Background: Drawing of a silk cotton tree by Richard Spruce on his travels with Alfred Russel Wallace, 1850
(Image ©The Royal Society)

From Darwin to DNA

A statement from the Royal Society celebrating the 150th anniversary of the publication of *The Origin of Species*

EXCELLENCE IN SCIENCE

THE ROYAL SOCIETY

From Darwin to DNA

Introduction

One of the most remarkable achievements of science over the last two hundred years has been to show how humans and all other organisms on the Earth arose through the process of evolution. Others had postulated the existence of evolution, but it was Charles Darwin who first encapsulated this notion of the essential interrelatedness of all organisms in a 'tree of life'. Today, his insight is the basis for the science of biology. Darwin's idea underpins the advances in agriculture and medicine that modern society takes for granted. Crops bred on his principles mean that we can sustain a growing population, while we must learn how to combat agents of disease that are themselves constantly evolving. Humans are facing serious emerging threats, including the loss of biodiversity, climate change caused by our profligate release of greenhouse gases, and the ever-increasing pressure to clear natural habitats for crop production. Practical Darwinism is the best hope of solving many of these problems confronting the planet.

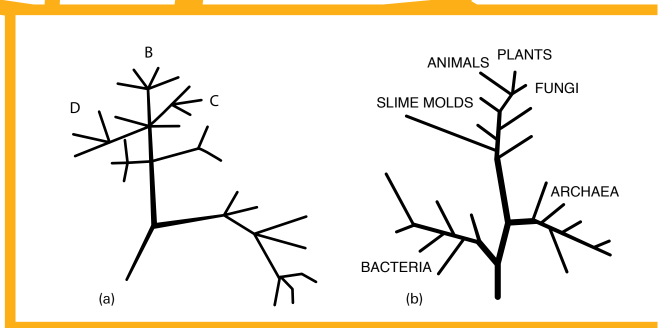
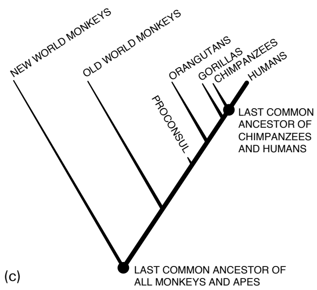


Fig 1. (a) Charles Darwin first drew a sketch of representing the interrelationships between organisms as a 'tree of life' in 1837; (b) the actual relationhships among living organisms show that his ideas were remarkably accurate; (c) the tree of relationships among man and other primates.

Scientists achieved their grasp of the processes whereby the Earth came to support such a diversity of life using a standardised scientific approach. This involved the development of a theory to explain the observed facts, followed by further observation and experimentation to test the theory. The results obtained by these approaches are subject to rigorous testing and then re-evaluated on the basis of new information as it emerges. Scientific conclusions about evolution are thus based on the accumulated mass of evidence, and what were initiated as hypotheses become strengthened or rejected over time as a result of the testing process. In the case of evolution this testing of the original theories, expounded by pioneers such as Darwin and Alfred Russel Wallace, has led to a widespread acceptance that the biodiversity seen on the planet today can largely be explained by the evolutionary process of natural selection, in which changes in the genetic composition of populations arise as a result of differences in the survival rates of organisms and the rates at which they reproduce. We do not understand everything about evolution, but we know a great deal. Evolution is no longer 'just a theory'; it has been scientifically verified.



This document is a short outline of Darwin's original argument, presented in his classic work of 1859 *On the Origin of Species by Means of Natural Selection*, together with a description of some of the evidence that has proved he was right. This year sees the 150th anniversary of the publication of *The Origin of Species* and the associated celebrations have done much to promote a general understanding of the evolutionary process.

It is a remarkable testament to the foresight of the pioneers of evolutionary theory like Darwin and Wallace that much of the most significant evidence has emerged long after their deaths, and continues to add ever growing support to what we know about evolution by natural selection.

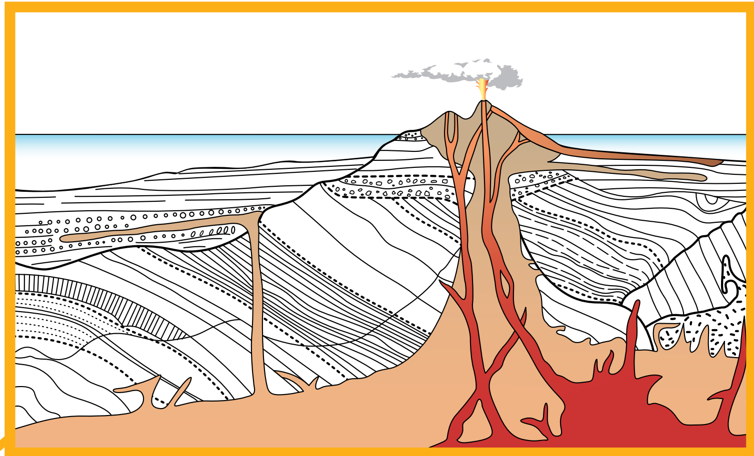
Darwin's basic contention was that because organisms are in competition with each other for food, for light, for water, for sex and for other resources, individuals that are better adapted to their local circumstances will leave more offspring than those that are less well suited. The fastest deer has the best chance of escaping the wolf, and in desert plants individuals with traits enabling conservation of water have an advantage. If differences in speed and water retention are inherited, in time, legs will become longer and watertight coats thicker until fleet deer and thick-skinned cactuses evolve. The force that drives the process of natural selection – predation by wolves or water limitation in these examples – is termed selection pressure. It is summed up in three stages: organisms vary; the variations are inherited; different variants survive at different rates, leading to changes in their relative abundances. Darwin himself famously observed that this process had occurred in the finches of the Galapagos Islands, with each of fourteen species having a differently shaped bill suited to different kinds of food; he worked out that "one species had been taken and modified for different ends". New species are still being formed; the commonest grass in salt marshes all around Britain is a brand new species – common cord-grass – that evolved within the last 100 years, and whose evolution was closely monitored by scientists. It is so successful that it has been planted all over the world to help reclaim land in estuaries.

