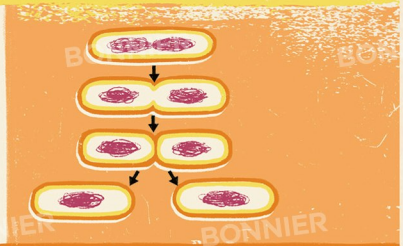
During the 19th century, scientists gradually showed that animals and plants did not spontaneously generate, but little was known about microbes as they were so small. French chemist **Louis Pasteur** showed that if beef broth was boiled inside a special 'swan-necked flask' it would stay fresh for a long time. The boiling killed any microbes in the broth, and the shape of the neck trapped microbes from the air before they could reach the broth.

WHAT REALLY HAPPENS...

Some organisms can reproduce by asexual or sexual reproduction, often depending on conditions or the stage in their life cycle. How do these systems work?

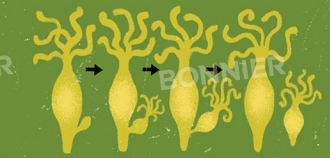
ASEXUAL REPRODUCTION

Asexual reproduction just needs one individual. The simplest form is called binary fission and involves one cell splitting in two, then growing to the original size. This is how single celled organisms like bacteria and amoeba reproduce.



BUDDING

A new, small organism grows on the old one, detaches and becomes independent.



VEGETATIVE REPRODUCTION

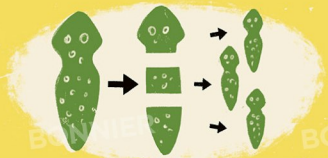
Many plants can grow new plants from their leaves, stems, roots or bulbs. For instance, strawberries use runners (horizontal stems) and daffodils use bulbs.

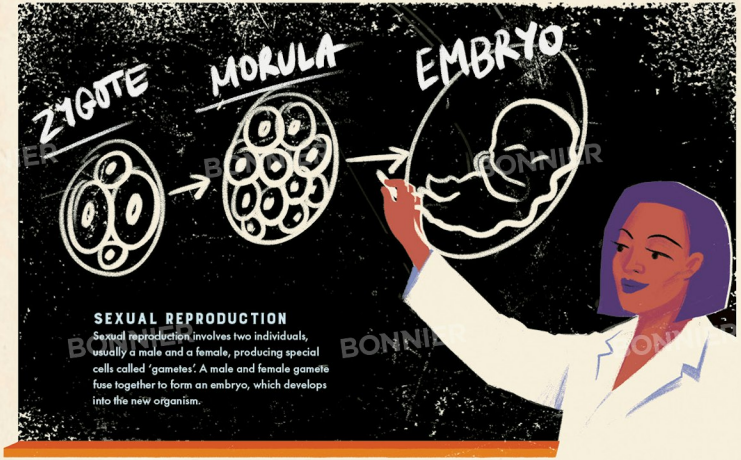
SPORE FORMATION

Fungi produce tiny structures called spores, which are a bit like seeds, and are blown around by the wind. They can survive harsh conditions and then grow into a new individual.

FRAGMENTATION

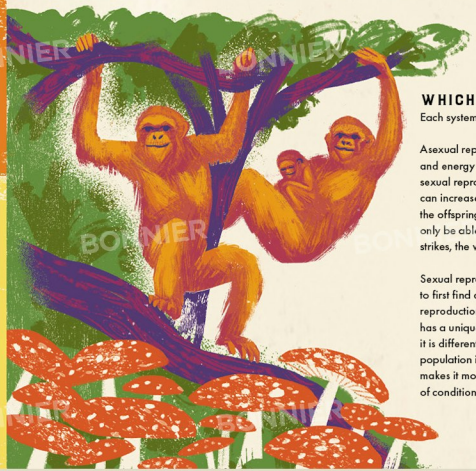
If you break some organisms into pieces, each piece will grow into a whole new one! A range of plants and some simple animals, like sponges and flatworms, can do this.





SEXUAL REPRODUCTION

Sexual reproduction involves two individuals, usually a male and a female, producing special cells called 'gametes'. A male and female gamete fuse together to form an embryo, which develops into the new organism.



WHICH IS BETTER?

Each system has advantages and disadvantages:

Asexual reproduction only needs one parent, so there is no time and energy used looking for a mate. It is usually faster than sexual reproduction, so if conditions are suitable, a population can increase quickly. But, it doesn't produce any variation: all the offspring are exactly like the parent. This means they might only be able to survive in one set of conditions, and if a disease strikes, the whole population could be wiped out.

Sexual reproduction needs two parents, so an individual has to first find a mate. The process may be slower than asexual reproduction, but it produces variation: because the offspring has a unique combination of genetic material from its parents, it is different from the other offspring. This means a whole population is unlikely to be wiped out by a single disease and makes it more likely that the population can survive in a range of conditions.

Most civilisations have legends of strange creatures that used to roam the Earth. Griffins guarded hoards of gold. Dragons menaced villages. Venomous snakes and huge animals had once threatened humans – and the evidence was there in the ground: fossils. Fossils of species that were unlike the living things that people were familiar with led to many stories of monsters and mythical creatures, but also led some scientific thinkers of the ancient world to interesting conclusions.

The Greek philosopher Xenophanes suggested that the whole surface of the Earth had once been under the sea when he saw fossils of marine species on mountains. In China, scientist Shen Kuo realised that these marine fossils suggested geological processes could cause seashores to shift, and even argued that climate change could explain the presence of fossilised bamboo in areas where it was no longer found.

Until the 17th century, many people thought fossils were the work of evil spirits or were evidence of animals destroyed in the ancient floods described in many religions and myths. In the 17th century however, Georges Cuvier and other early palaeontologists (people who study fossils) began to classify fossils and noticed that different types were found in rock strata of different ages. This allowed the ages of fossils to be worked out. These fossils would provide important evidence for Darwin's Theory of Evolution (see page 55).

THE FABULOUS WORLD OF FOSSILS

Fossils are the remains of living things which have been preserved instead of decaying. If the hard parts of an organism – like bones, teeth, shells or seeds – get buried in mud or sand, pressure and heat can gradually harden this around them, forming sedimentary rock like sandstone. At the same time, the remains are gradually replaced by tiny mineral particles, turning them to rock too.

Body fossils are actual body parts like bones, shells or seeds. Trace fossils, like burrows and footprints, leave a 'mould' that can fill with minerals and turn to rock. There are other ways for fossils to be preserved too.

POLYMERIZATION

Insects were sometimes caught in the sticky resin of conifer trees and trapped as it hardened into amber, in a process known as 'polymerization'.

STICKY POOLS

If animals fell into tar pits or asphalt lakes, their entire skeletons could be preserved. A famous site is the La Brea Tar Pits in Los Angeles, California. Fossils found there include sabre-toothed cats, dire wolves and woolly mammoths.

PETRIFICATION

Tree trunks can become petrified (turned to rock) as the wood is replaced by minerals. One famous site is the Petrified Forest in Arizona, USA. The preservation is so good that the annual rings can be counted and measured, giving information about the climate at the time the trees lived.

FROZEN ICE

Freezing occasionally preserved mammoths and woolly rhinoceros in the permafrost of Siberia. A man now known as Ötzi the Iceman was found frozen in a glacier in the European Alps. He is thought to have been there for about 5,300 years.

UNUSUAL DISCOVERIES

Occasionally, ancient bodies are found preserved in peat bogs. Tollund Man was discovered in Denmark in 1950, and lived about 2,300 years ago. Lindow Man was found in Cheshire, UK, in 1984 and is thought to be around 1,900 years old.

The chance of any organism being fossilised is small, but in some places, huge numbers of fossils have been found. The Ludlow Bone Bed contains the remains of huge numbers of armoured fish, thought to have been killed by a sudden change in water composition. The Dinosaur National Monument in the USA contains the fossils of many dinosaurs, which probably drowned in a sudden flood.

Bone Cabin Quarry is a famous dinosaur graveyard in Wyoming, USA. It takes its name from the hut built by a local shepherd, who constructed it from the hundreds of conveniently sized 'stones' lying around, not realising they were dinosaur bone fossils.

IMPORTANT FOSSILS

Fossils can give us a great insight into the history of life on our planet. Not only can we understand how these prehistoric creatures behaved, what they ate and how they moved, paleontologists can also use fossil data to provide evidence for how Earth has changed over time.

Trilobites (400–252 million years ago) are extinct marine animals related to insects, spiders, scorpions and crabs. The distribution of trilobite fossils gives information on ancient geography. For instance, they have helped to show that at one time, Scotland was situated near North America and was separated from England and Wales by an ocean.

Ammonites (450–66 million years ago) were marine organisms related to modern squid and octopus. Their coiled shells – which can be up to 1m across – are often found as fossils. People used to think they were snakes that had been turned to stone and had lost their heads, so they were called 'snakestones' in some areas. Ammonites evolved quickly, and finding a particular species in a rock stratum helps determine its age more precisely.

Belemnites (250–66 million years ago) were marine animals related to modern squid and cuttlefish. They can be bullet- or finger-shaped, which has led to them being called 'fossil bullets' and 'devil's fingers'. These important fossils provide information about ancient ocean temperatures and currents.

Diplodocus (155 million years ago) is one of the best known dinosaurs, famous for its long neck and tail. The first fossil was found in 1877 in Colorado, USA. These huge creatures were herbivores, stripping leaves from trees.