Natural selection has been very loosely understood in terms of 'the survival of the fittest'. Fitness in the evolutionary context refers not to physical strength, but to the ability to leave more offspring, or more specifically to leave more copies of one's genes, in the next generation. Sometimes, in fast breeding creatures like bacteria, we can see this in the laboratory. More often, we must infer its action from what it produces. Just as some offspring are more successful, others must be less so, and in some cases, this leads to the extinction of populations of organisms and even whole species.

It was a characteristic of Darwin's approach that *The Origin of Species* is full of evidence, of many different kinds: from fossils, from farms, and from geography. It starts with the familiar – with pigeons, or dogs – as evidence that selective breeding works, which is how we have made pugs and pit-bulls from wolves in a few thousand years (and breeds like the Jack Russell Terrier since Darwin's day). It moves on to geology, to island life, to embryology and more, and ends with a spirited defence of the notion of evolution (although the word itself does not appear in the book).

Modern science has led to the confirmation and amplification of most of Darwin's conclusions in these different realms of investigation, while at the same time adding new knowledge in disciplines such as ecology and molecular genetics that had not been developed in his day.

Fig 2. One of Darwin's main influences was to emphasise a realisation derived from geology that the world was many millions of years old, as demonstrated by Charles Lyell in his diagram of the Earth's crust.



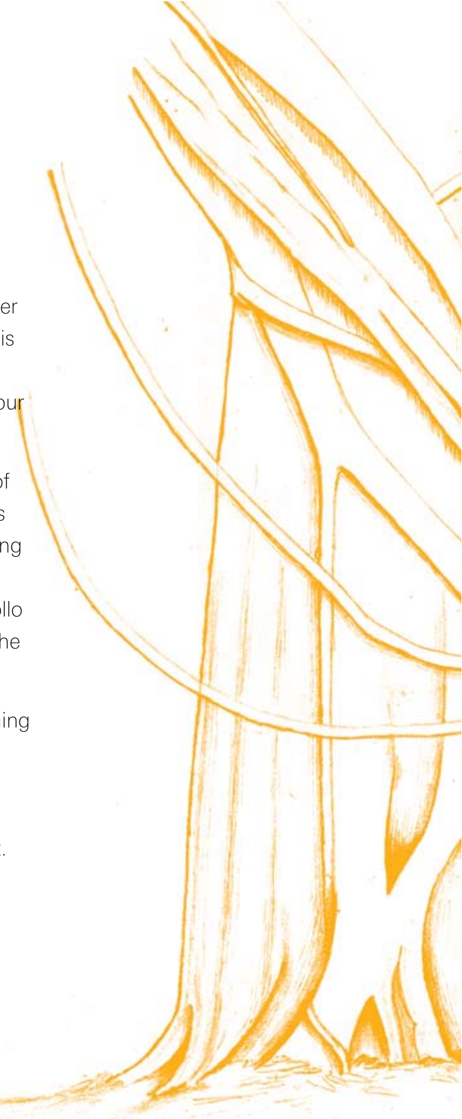
The timescale

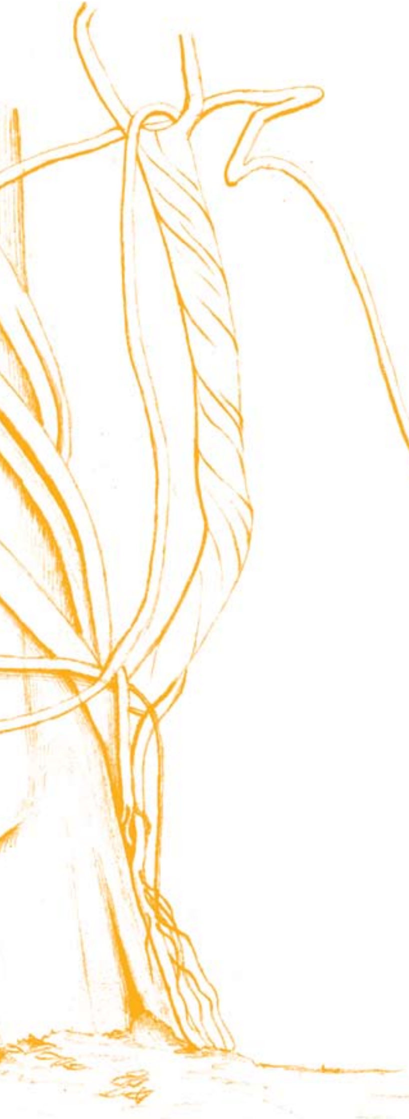
Prior to Darwin, a widely accepted view was that the Universe, the solar system and the Earth within it were relatively 'young' having been formed perhaps only 6,000 to 10,000 years ago. Darwin, in parallel with his contemporary Charles Lyell, made calculations of the rates of deposition and erosion of sediments making up major geological sequences and calculated that many of these had been deposited over millions of years. Modern technology has proved these pioneering analyses to be correct, while at the same time providing more precise estimates of the time-frame within which evolution could take place.

Our Sun – a star – lies within a galaxy that contains about 100 billion other stars; our galaxy is itself just one of billions that are visible through a large telescope. Measurements made by instruments such as the Hubble Telescope reveal that distant galaxies are receding from ours in every direction. The implication of these observations is that the Universe is expanding and that in previous times it must have been more condensed. The evidence suggests that all the matter and energy of the Universe emerged from an exceedingly hot and dense initial state – the 'big bang' – and that this happened nearly 14 billion years ago. As the material expanded and cooled, structures began to form. Our galaxy has existed for about 10 billion years; during its entire life, new stars have been formed. Very many stars are, like our Sun, orbited planets.

The age of our particular solar system has been calculated using a number of different independent methods, all of which give a similar answer of around 4.5 billion years. One of the most widely used of these dating tools involves the use of naturally occurring radioactive elements, such as uranium. Radioactivity decays at known rates, providing a kind of clock that enables us to determine the age of the rocks in which these elements occur. Using these time keepers, it has been shown that 4.5 billion years is a good estimate of the ages of lunar rocks returned by the Apollo mission and of meteorites, which represent remnants of the original solar nebula (the cloud of gas left over from the formation of the Sun). The oldest minerals known on Earth are very similar in age – about 4.4 billion years old.

Because known life is based on the carbon atom, emphasis has been placed upon detection of molecules containing carbon. Numerous laboratory experiments attempting to simulate the Earth's early atmosphere have suggested that condensation of carbon-rich molecules would have occurred during the first stabilisation of the Earth's crust. The combination of very great age and subsequent geological deformation make it very improbable that these earliest organic structures, or indeed any of the molecules that existed at the time, will have been preserved intact. For this reason geochemists and those seeking evidence of early life forms are necessarily circumspect in their considerations of 'origins'.