Archaeopteryx (about 150 million years ago) is one of the most important fossils ever found. The first Archaeopteryx fossil was found in Germany in 1861. It was about the size of a large chicken, and had feathered wings like a bird, but teeth and a bony tail, like a typical dinosaur. It is regarded as one of the earliest birds and shows how these may have evolved from small meat-eating dinosaurs.

PILTDOWN MAN – THE FAKE FOSSILS

In 1912, a set of fossils was discovered in Sussex, UK, by an amateur geologist, **Charles Dawson**. The fossils seemed to be of an early human and provided an important missing evolutionary link between apes and humans. Over several years, teeth, parts of a skull and jawbone, and even simple tools were excavated. The jaw resembled those of apes, but the skull looked human. Human fossils found in the 1920s and 1930s didn't resemble Piltdown Man, however, and chemical tests eventually showed some bones were only about 500 years old, not 500,000 as had been claimed. A thorough investigation in 1953 proved that the Piltdown find was a fake. The jaw and teeth belonged to an orangutan, and the skull was from a medieval human. They had even been stained to make them look older!

LIVING FOSSILS

'Living fossils' is a term coined by **Charles Darwin** (see page 51) to describe a living species that closely resembles those known only from fossils. The living species is not identical to its fossil relatives since evolution has still affected it, but often at a very slow rate. This is generally because these species are already very well adapted to their environment, or their environment has only changed very slowly and the random mutations (see pages 56–57) that are the raw material of evolution are unlikely to improve their ability to survive.

COELACANTHS

The first living coelacanth (a type of fish) was discovered in the Indian Ocean in 1938. Until then, coelocanths were only known from fossils and were assumed to have gone extinct more than 60 million years ago. There are two living species, usually found at depths of 100–250m, which helps explain why they had gone unnoticed for so long despite being up to 2m in length.

HORSESHOE CRABS

Horseshoe crab fossils date from over 450 million years ago and some from 200 million years ago are very similar to the four species still around today. The name is misleading: they aren't crabs at all, but are more closely related to sea scorpions, which are now extinct, and living spiders. Populations of horseshoe crabs are decreasing, as they are killed for use as fishing bait and fertiliser. They are also caught and bled before being released, so that their blue blood can be used in the biomedical industry.

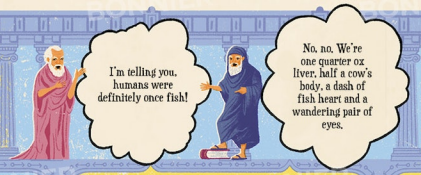
GINKGO TREES

Ginkgo fossils are more than 250 million years old. The single species that still survives (although it is now extinct in the wild) is thought to be unchanged for 51 million years. These trees have long life spans (some are over 3,000 years old) and can cope with a wide range of conditions, so are often planted in cities where they survive in spite of traffic fumes.

EARLY IDEAS ABOUT EVOLUTION

How long is a million seconds? Have you been alive for one billion seconds? What was happening a million days ago? We find it very difficult to comprehend these huge numbers. If we don't have a feel for how long a million seconds is, how can we possibly comprehend time spans of millions or billions of years? This is one reason why some people have a problem with evolution. The idea that single, primitive cells evolved into all the species that have ever lived seems incredible, unless you get to grips with the timespans involved.

In ancient Greece, philosopher **Anaximander** suggested that one type of animal could change into another, while **Empedocles** thought that new types of living things could be made from a range of parts that already existed.



Theologians **Gregory of Nazianus** and **Augustine** both thought that although God had created all the original animals and plants, new types had developed from them. Their idea was in response to the practical problems that would have arisen from trying to get two of everything into the Ark.

The naturalist **George-Louis Leclerc** proposed a way for the Earth to have formed from debris in space. Although he believed in spontaneous generation, he thought that animals could change as they migrated to different conditions. This let him explain the discovery of elephant fossils in North America, and mammoth fossils in Siberia, although living elephants are today only found in Africa and South Asia. He suggested the American ones had become extinct, while the mammoths had changed as they migrated south.

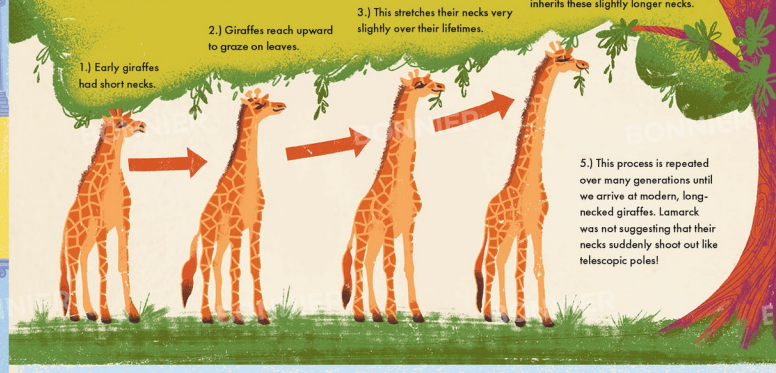
Erasmus Darwin was Charles Darwin's grandfather. He was a doctor, poet and naturalist, and in his book *Zoonomia*, or, *'The Laws of Organic Life'*, he was one of the first people to propose a theory of evolution. He never hit on the idea of natural selection, but did recognise the importance of sexual selection (see page 59) and realised it could cause changes in species.

Answers: 1,000,000 seconds = 11 days, 13 hours, 46 minutes and 40 seconds.
You will have your billion (1,000,000) second birthday when you're 31 years, 251 days, 1 hour, 46 minutes and 40 seconds old!
1,000,000 days ago Rome was colonising areas around the Mediterranean about 180 BCE.

GRADUAL CHANGES

In the early 1800s **Jean-Baptiste Lamarck**, inventor of the terms 'invertebrate' and 'biology', was the first person to develop a coherent theory of the development of life on Earth and its evolution. He believed that life had originated by spontaneous generation, rather than creation by a deity, and had then become more complex and varied over many generations. Lamarck suggested how this could happen. His idea is often called the 'Theory of Evolution by Acquired Characteristics'. In simple terms, he thought that the more an animal used an organ during its lifetime, the more well-developed it would become and that these changes could be inherited by offspring if both parents had the same developments.

THE EVOLUTION OF THE GIRAFFE'S NECK, ACCORDING TO LAMARCK:



THE PROCESS ALSO WORKED THE OTHER WAY:

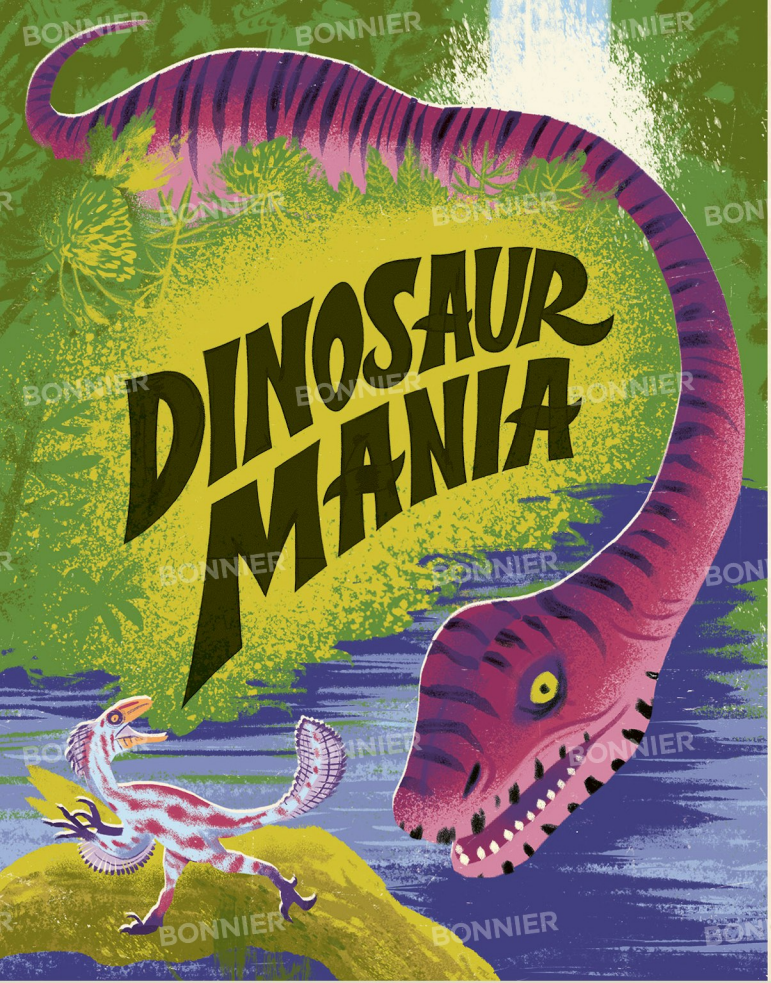
1.) Early penguins had wings with which they could fly.

2.) Penguins spend most of their time swimming and very little flying.

3.) Their wings become smaller, with smaller feathers, from lack of flying.

4.) The next generation of penguins inherits these smaller, more flipper-like wings.

5.) This process is repeated over many generations until we arrive at the modern penguin, which can no longer fly and whose wings are now adapted to help it swim instead.



For centuries, people had found huge bones and teeth that couldn't have come from any living animal. They assumed they must've been from dragons or other mythical creatures. However, in the 19th century, proper scientific study of these fossils began to reveal the truth, and the word 'dinosaur', meaning 'terrible lizard', was coined to describe these astonishing animals from the past.