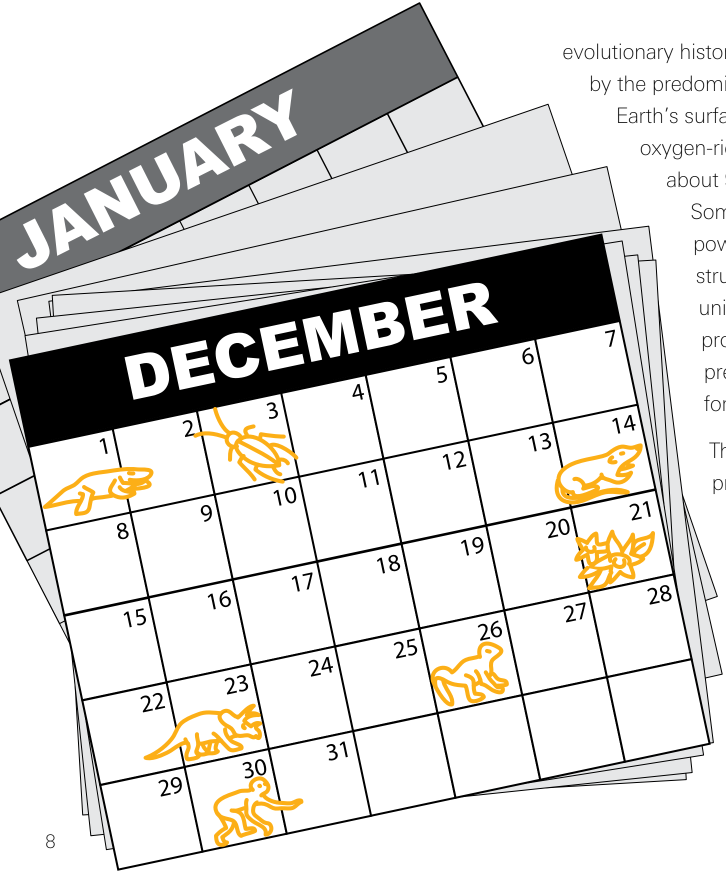


Evidence for the presence of such molecules, at least in fragmentary form, has been sought in the oldest sedimentary rocks. Analysis of different forms of carbon (known as isotopes) has helped to discriminate between non-biological and biological molecules. Two isotopes of carbon – Carbon 12 and Carbon 13 – have been particularly useful. Photosynthesis, the process by which plants use carbon dioxide in the atmosphere to obtain the carbon they need to grow, involves a key enzyme (rubisco) that is more efficient at capturing Carbon 12 from the atmosphere than Carbon 13. So the ratio of the two isotopes differs in plant material (and in the animals that eat them) from that found in non-biological substances. The isotopes suggest that photosynthetic activity, and hence the presence of life forms capable of photosynthesis, occurred in the period between 3.5 and 2.8 billion years ago. The organisms were probably photosynthesising bacteria called cyanobacteria. So far none of their fossils have been definitely found, although structures called 'stromatolites' made by modern photosynthesising bacteria seem to occur as fossils as far back as 3.5 billion years ago. But structures of the same shape can be formed by non-biological processes and the jury is still out as to whether they really are evidence of ancient life. On the basis of the evidence available at present it is thought most likely that the first life forms arose between 3.5 and 3.1 billion years ago, and that the cyanobacteria had evolved by about 2.9 billion years ago.

While not all scientists agree about the very earliest life forms, there is consensus that by 2.7 billion years ago, bacteria were relatively common. The evidence comes from the presence of oxides of iron, sulphur and manganese, which are proof of photosynthesis – the only environmental process capable of releasing free oxygen. What is more, carbon-based molecules similar to those made by cyanobacteria begin to appear in the rocks.

By about 2.4 billion years ago, sufficient oxygen was released that, for the first time, there was enough in the atmosphere to enable the development of a variety of life forms. Most scientists agree that a very long period of

Fig 3. If the Earth's entire history were condensed into a year, the first insects would not appear until early December, the first mammals appeared in mid December and primates not until the final week of the year. On an evolutionary timescale, humans are very recent additions to the Earth's diversity.



evolutionary history stretching from about 2.4 until about 1.5 billion years ago was characterised by the predominance of photosynthetic cyanobacteria in water. Their actions changed the Earth's surface environment from one that was essentially lacking oxygen (anaerobic) to the oxygen-rich (aerobic) environment that we know today. Even so, life stayed simple until about 900 million years ago. Then, larger (but still single-celled) organisms appeared. Some engulfed simpler organisms, creating a wholly new kind of cell: the energy powerhouses of the cell, the mitochondria, arrived in this way, as did the green structures called chloroplasts found in many plants. First came a proliferation of uni-and multi cellular planktonic species in the marine environment and soon after, probably by 500 million years ago, the emergence of plants on to the land. The presence for the first time in the terrestrial environment of plants paved the way for the emergence of herbivorous animals and then the carnivores that eat them.

The fossil record confirms that the arrival and extinction of species has occurred progressively but unevenly to the present day, the process being interrupted periodically by mass extinction events that often established new pathways of differentiation. Vertebrates first appear in the fossil record around 490 million years ago. From these evolved the fish, amphibians, reptiles, birds and mammals. At last, about 2.4 million years ago, an ape-like animal appeared that we now recognise as being so similar to ourselves that it is classified in the same genus, *Homo*. It was from this ancestor that modern humans eventually emerged between 100,000 and 150,000 years ago.

Some 20th century advances in evolutionary biology

The pioneering work of **Charles Darwin**, **Charles Lyell**, **Alfred Russel Wallace** and **Gregor Mendel** meant that by the end of the nineteenth century, we understood the theoretical basis of how evolution works. During the twentieth century, other great scientists advanced our understanding. **William Bateson** developed Mendel's ideas and coined the term 'genetics'. **Ronald Fisher**, **J B S Haldane** and **Sewell Wright** founded the discipline of population genetics, applying evolutionary principles to populations of organisms – this allowed work on genetics and evolutionary biology to be synthesised into a unified understanding. **Linus Pauling** proved that abnormal proteins caused by genetic factors could cause human diseases. **Rosalind Franklin** used X-ray diffraction to study the molecular arrangement of DNA, paving the way for the famous discovery by **James Watson** and **Francis Crick** of its double-helix structure. **Frederick Sanger** showed that proteins were not heterogeneous but had a defined chemical composition that might map on to the DNA code. **Bill Hamilton** developed a rigorous theoretical basis for the existence of traits such as altruism that had previously been difficult to place in a Darwinian context. These and many other researchers have continued to develop, refine and advance Darwin's ideas. The start of the twenty-first century saw the publication of the first complete map of the human genome, another major milestone in our understanding of evolution.

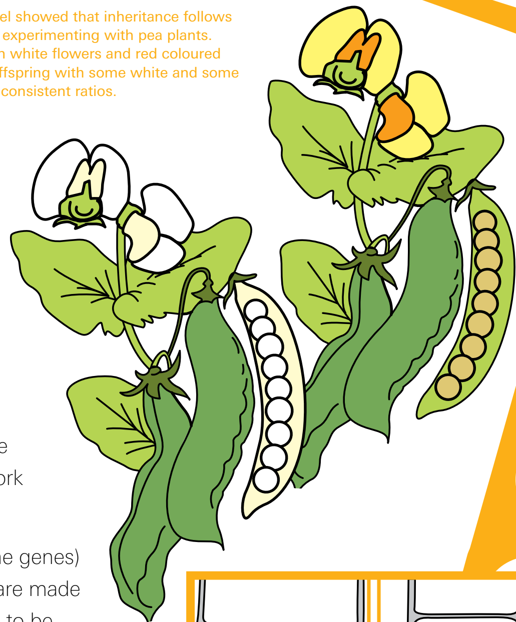
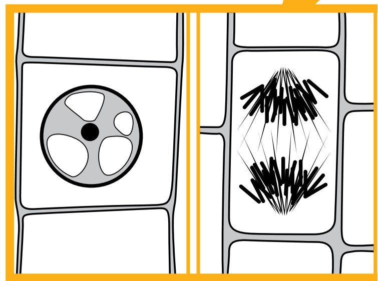


Fig 4. Gregor Mendel showed that inheritance follows predictable laws by experimenting with pea plants. Crossing plants with white flowers and red coloured flowers produced offspring with some white and some coloured flowers in consistent ratios.