Dinosaur frenzy soon took off. The Great Exhibition, staged in London in 1851, included life-sized models of several dinosaurs (though we now know they didn't look much like these models). In 1912, Sir Arthur Conan Doyle wrote *The Lost World*, a science fiction novel in which dinosaurs were discovered to still be living in an isolated part of the Amazon. Dinosaurs remain a source of fascination today.

Dinosaurs were the dominant animals on Earth for over 140 million years. They were much more successful than other reptiles as they had straight legs that were positioned under their body, not bent legs that stuck out to the side (like modern crocodiles). This allowed them to move more efficiently in a greater variety of environments.

New species of dinosaur are still being discovered, and early assumptions that they were all unintelligent, lumbering giants have been disproved. Some of them were indeed large and slow, but as they ate plants and were big enough to put off most predators, they didn't need to be physically or mentally agile. However, recent studies of *T. rex* fossil skulls show them to have large brains and highly developed senses, which allowed them to be successful predators.

THE DINOSAUR DETECTIVES

In the 19th century, amateur scientists discovered, investigated and named many species of dinosaur. But just who were these dinosaur detectives?

MARY ANNING (1799–1847)

Anning was born into a very poor family in Lyme Regis, England. As a child, she helped her father collect and sell the fossils which were common in the nearby cliffs. He died when she was 11 years old and she continued fossil hunting to help support her family. In 1811, Anning uncovered a near complete skeleton – 5.2m long – of an animal never before seen. After years of study by scientists, it was named *Ichthyosaurus*, or 'fish-lizard'. She sold it for £23 – enough to feed her family for six months. Anning went on to find the first complete *plesiosaur* ('sea dragon') skeleton in 1823 and the first pterosaur ('flying dragon') in 1828.

Most scientists in the UK at that time were wealthy men, and the idea that an uneducated woman – even one who had taught herself geology and anatomy – could be their intellectual equal seemed ridiculous to many of them. As a result, Anning often got no credit in scientific papers discussing fossils she had found, and the importance of her work was undervalued during her lifetime. Only now is she being properly celebrated and has recently had an ichthyosaur named in her honour – *Ichthyosaurus anningae*.

WILLIAM BUCKLAND (1784–1856)

Buckland was a geologist and palaeontologist from the UK. In 1824, he found fossils of an unknown reptile which he named *Megalosaurus*. This was the first scientific description of a dinosaur. He also found fossil remains of hyenas, elephants and rhinoceros in Yorkshire and argued that these animals had once lived there, though most people at the time believed their bodies must have been washed there by the biblical flood. His argument was based on the presence of bones gnawed by hyenas. Buckland obtained a hyena and fed it ox bones to check the tooth marks matched. He even found fossilised hyena dung. This showed environmental conditions changed over time – modern hyenas are only found in hot climates.

RICHARD OWEN (1804–1892)

Owen was a leading Victorian anatomist and palaeontologist. During his training as a surgeon, he studied human anatomy by dissecting the bodies of executed criminals. In London, his skill in dissection led to him being sent any animal that died at London Zoo. Owen became fascinated by fossils and coined the word 'dinosaur' in 1841 to describe creatures whose fossil remains shared a number of features. He became convinced that the natural history collection of the British Museum deserved its own museum and, from the 1850s, he worked towards the establishment of the now world-famous Natural History Museum in London, which opened in 1881.

GIDEON MANTELL (1790–1852)

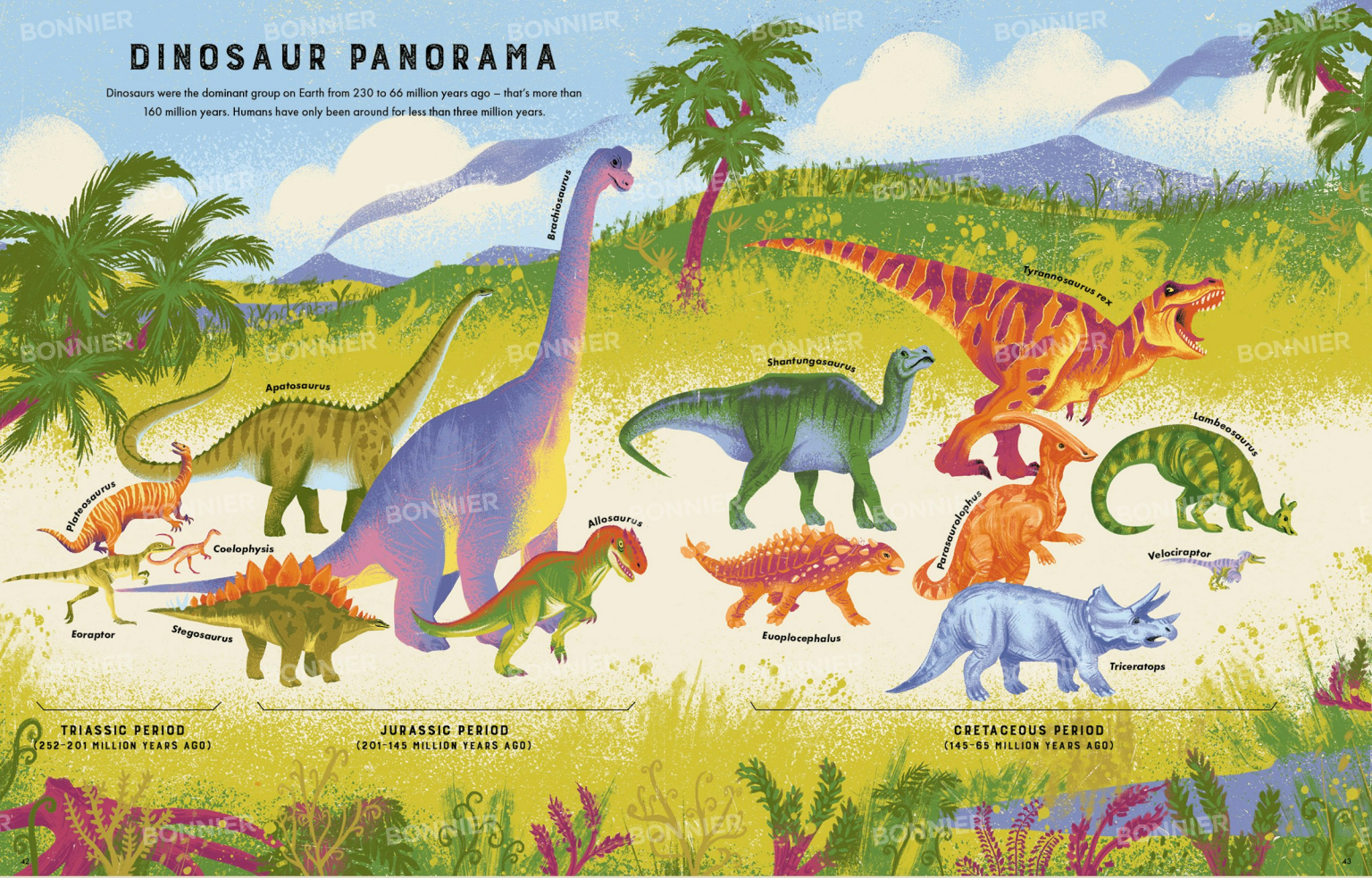
Mantell was a doctor, geologist and fossil collector. In 1822, he and his wife Mary found a huge tooth from a previously unknown animal. After finding more fossils of the creature, he named it *Iguanodon* in 1825. In 1833, he also found and named *Hylaeosaurus*. Mantell neglected his medical practice to study fossils and was constantly short of money. In 1841, his situation became even worse when he damaged his spine in a carriage accident leaving him partially paralysed and in constant pain.

THE GREAT COPE-MARSH RIVALRY

American palaeontologists Othniel Charles Marsh (1831–1899) and Edward Drinker Cope (1840–1897) began as friends excavating dinosaur fossils, but ended as bitter enemies. They fell out spectacularly when Marsh secretly arranged to buy the fossils found in a quarry that Cope had shown him. Cope was further humiliated when Marsh pointed out that he had reconstructed the skeleton of an *Elasmosaurus* with the head attached to the tail, instead of the neck! The two men spent the rest of their careers trying to outdo each other, rushing to name as many new dinosaurs as possible, sometimes identifying fossils as new species when they belonged to one that had already been discovered and named.

DINOSAUR PANORAMA

Dinosaurs were the dominant group on Earth from 230 to 66 million years ago – that's more than 160 million years. Humans have only been around for less than three million years.



WHERE DID THEY GO?

The creatures of the Burgess Shale (see pages 22–23) look extraordinary to us now because there is nothing remotely like them left on Earth. This is true for many fossil species. 99% of all the species that have ever existed have gone extinct. Species evolve and die out naturally all the time, at a rate of between 0.1 and 1 in every 10,000 species per 100 years. Five times in Earth's history, however, mass extinction events have killed at least 75% of all species in existence.

444 million years ago, during the Ordovician-Silurian extinction, many marine organisms died out. This was thought to have been caused by global cooling and drastically falling sea levels, creating conditions impossible to survive in.

About 370–360 million years ago, the Late Devonian extinction – possibly triggered by enormous volcanic eruptions or asteroid strikes – wiped out many tropical marine species.

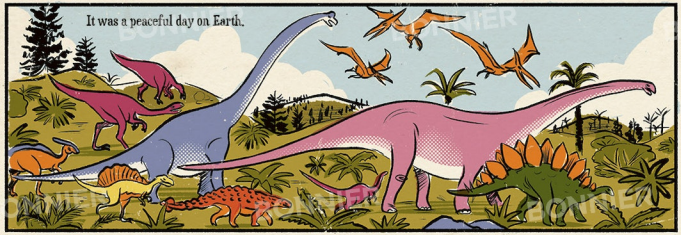
252 million years ago, the largest mass extinction event in Earth's history – the 'Great Dying' Permian-Triassic extinction – destroyed many vertebrate species. It is thought to have been caused by intense volcanic activity, resulting in extreme global warming.