The molecular basis of evolution

Darwin was familiar with many of the basic features of the fossil record, but he was not aware of the underpinning evidence of evolutionary relationships between organisms. This has subsequently been derived from studies of the molecular structures involved in the transfer of hereditary information from ageneration to generation.

At the very time that Darwin and Wallace were formulating their ideas, Gregor Mendel was conducting experiments in breeding pea plants that led him to the view that characteristics are inherited via discrete hereditary factors. Nobody knew what the nature of these factors might be, and for a time Mendel's work was ignored.



At the beginning of the twentieth century, it became clear that Mendel's factors (by now given the name genes) could provide the raw material for evolution. Meanwhile, it had been established that living organisms are made up of discrete cells, and that during growth, cells repeatedly divide into two. Cell division was observed to be accompanied by the appearance of bodies called chromosomes, which themselves divide and are assorted to the two new cells that result from the division of the original one. Chromosomes appeared to be plausible carriers of the genes, and during the following decades this hypothesis was confirmed by extensive experiments in fruit flies. But it was still unclear what material the genes were made of, and nobody knew how they worked.

It took another 50 years to establish first that the hereditary material is a substance called DNA, and finally in 1953 to establish the nature of DNA. In one extraordinary decade the key processes of life were uncovered. The structure of DNA, consisting of two intertwining strands, each carrying a specific sequence of four different chemicals (called bases), itself immediately suggested a mechanism for heredity – a leap of understanding that has now been thoroughly validated. At the same time X-ray crystallography began to reveal the structure of proteins, which are the major building blocks of the body; it was already known that proteins are not random in form but come in discrete types. We now know that the discrete genes in the DNA provide a code that determines the structure of discrete proteins. We also know that inherited variation is caused by changes in the gene sequences of organisms, called mutations. They can arise from errors introduced when DNA is copied, and from damage due to background radiation or chemical reactions. During reproduction, those mutations that are retained are repeatedly reassorted by a process called recombination, such that new combinations constantly appear. Sometimes errors result in the duplication of a gene, or even of an entire genome; the duplicate copies then evolve separately, such that new functions can arise. Many examples of this process are known.

The recognition of gene sequence as the determining mechanism of heredity provided an explanation for the variation between individuals and populations that Darwin documented so effectively in his book. Thus a century after the publication of *The Origin of Species*, the mechanism of heredity was at last clear.

By the 1960s, it was obvious that the fundamentals of life are the same in all organisms. It was already understood that the process for generating energy from nutrients and oxygen is much the same in bacteria, plants and animals, but now the detailed nature of the molecules involved also turned out to be very similar. Analysis of the small variations between the corresponding molecules in different species allowed patterns of relatedness to be built up, and the 'family trees' that emerged usually corresponded closely to those already deduced from physical characteristics.

Since the accumulation of mutations in a given gene is dependent on the passage of generations, the process can be seen as a molecular clock in which the number of differences between molecules in different species measures the time elapsed since they last shared a common ancestor.

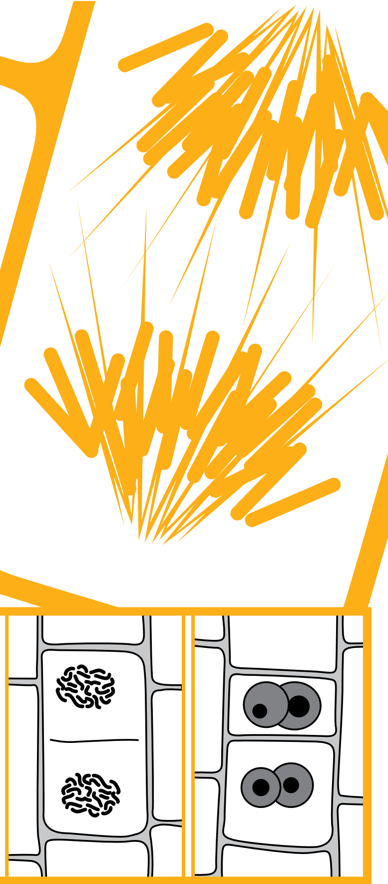


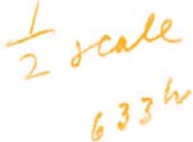
Fig 5. A dividing onion cell shows how two sets of chromosomes in the original cell (on the left) are divided (in the middle) and then allocated to two daughter cells (on the right).

In the late twentieth century, it became possible to read out the entire sequence of DNA (or genome) from each species. As the results flowed onto the internet, and scientists scanned the data for matches to the genes that were of particular interest to their research, similarities emerged everywhere. Researchers moved to and fro between organisms, comparing and contrasting. Functional experiments showed that a gene taken from one organism could often work in another. Genes with specialised functions could clearly be seen to have arisen by modification of older genes.

All but the simplest organisms have long stretches of DNA that fall between the protein-making genes and appear to be unused. When different species were compared, these unused sequences differed much more than the genes did. The reason is that the majority of changes within genes are deleterious – they are altering things about an organism that is already broadly suited to its environment. So natural selection weeds most mutations within genes out of the population. In unused regions of DNA, there is no such selection, so most mutations are retained.

DNA evidence differs from the fossil record because we are only seeing the twigs of the family tree – we cannot currently find intact DNA more than a million years old. But in a way, DNA itself makes every creature a living fossil, containing within itself the genes of its ancestors. For example, human DNA is more than 95% the same as that of a chimpanzee; it is rather less similar to the DNA of a mouse, although we share many of the same genes; and we are more different still from fruit flies, although we still share half our genes with them. There is a deep and inescapable unity of life.

A striking feature of the thousands of sequenced genomes is just how untidy they are. Great chunks of DNA have been transferred from place to place or from one organism to another, while some genes are duplicated and modified to fulfil alternative functions and others discarded altogether: everything fits well with the process of evolution as



(There were a vast many more twiners, which the voracious mosquitos did not allow me to sketch.)

dos Maués. R. S.

envisaged by Darwin, in which the hereditary material is subject to natural selection working on errors that arise at random, rather than being governed by a master plan.

It is particularly significant that during evolution, parts of the body become redundant and are even lost altogether. We are all familiar with the apparently useless and occasionally life-threatening appendix in our own bodies, and the only plausible explanation of its existence is that it is a dysfunctional vestige of some organ that performed some useful function in our evolutionary ancestors. In the same way, the whole genome is littered with ‘pseudogenes’ – tracts of DNA that look like genes but are full of errors. Such mistakes build up in genes whose functions are no longer required and so are no longer exposed to natural selection. A striking example comes from the closely related genomes of the two kinds of bacteria that are responsible for tuberculosis and leprosy. The latter has a very high proportion of pseudogenes, each of which corresponds to a functioning gene in the former. We deduce that the common ancestor of the two had a fully functioning set of genes, but that whilst the tuberculosis bacterium retained the whole set, the leprosy bacterium allowed many genes to be corrupted and became reliant on the products of its host cell for its survival. Such information is of value to medical researchers who wish to find better ways to tackle leprosy.

Studies at the molecular level reveal many systems of great complexity, which challenge us to explain their origins. An example that has been much discussed in recent years is the flagellum – the motor by which a bacterium propels itself through water. The flagellum comprises some 50 components, all essential to its operation. How could it have evolved from simpler structures if they were not themselves useful? Part of the answer turns out to be that pieces of the flagellum are useful in other contexts, notably the secretory system used by the bacterium to inject toxins into other organisms.

This line of reasoning at the molecular level is comparable with that long used at the morphological level. For example Darwin was himself concerned with answering the question: ‘Of what use is half an eye?’ It seemed to some that the origin of the human eye was a serious problem for evolutionary theory. Darwin realised that this is the wrong question: the correct one is: 'Of what use is a rudimentary eye?' The answer to that is, a great deal. Even the simple detection of light with no imaging capability is of value compared with no sensation of light at all. Indeed, even plants, which clearly do not have eyes, have sophisticated mechanisms to detect light, which is essential to their growth. Eyes of differing complexity are known in various animals. We can therefore easily understand how natural selection could have given rise, step by step, to our own complex eye.

Not surprisingly, the human genome is subject to continued study, not least because for practical reasons we would like to know as much as possible about its variants and their consequences for our health. Analysis of human DNA has now become a recreational pursuit as people work out their personal ancestry, and great numbers of genomes have been scanned in part. At the moment the data are patchy, but within a couple of decades we can, if we wish, have a full picture of the interrelationships across the human family. Soon 1000 individual humans will have had the sequence of their DNA read in full, and this information will tell us a great deal about our ancestral relationships.

The implications of evolution for a sustainable planet

The vast diversity of life on the planet has arisen through the process of natural selection described by Darwin, so we must understand evolutionary principles if we are to devise adequate strategies for protecting that biodiversity. When species become extinct, we lose their evolutionary history and diversity, generated over millions of years. As we begin to understand how important ecosystems are in sustaining our own existence, it becomes ever plainer how important an understanding of Darwin's work will be to the future of humanity. Ecosystems are complex, but evolutionary principles are just as important to issues that have more obvious and direct relevance to our daily lives, like food production and healthcare.