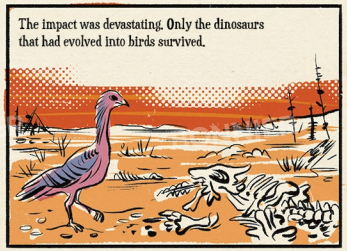
Around 210 million years ago, the Late Triassic event led to the extinction of other vertebrate species on land and ushered in the age of the dinosaurs. It was probably caused by the release of huge amounts of greenhouse gases due to volcanic activity, leading to another period of global warming. Acidification of the oceans by carbon dioxide wiped out many marine species.

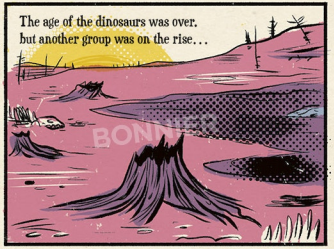
The Cretaceous-Paleogene extinction 66 million years ago ended the Age of Dinosaurs. An enormous meteor or comet strike is likely to have been the main cause.

THE END OF THE DINOSAUR AGE

For a long time, theories abounded about the demise of the dinosaurs – apart from their only surviving group, birds. Some scientists argued that they were too big and unintelligent to survive, while others claimed their eggshells were too thin and broke before the embryos could fully develop. It wasn't until the 1980s that the so-called 'asteroid theory' became popular, and today this is what most scientists believe caused the catastrophic end for non-bird dinosaurs.







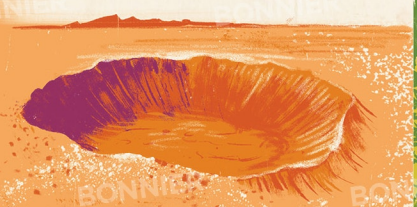
EXTINCTIONS

The asteroid theory seemed to explain what scientists had been puzzling over for years. But what evidence do we have that an asteroid really led to the mass extinction around 66 million years ago?

American geologist **Walter Alvarez** was studying rock strata (layers of rock) about 66–65 million years old, which formed the boundary layer between the Cretaceous and Tertiary periods (see pages 42–43), when he noticed two layers of sedimentary rock with lots of marine fossils. The layers were separated by a thin layer of claystone with no fossils at all.

He was curious, as he knew this was roughly when the non-bird dinosaurs had gone extinct, so he and his father (Nobel Prize winning-physicist **Luis Alvarez**) began to investigate. They discovered that this pattern of layers was found all over the world and that the clay contained an unusually high concentration of iridium, a chemical element that is rare on Earth but present in much greater amounts in asteroids. The Alvarezes suggested that a huge asteroid impact had been the source of the iridium, and that the impact was involved in the extinction event. All the geological evidence fitted – but where was the crater?

In fact, it had already been discovered by geophysicist **Glen Penfield** and his team researching for an oil exploration company – but the company didn't share news of the discovery widely. It wasn't until 1991 that the Chicxulub crater, buried under the Yucatan peninsula and neighbouring sea bed, was clearly linked to the Alvarez hypothesis. The 150km-wide crater was probably caused by an asteroid between 10 and 15km wide – big enough to cause blast waves, megatsunamis and enormous dust clouds that blocked out the sun and caused temperatures to drop, first killing plants, then the animals that depended on them.



MORE RECENT EXTINCTIONS

There is considerable evidence that we are in the middle of another major extinction event. Sadly, this time it is humans that have contributed to the extinction of numerous species. Below are just a few of the many animals that no longer exist.

DODO

The dodo was a large, flightless bird, which lived on the island of Mauritius in the Indian Ocean. Dodos were discovered by European sailors in 1598, and less than 100 years later they were extinct. It was originally thought they had been hunted to extinction by humans, but their meat wasn't very tasty. Instead it's likely that the rats, cats, dogs and pigs that came with the sailors destroyed the habitat, hunted the adult dodos and ate their eggs.

QUAGGA

The quagga was a sub-species of the common zebra and was found in huge numbers on the plains of South Africa. They were hunted to extinction for their meat and hides in the late 1800s. But perhaps the quagga isn't gone forever... Since 1987, a project based in South Africa has been trying to selectively breed common zebras to bring back a quagga-like zebra.

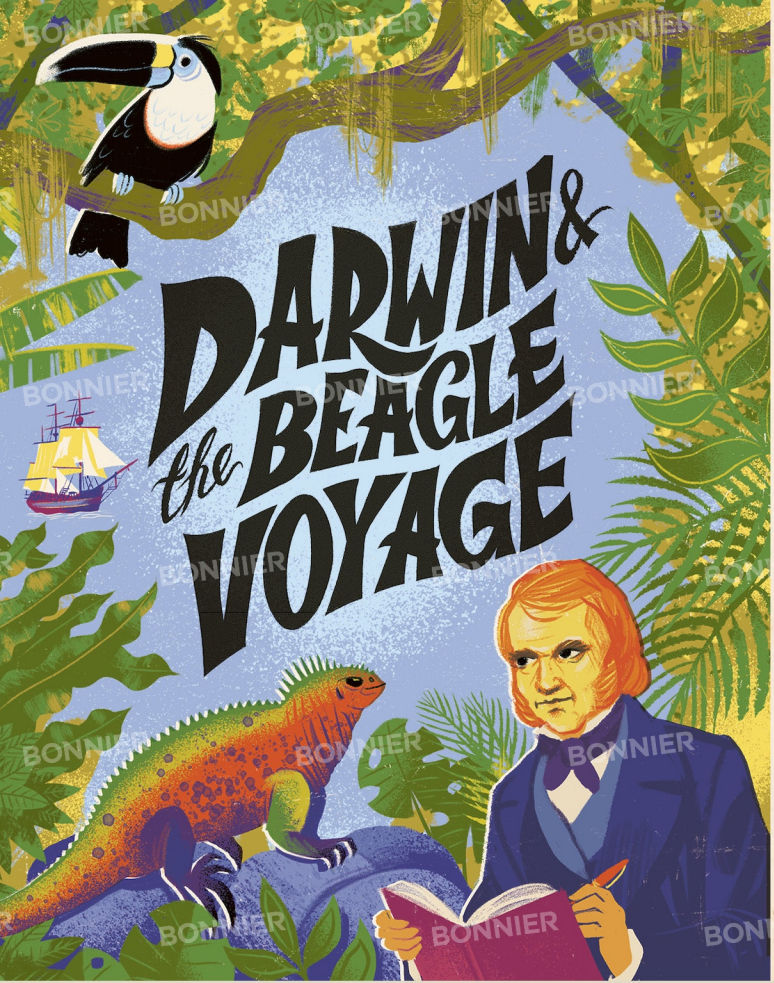
GOLDEN TOAD

First seen in Costa Rica in 1964, the golden toad was last spotted in 1989. It is now presumed to be extinct, probably affected by climate change as well as by the fungal infections that threaten many amphibians.

WEST AFRICAN BLACK RHINO

Illegal hunting and habitat loss led to the extinction of this once common rhino sub-species. The last rhinos were probably killed by poachers in 2003 and the West African black rhino was declared extinct in 2011.

Animal extinctions get most of the publicity, but numerous species of plants have also become extinct, usually because of habitat loss. Some sources estimate that almost 40% of plant species are in danger of extinction and that plants are disappearing faster than they can be discovered and named.