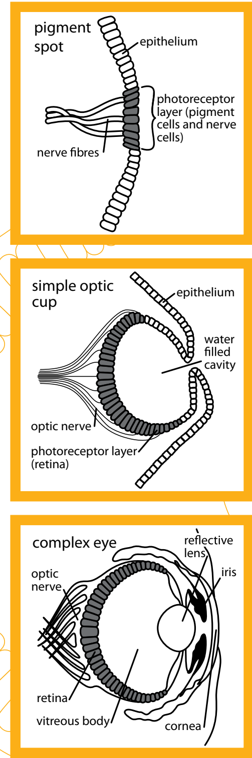
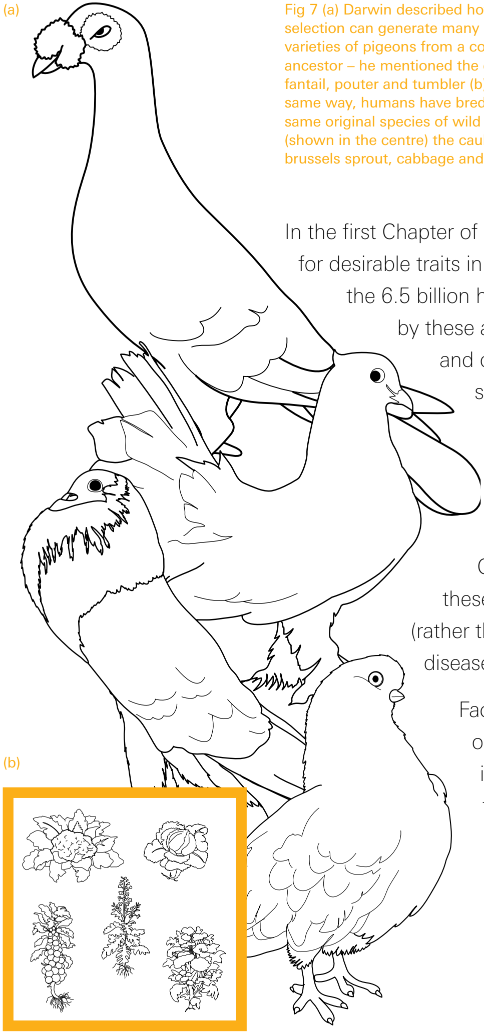


Fig 6. Eyes of different complexity in three marine invertebrates – the limpet (top), the nautilus (middle) and the octopus (bottom) – give some indication of how complex structures might have evolved from less complex constituents.

(a)



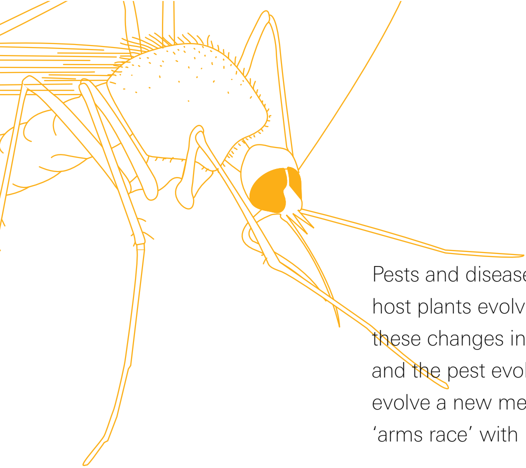
(b)

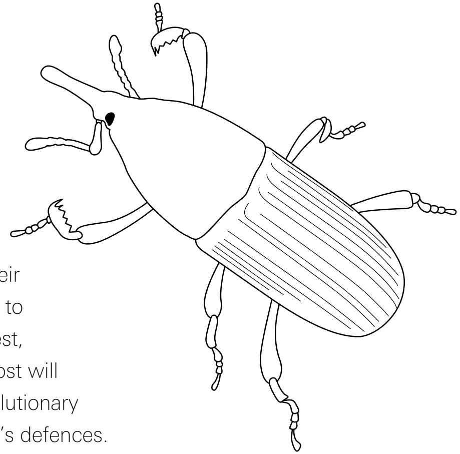
Fig 7 (a) Darwin described how artificial selection can generate many different varieties of pigeons from a common ancestor – he mentioned the carrier, fantail, pouter and tumbler (b) in the same way, humans have bred from the same original species of wild cabbage (shown in the centre) the cauliflower, brussels sprout, cabbage and broccoli.

In the first Chapter of *The Origin of Species*, Darwin emphasised the extent to which humans had artificially selected for desirable traits in domesticated animals such as pigeons. Such selection applied to plants is the basis by which the 6.5 billion humans on the planet can be fed. As an example of the extent of variation that can be achieved by these approaches we can take the wild cabbage (Brassica oleracea) which grows on some British cliffs and dunes; it is almost inedible, but today its descendents include cauliflower, broccoli, brussels sprouts, kale and kohl rabi. Each of these descendents is based on a few mutations. For instance, the cauliflower morphology of dense developmentally arrested flowerheads has arisen through a modification of two genes that control flower differentiation.

Of more global significance has been the selective genetic modification of cereal crops (wheat, rice, maize etc.) upon which most of the world's human population depends for its nutrition. Over roughly 10,000 years since the last Ice Age, humans have selected for several traits in these species. These include selectively breeding from plants that retain their seeds after flowering (rather than scattering them), which makes them easier to harvest, from strains with greater resistance to disease and from those that put less of their energy into inedible stems and more into edible seeds.