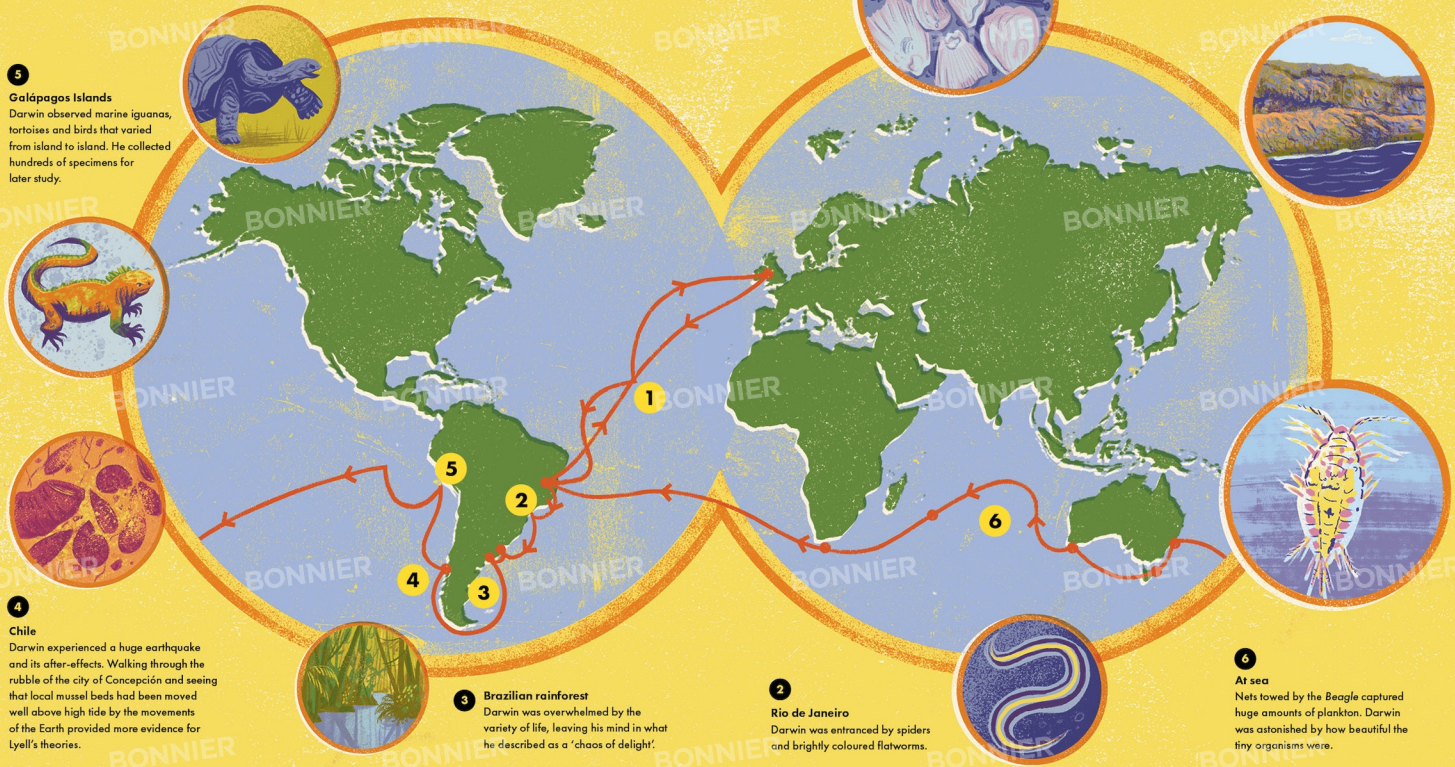
In 1826, Charles Darwin was a reluctant medical student at Edinburgh University in Scotland. He joined a natural history society and instead of attending lectures, spent much of his time studying the marine life of the nearby estuary, the Firth of Forth. He also took private taxidermy lessons with the taxidermist John Edmonstone. By 1827, Darwin had given up on the idea of a medical career and enrolled, without much enthusiasm, at Cambridge University to study theology. His second cousin William Darwin Fox was also there and introduced Charles to insect collecting, with which he became obsessed...

"I will give a proof of my zeal: one day, on tearing off some old bark, I saw two rare beetles and seized one in each hand; then I saw a third and new kind, which I could not bear to lose, so that I popped the one which I held in my right hand into my mouth. Alas it ejected some intensely acrid fluid, which burnt my tongue so that I was forced to spit the beetle out, which was lost, as well as the third one." (From *The Autobiography of Charles Darwin,* 1887)

Although he finished his degree, Darwin had no interest in becoming a parson, and was delighted when, in 1831, he was offered the chance to accompany Captain Robert Fitzroy on a voyage to survey the coast of South America. Fitzroy was only 26 and was looking for another young 'gentleman' to keep him company, ideally one who was also a naturalist. Darwin leapt at the chance and on December 27th, HMS *Beagle* set sail, carrying Darwin and his scientific equipment. The voyage would later become legendary.

THE VOYAGE OF THE BEAGLE

From 1831 to 1836, HMS *Beagle* circumnavigated the world. Although the voyage took five years, Darwin, who was tormented by severe seasickness, only spent around 18 months on board. The rest of the time he roamed on shore, observing, making notes and collecting specimens.



1 Cape Verde Islands
Darwin saw layers of oyster shells in the local rocks 10m above sea level. This confirmed Lyell's ideas (see page 15) about land rising and falling over time.

2 Rio de Janeiro
Darwin was entranced by spiders and brightly coloured flatworms.

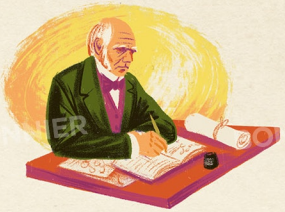
3 Brazilian rainforest
Darwin was overwhelmed by the variety of life, leaving his mind in what he described as a 'chaos of delight'.

4 Chile
Darwin experienced a huge earthquake and its after-effects. Walking through the rubble of the city of Concepción and seeing that local mussel beds had been moved well above high tide by the movements of the Earth provided more evidence for Lyell's theories.

5 Galápagos Islands
Darwin observed marine iguanas, tortoises and birds that varied from island to island. He collected hundreds of specimens for later study.

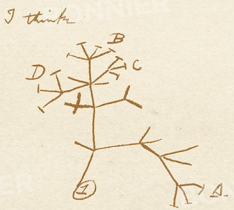
6 At sea
Nets towed by the *Beagle* captured huge amounts of plankton. Darwin was astonished by how beautiful the tiny organisms were.

DARWIN'S THEORY



"The affinities of all the beings of the same class have sometimes been represented by a great tree. I believe this simile largely speaks the truth. The green and budding twigs may represent existing species; and those produced during each former year may represent the long succession of extinct species. At each period of growth all the growing twigs have tried to branch out on all sides, and to overtop and kill the surrounding twigs and branches, in the same manner as species and groups of species have tried to overmaster other species in the great battle for life." **(Darwin, 1859)**

Darwin sketched a simple tree in his notebook in 1837 to represent how he thought species changed over many generations. "*I think*" he wrote on it, cautiously. He included a newer version of it by William West as the only illustration in his epic book *On the Origin of Species by Natural Selection*. From that little sketch came a huge idea: that species were descended from common ancestors.



THE THEORY OF EVOLUTION

Darwin had worked on his theory of evolution for years without publishing anything about it. In the end, it was a letter from another scientist, **Alfred Russel Wallace**, which forced his hand...

ALFRED RUSSEL WALLACE

Alfred Russel Wallace (1823–1913) worked as a teacher and surveyor before setting off in 1848 to study the wildlife of the Amazon rainforest. Already fascinated by the idea of evolution, he was trying to devise a theory to explain it. Four years later, as he sailed back to England with a huge collection of specimens, drawings and field notes, his ship caught fire and sank. The passengers and crew were saved, but most of Wallace's belongings were lost.

Within a year, he set out for the Malay archipelago for an eight-year expedition, during which he obtained specimens of over 5,000 species unknown to Western scientists. Wallace became ill during the expedition and, one feverish night in 1858, realised how evolution could work: by the best-suited individuals surviving to breed and pass on the characteristics that made them successful. He wrote an essay explaining his ideas and sent it to Darwin, with whom he had already been corresponding and who had been working on the same theory for 20 years.

DARWIN'S RESPONSE

Darwin was horrified. *"I never saw a more striking coincidence. If Wallace had my M.S. sketch written out in 1842 he could not have made a better short abstract! ... So all my originality, whatever it may amount to, will be smashed,"* he wrote to geologist Charles Lyell.

Darwin, Lyell and James Hooker decided Darwin's and Wallace's theories should be presented together at a meeting of the prestigious Linnean Society in London on July 1st 1858. The joint paper, *On the Tendency of Species to Form Varieties; And On the Perpetuation of Varieties and Species by Natural Means of Selection,* was published in the Linnean Society journal in August 1858.

Darwin laid aside the huge book he had been planning on evolution and instead, in November 1859, published what he called an 'abstract' commonly known as *On the Origin of Species*. It was an immediate success and has never been out of print.

Darwin and Wallace jointly developed the Theory of Evolution by Natural Selection, which convincingly explained how species changed over long periods of time, driven by environmental conditions. It was widely known as the Darwin-Wallace theory during their lifetimes, but Wallace's contribution is often forgotten now.

NATURAL SELECTION

Both Darwin and Wallace had read English economist **Thomas Malthus's** (1766–1834) book *An Essay on the Principle of Population* and reasoned that what Malthus said about human populations would also be true for animals – namely that populations would grow until they were limited by environmental conditions like food availability or suitable habitat.

The Darwin-Wallace theory was based on the following observations:

1.) Living things produce more offspring than survive to become adults.

2.) There is variation between members of a species. For instance, some may be able to run faster, have longer roots or can survive longer without water. Some of this variation is inherited – that is, in the genes.

3.) There is competition between the offspring for things like food, water, shelter and mates. Darwin called this the struggle for existence.

4.) The individuals best suited to their environment will survive long enough to breed. If their favourable characteristics are in their genes, their offspring may inherit these. The less well-adapted offspring are more likely to die without breeding, so some of their characteristics will not be passed on.

5.) Over many generations, the useful variations will gradually spread through the population and the species will become better suited to its environment. This is called natural selection, because it is the natural conditions which determine the variations that help survival.

THE STRUGGLE FOR EXISTENCE

What exactly did Darwin mean by 'the struggle for existence'? There are two types of struggle: those between different species and those within the same species. Struggles between species are generally competition for space, shelter, food and water. An obvious example is the competition between predators and prey. Natural selection gradually makes predators better at catching and killing prey, while prey become better at evading capture.

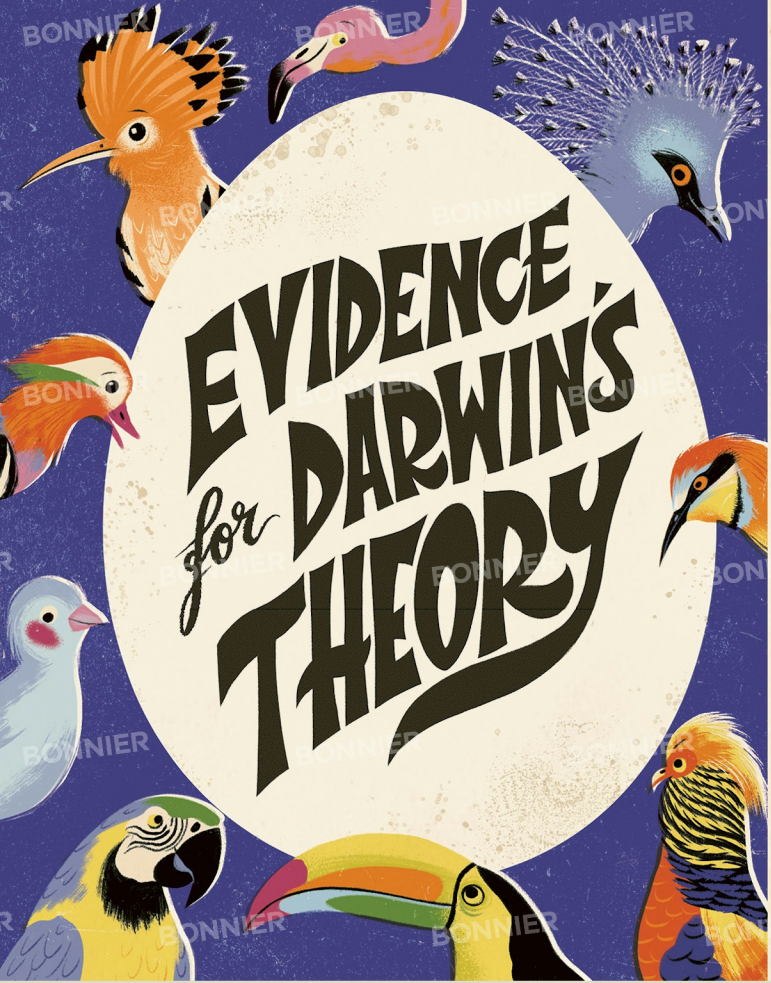
Predator adaptations include speed and endurance to run prey down, forward-facing eyes – for judging distances when pouncing, and sharp teeth and claws for killing prey.

Prey adaptations include camouflage to avoid being spotted, eyes positioned at the sides of the head for all-round vision to spot the approach of a predator, and speed and agility to evade a chasing predator.

SEXUAL SELECTION

Within a species there is competition for space, shelter, food and water, but there is also competition for mates and this often involves sexual selection. Darwin was aware that there were some physical characteristics that were difficult for his theory of evolution to explain because they should be a disadvantage to the animal. For example, a peacock's tail makes it noticeable to predators and affects its ability to fly. Why would creatures evolve apparently unhelpful features? To explain this, Darwin proposed the theory of sexual selection.

Most female birds choose the male they will mate with. This has led to males developing songs, plumage and behaviours to attract females. The males may have to compete for a mate by dancing or singing. In the case of the peacock, this has led males to evolve longer and longer tails. The beautiful display of iridescent feathers when they are fanned out makes them extra attractive to females, and because only strong, healthy males could survive with the disadvantage of a huge tail, it demonstrates to the female that they are the 'fittest' mates.



Darwin's theory was logical and explained a great number of observations, but there were gaps. He made no attempt to explain how new species arose, and more evidence was needed to make a thoroughly convincing case for evolution. Ironically, Darwin seems not to have appreciated the significance of the varied beak shapes of the finches he had collected from the Galápagos Islands during the Beagle voyage (see page 65), but even today, continuing studies of these birds are adding to our understanding of evolution.

Important evidence was available to Darwin, however, from studies of domesticated species, like dogs and pigeons, which existed in a variety of breeds developed by humans through selective breeding. Comparative studies of the anatomy of mammals, birds, reptiles and amphibians showed how the same basic bone structure became adapted by evolutionary change for different functions.

Since Darwin and Wallace developed their theory, research on organisms which reproduce rapidly has allowed a much deeper understanding of how evolution works in real life, as changes which take place over many generations can be studied in a few years. Scientists can also directly study the chemical DNA, which encodes all the characteristics of living things, and investigate the effect of changes in this code on the whole organism.

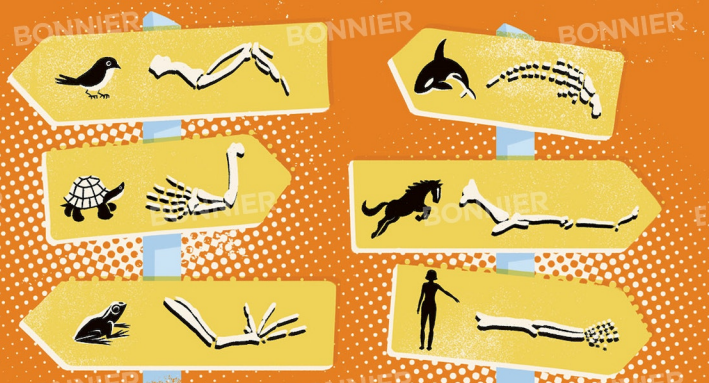
SELECTIVE BREEDING

Selective breeding has been used for thousands of years to 'improve' domesticated animals and plants. Breeding pairs are chosen by people in the hope that the offspring will show new combinations of useful characteristics. For example, a rose with fragrant flowers might be bred with one with large flowers to try and produce new plants with large, fragrant flowers.

Domestic dogs show what selective breeding can achieve. They are all descended from wolves, but over thousands of years, by people selecting puppies for friendliness or aggression, physical characteristics, behaviour and intelligence, dogs have been shaped into many different breeds. They are all still the same species and can, in theory, breed with each other.

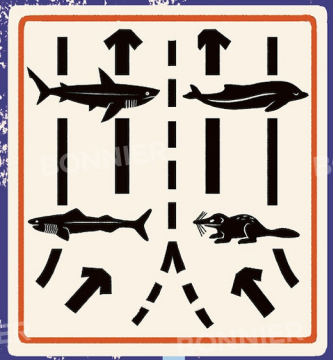
The same process has been used to produce useful characteristics such as crops with higher yields and disease resistance, or cattle bred to produce more milk or leaner beef. However, it has also produced some less useful organisms: munchkin cats with unusually short legs, tumbler pigeons which roll over as they fly and tailless Manx rats.

Selective breeding is a bit like a speeded up version of evolution, but there are important differences. Humans, not environmental conditions, do the selecting, and changes in the organism don't necessarily make it better at surviving. For instance, in the wild, munchkin cats would be poor hunters, so they would be unlikely to survive.



DIVERGENT EVOLUTION

The front limbs of amphibians, reptiles, birds and mammals are all based on the same basic design and most contain the same bones. However, over time the limbs have become adapted for different purposes, and so the bones are now different shapes and sizes. This is an example of what is often called divergent evolution.



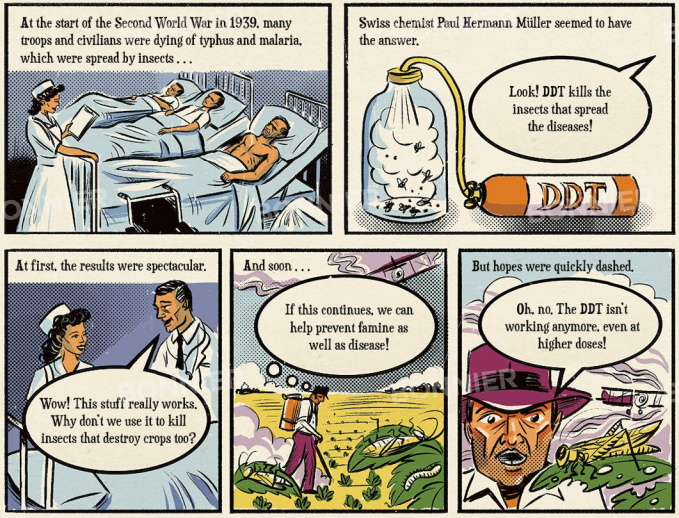
CONVERGENT EVOLUTION

Sharks and porpoises look very similar in terms of body shape, but sharks are fish and porpoises are mammals. They resemble each other more closely than their ancestors did because they have become adapted to live in the same environment, so the same characteristics are advantageous. This is called convergent evolution.

Other examples of convergent evolution include the wings of butterflies and bats, and the hind legs of kangaroos and locusts. Their shared functions make these structures look similar, although the animals are only distantly related.

RECENT EVIDENCE FOR EVOLUTION

Many people think of the Theory of Evolution as a 'finished' piece of science, but research is still refining our understanding of how the process works. But it is not just research that is contributing to our awareness of evolution... Sometimes blunders in how we use chemicals or drugs provide unexpected insights, as seen in the now banned pesticide DDT (Dichlorodiphenyltrichloroethane).



Unfortunately, DDT also killed harmless insects and accumulated in and poisoned birds and animals who ate the insects. It was banned for agricultural use in 2004.

In recent years, a similar thing has happened with antibiotics. The drugs killed most bacteria at first, but the resistant ones survived to breed, and now some types of bacteria are resistant to almost all antibiotics.

"One might really fancy that from an original paucity of birds in this archipelago, one species had been taken and modified for different ends."
Charles Darwin, *The Voyage of the Beagle*, 1839

DARWIN'S FINCHES

The Galápagos Islands are about 1000km off the coast of Ecuador. There was no life on them when they formed millions of years ago by volcanic eruption; animals and plants arrived there from the mainland, blown by winds or carried on drifting wood. Darwin collected specimens of more than a dozen finch species found on the various islands, which have different sizes and shapes of beak. It would be almost a hundred years until their significance was fully appreciated.

David Lack (1910–1973) was a British ornithologist and evolutionary biologist. His work on Darwin's finches showed that beak size and shape were adaptations to the type of food each species of finch ate. His book *Darwin's Finches*, published in 1947, showed the importance of the birds in illustrating how evolution, and the development of new species, could take place.

Biologists **Peter and Rosemary Grant** (both b.1936) carried out a 40-year study of the medium ground finch on the Galápagos island of Daphne Major. It showed that birds with small beaks tended to die during droughts, when the major food source was large seeds whose shells they couldn't crack. In rainy years, fast-growing plants with small seeds were the main food source, which favoured the birds with smaller, more pointed beaks, as they could pick up tiny seeds. This was important evidence that evolution could cause changes in a very short time.

THE PEPPERED MOTH

The peppered moth was originally a pale, speckled moth which was well-camouflaged when it rested on lichen-covered tree trunks. Occasional black individuals (the first one was recorded in 1848) were easy for birds to see and eat, so were rare. But the industrial revolution in the 19th century changed this. Soot from coal-powered factories blackened trees and killed lichens. Suddenly light moths were easily seen and the dark ones were well hidden: changes in the environment had reversed which characteristic helped the moths survive. By 1900, in industrial regions 98% of peppered moths were black. As industry declined and fuels became cleaner, lichens returned and tree trunks became lighter again. In the past 50 years, the percentage of dark moths has dropped as survival of the fittest takes a new direction again.

VARIATION & SPECIATION

Darwin's theory described how evolution could change the features of existing species, but it didn't properly explain how completely new species could appear. How do the variations on which natural selection works arise in the first place? How different do groups of organisms have to become before they can be considered a new species? And what exactly is a species anyway?

Unknown to Darwin, the answers to some of these questions were being discovered at the same time as he was developing his theory. The research being carried out in a monastery in what is now the Czech Republic provided the basis for a whole new science – genetics – but it would be decades before its significance would be fully understood. Nowadays, genetics continues to provide some of the most exciting insights in biology and breakthroughs in healthcare as well as further evidence for Darwin's theory.

It's important to remember that the changes needed for a new species to develop usually take place over millions of years – a timescale difficult for us to imagine. This gives plenty of time for tiny changes to 'add up' to a point where two closely related groups of organisms become different enough from each other to be classified as two separate species.

VARIATION

Gregor Mendel and Charles Darwin were contemporaries, but they never met. In fact, Darwin seems not to have known of Mendel's existence, though Mendel had definitely read Darwin's *On the Origin of Species* by the time he published his work on plant breeding.

Gregor Mendel was a Czech monk, mathematician and botanist. In 1844, he began a series of pea plant breeding experiments to investigate how characteristics were inherited. These characteristics, such as colour and shape, were controlled by what we now know as genes. Mendel's work was the foundation of the science of genetics, although his results lay forgotten for about 40 years before other scientists recognised their importance, and the molecule on which inheritance depends – DNA – wouldn't be understood until over a century later.

DNA (deoxyribonucleic acid) is a complex molecule made of long strings of smaller parts called nucleotides. The order of the nucleotides forms a code that instructs cells how to make different proteins by specifying the order in which particular subunits called amino acids are joined. The code for a single protein is called a gene. The helix structure of DNA was discovered in 1953. Not only did it explain how DNA could code for proteins, it also showed how variation could arise by genetic changes, or mutations.

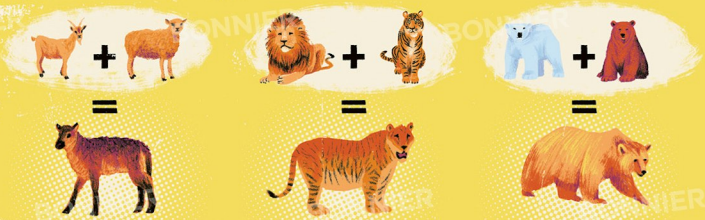
HOW DOES DNA WORK?

Living things begin as a single cell which grows and divides repeatedly to produce the adult organism. DNA is copied each time a cell divides so that every cell has a complete set of DNA. Mistakes in this copying are called mutations. They result in a 'wrong' amino acid becoming part of a protein, which changes the protein's shape and can affect its function. In most cases, these random changes are harmful or useless, but occasionally one mutation comes along that makes the individual better suited to its environment.

Now that we understand how DNA works, scientists can reconstruct evolutionary history by comparing the DNA of different species. The more closely related they are, the less their DNA will vary.

WHAT EXACTLY IS A SPECIES?

There are several definitions of a species, but one of the most commonly used is that a species is a group of organisms that can breed with each other to produce fertile offspring; that is, offspring who can also go on to reproduce. So, a male and female horse, or a male and female donkey, can produce foals which will be able to reproduce when they are older. But a female horse mated with a male donkey will produce a mule, which is sterile (unable to reproduce). Other examples are:



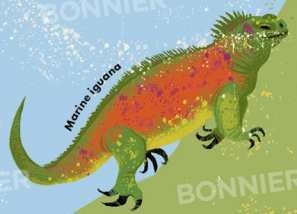
Goat + Sheep = Geep

Lion + Tiger = Liger

Polar Bear + Grizzly Bear = Pizzly Bear

HOW DO NEW SPECIES ARISE?

Sometimes a population becomes split into two groups. This could be caused by a flood, drought, change in the course of a river, landslide or earthquake, for instance. The two parts of the population are now isolated from each other. If the conditions in these areas aren't identical, natural selection will work in slightly different ways. The longer the groups are separated, the more different they will become. If this process continues, eventually the two groups will become so different from each other, that even if they were no longer separated, they wouldn't be able to breed. They are now two separate species.



A similar process on the Galápagos Islands led to the evolution of the only saltwater aquatic lizard in the world, the marine iguana. Land-living iguanas probably arrived on the islands carried on driftwood. With no competition, the population increased until food and living space began to run short and some iguanas were forced onto the shore. This competition gradually led to the population splitting into two species. The marine iguana has a flattened tail and webbed feet to help it swim, and mainly eats seaweed. The terrestrial iguana has an unflattened tail, no webbed feet and eats leaves and other vegetation.

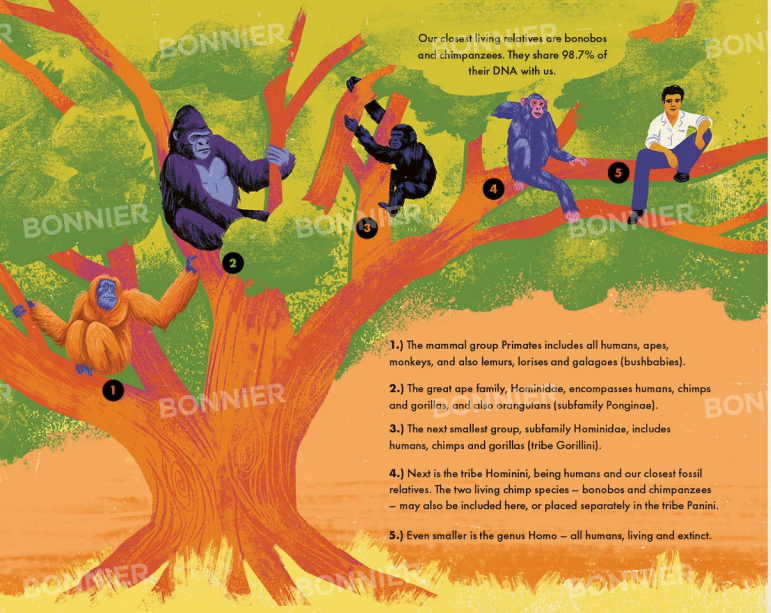
One of the reasons Darwin's Theory of Evolution was at first so controversial was because it implied that humans had evolved in the same way as other animals, whereas most people at that time believed that humans had been specially created by a god who ruled over the animal and plant kingdoms. Darwin's idea that humans and great apes shared a common ancestor was often misrepresented as implying that humans were descended from living apes – not what Darwin meant at all.

Although our own species, *Homo sapiens*, has been around for 300,000 years or so, we have had more effect on the planet than any other species. Officially, we are in the Holocene epoch (the current geological epoch which began around 11,700 years ago). But some people suggest the time we live in now should be called the 'Anthropocene', from the Greek 'anthropo' (human) and 'cene' (new). In 2016, the Anthropocene Working Group research party decided the 'Anthropocene' started in 1950 with the Great Acceleration – a dramatic increase in human activity influencing the planet.

There is no doubt that humans have affected the planet in many ways, destroying habitats, altering the composition of the atmosphere, releasing radioactive elements in nuclear bombs and accidents, polluting the oceans with plastics and causing climate change. Geologists are unsure if this will leave a permanent trace in rocks or fossils, which would officially make the Anthropocene a new geological epoch, but radioactive and plastic pollutants have the potential to survive for millions of years in rocks being formed now.

OUR CLOSEST RELATIVES

Studies of fossils, DNA and proteins suggest that the last common ancestor we humans shared with our closest relatives, chimpanzees, lived some time between 12 and six million years ago. After that, things become much less clear, as only a small number of fossils, mostly incomplete have been found.



1.) The mammal group Primates includes all humans, apes, monkeys, and also lemurs, lorises and galagoes (bushbabies).

2.) The great ape family, Hominidae, encompasses humans, chimps and gorillas, and also orangutans (subfamily Ponginae).

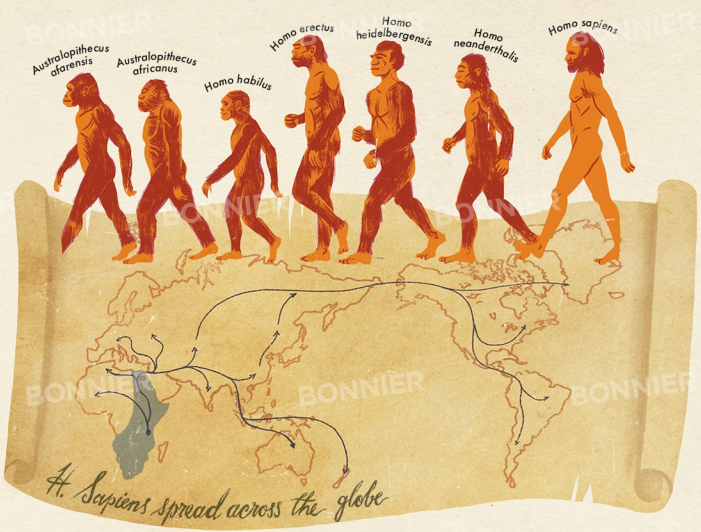
3.) The next smallest group, subfamily Hominidae, includes humans, chimps and gorillas (tribe Gorillini).

4.) Next is the tribe Hominini, being humans and our closest fossil relatives. The two living chimp species – bonobos and chimpanzees – may also be included here, or placed separately in the tribe Panini.

5.) Even smaller is the genus Homo – all humans, living and extinct.

TRANSFORMING SKELETONS

As humans evolved, our brains became larger, our jaws and teeth became smaller, and our spines, legs and feet changed shape to allow us to walk upright all the time. Changes in the shape of our hands gave us greater dexterity.



THE HUMAN LINEAGE

Modern humans evolved from a series of ancestors, including several earlier forms of humans. Today, only one species of human exists – ourselves, *Homo sapiens*. Fossil evidence of our evolution is scarce, but scientists continue to find new indicators as to how humans developed.

In 1924, a fossil skull of *Australopithecus africanus* was found in a South African quarry. *Australopithecus* walked upright and had hands and teeth like modern humans, but its brain size was only about 450cm^3, compared with about 1,350cm^3 found in the average modern human.

In 1974, an even older form of *Australopithecus* – *A. afarensis* – was discovered in Ethiopia. Named Lucy, she lived about three million years ago but was only around 110cm tall with a 400cm^3 brain. Modern humans are on average between 163cm and 176cm tall. She walked erect, but her feet and her leg muscles were different to ours.

Homo habilis existed by two million years ago. The name means 'Handy human'. These were thought to be the first hominins to use stone tools.

Homo erectus evolved by 1.5 million years ago and moved through Africa into Asia. The first fossils of *H. erectus* were found in Java and near Beijing in China. Remains found with the fossils also gave some insights that *H. erectus* lived lived in huts, wore animal skins and built fires.

Homo heidelbergensis lived 600,000 to 200,000 years ago and is believed to be the direct ancestor of *H. sapiens*, which first appears as a fossil around 300,000 years ago.

Early *H. sapiens* were only one of several species of human in existence at the same time. *H. neanderthalensis* – Neanderthal human – is well known, and in 2010, fossil fragments from a new hominin were discovered in Siberia. Little is known about these Denisovans due to the small quantity of fossil remains found, but they lived at the same time as ourselves and Neanderthals, and the three seem to have interbred: DNA characteristic of both Neanderthals and Denisovans is found in modern humans. It seems likely that all three share *H. heidelbergensis* as a common ancestor.

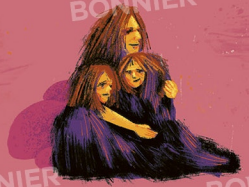
There is still much we don't know about the evolution of humans, and the picture has been further complicated by the discovery of fossils of several more hominins, such as *H. floresiensis* and *H. naledi*.

NEANDERTHALS

Modern humans, Neanderthals and Denisovans co-existed for thousands of years and probably interbred. By some definitions, this means they all belonged to the same species. Neanderthals died out about 40,000 years ago. It's thought that Denisovans might have been around 30,000 years ago. Why did these two groups die out? No one knows the answer to this yet, but today only H. sapiens is left. As more evidence emerges about Neanderthals, however, it is becoming clear that they lived in societies that were more advanced than we used to believe.

NEANDERTHAL LIFE

Neanderthals were adapted to life in very cold conditions. They were short and muscular, and their large, broad noses helped to warm the air they breathed. Their brains were as large, or larger, than ours. They constructed shelters, made animal-skin clothes, created a range of sophisticated stone tools, used spears to hunt and made fires to cook meat. They were the first hominins to bury their dead and sometimes left offerings on graves.



65,000 years ago, Neanderthals produced the first cave art, using red lines, dots and hand prints – thousands of years before *H. sapiens* reached the area.

THE EVOLUTION OF CONSCIOUSNESS

What is consciousness? A simple definition is that it is the awareness of your own existence as an individual. We humans have this self-awareness, and for a long time assumed we were unique in this respect, but we now know that many other animals are self-aware.

One of the most commonly used tests is the mirror test. The skin of an animal is marked, in a place it can't see directly, but can see in a mirror. If the animal is shown its reflection and behaves in a way that shows it has noticed the mark, this indicates it recognizes itself in the mirror. Using this test, chimps, bonobos, orangutans, gorillas, elephants, bottlenose dolphins, killer whales and magpies are self-aware. But what about animals that don't rely primarily on vision? The mirror test suggests that dogs are not self-aware, but many pet owners would disagree and a test that uses smell (the dominant sense in dogs) indicates that they are.

HUMANS AND FIRE

It's still not clear exactly when early humans were able to make and control fire. Originally, they used fires started by lightning strikes and made them last by adding more fuel, such as dry leaves or fallen branches, but the ability to start fires developed much later. Fire provided heat, light, protection from predators and a way to cook food. Gathering round a fire brought people together, which may have influenced the development of language and social interactions.

EVOLUTION IN THE 'ANTHROPOCENE'

It's easy to think of evolution as something that happened in the past, but of course, it's still happening all around us. How is evolution affecting humans and how are humans affecting evolution?

ARE HUMANS STILL EVOLVING?

We seem to cheat evolution every day. Houses shelter us from the worst of the weather; the inventions of printing and the Internet make it easier to pass on knowledge from generation to generation. We have medicine, science and technology to keep us alive. Surgery can mend severe injuries; antibiotics stop us dying from bacterial infections.

But we haven't really cheated evolution. There is still variation between humans caused by DNA mutations. Some of these mutations spread through populations, so we are still changing very gradually. In the past few years, we have acquired the ability to edit DNA directly, giving us – potentially – the ability to wipe out a number of inherited diseases.

But this raises its own problems. Where do we stop? Most people would agree that preventing incurable and sometimes fatal genetic conditions like muscular dystrophy and sickle cell anaemia is a good thing, but should we 'edit out' short-sightedness? Or 'edit in' tallness – a trait prized by many cultures? These are important moral questions that we may need to answer soon.

THE NEED FOR MILK

All mammals are fed with milk when they are newborn, but when they grow up they lose the ability to digest it, so don't drink it any more. However, in Europe, over 70% of people can still digest milk as adults. This change probably took place when European humans domesticated animals like sheep and cows 10,000–5,000 years ago. Being able to drink milk was a useful adaptation because it was a valuable source of nutrients.

A THIRD ARTERY

Studies by anatomists in Australia show that increasing numbers of people have a third artery in their forearms. About 10% of people had this artery in the mid-1800s, but it is now found in around 30% of people. This could offer benefits by increasing overall blood supply.

FISHING AND HUNTING

Commercial fishing generally takes the largest fish. There is evidence that the size of adult fish is decreasing, and they are reaching sexual maturity earlier, increasing their chances of breeding and passing on these characteristics before they are caught.

GENETIC MODIFICATION

Our DNA-editing abilities can also be used on other species. For example, work is taking place to produce cattle that are resistant to foot and mouth disease and bovine tuberculosis.

HOW DO WE AFFECT THE EVOLUTION OF OTHER SPECIES?

As well as evolving ourselves, humans are also affecting the evolution of other species. We alter the environment, for instance by draining marshes, felling trees and releasing chemicals into water. This alters the conditions for species in these areas, changing the selection pressures and the way in which they evolve.

Male bighorn sheep in Canada use their horns to fight each other to secure mates, but mainly in the past, hunters also shot the males with the biggest horns since they made the most impressive trophies. Bighorn sheep horns are evolving to be smaller, as it's no use being attractive to a mate if you're killed before you can pass on the genes that give you big horns.

Mosquitos carry several devastating human diseases, including malaria and yellow fever. Female mosquitos transmit these diseases, as only they feed on blood. DNA editing can produce sterile females, which could be used to reduce the number of mosquitoes capable of spreading these diseases.

OUR LEGACY

Evolution has shaped every species on Earth and continues to do so, but humans are in the unique position of being able to influence our own and other species' evolution. This puts an enormous responsibility on us. Life changes – that's one of its defining characteristics. But through extinction, selective breeding, habitat destruction and gene editing we have unprecedented power over the evolution of other species.

We haven't been here for nearly as long as sharks or crocodiles. One day we may be extinct while they are still here. If the 'Anthropocene' does become a new geological epoch, what traces will we leave? Plastic and radioactivity would be a depressing legacy of our time as the dominant species, but perhaps if we begin to take more care of the planet and its other inhabitants we can leave it in good working order for... who knows? We can only imagine how life might change in the next few million years...