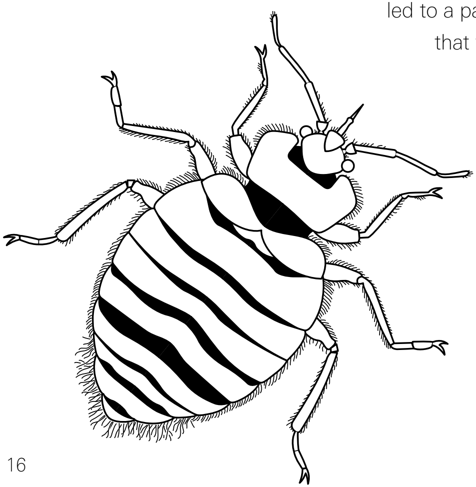
Faced with famine in parts of central America and India, breeders experimented with 'short stem' or 'dwarf' varieties of rice and wheat. The plants allocated more effort to seeds than stems, and increased yield by ten times. This 'Green Revolution' – experimental evolution – enabled India to become an exporter of food when it had previously been threatened by famine. If we are to sustain a population increase to nine billion by the year 2050, farmers will require further advances in breeding technology.





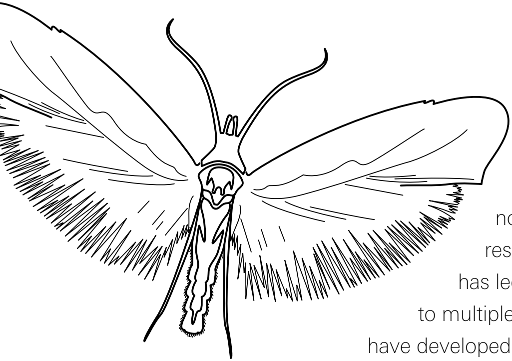
Pests and diseases can cause major problems in food production. As their host plants evolve, pests and diseases must themselves evolve to adapt to these changes in the plants they affect. The host evolves to resist the pest, and the pest evolves a way of circumventing the resistance. Then the host will evolve a new mechanism for resistance, and so on. This leads to an evolutionary 'arms race' with host and pest continually adapting to combat the other's defences.

Sometimes we ourselves join in; and sometimes we win – but the pests can fight back against us, too. The extent of the threat to food production caused by insect pests alone was estimated by the mid 1950s to be equivalent to $1 billion, and this inevitably led to attempts to develop measures that would control the insect populations. One such advance was the widespread use of the pesticide DDT, the extensive application of which during the 1940s and 1950s led to a particularly good example of how quickly selection pressures can drive evolution. By the 1970s, insects that were largely resistant to the chemical had emerged, rendering it ineffective against at least 200 species.



The emergence and re-emergence of infectious diseases in animals and in ourselves are also the result of Darwinian selection. Antibiotic resistance – the ability of certain bacteria to resist the effects of chemicals that were previously lethal to them – comes once again from natural selection, over just a few years. This is natural selection in action and its effects are seen very rapidly in microbial populations because the life cycle of bacteria is short (when conditions are right, many generations can be completed each day).

Even in the first clinical trials of penicillin (an antibiotic produced by a fungus) in the 1940s, Howard Florey noticed that of the 15 test patients first exposed to the compound, one showed



no clinical improvement because the infection was naturally resistant to the drug. Greater exposure to these compounds has led not only to resistance to particular drugs, but also resistance to multiple drugs. Some strains of the bacterium that causes tuberculosis have developed resistance to all the antibiotics that were previously deployed against them. Patients infected by these strains are kept in the strictest isolation for fear that release of their pathogens into the wider environment will lead to an uncontainable global pandemic of the disease. In the same way, the methicillin-resistant strain of *Staphylococcus aureus* (MRSA) is resistant to a large spectrum of antibiotics and so constitutes an increasing threat to healthcare environments, causing a range of clinical conditions from skin problems to life-threatening diseases such as pneumonia and meningitis. The basis of resistance lies in a suite of different biochemical responses in the bacterium, including the production of enzymes that degrade the antibiotic. The overuse of antibiotics has almost certainly increased the selection pressure on these types of bacteria and so contributed to their emergence as threats to clinical practice.

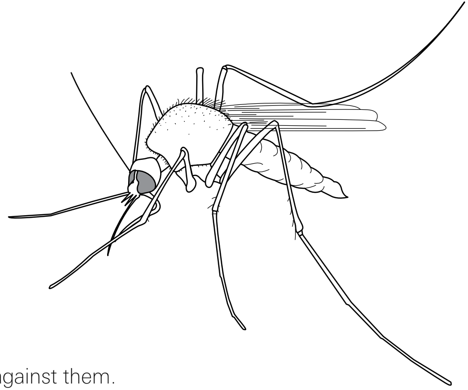
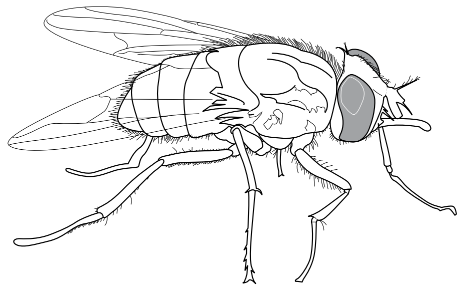


Fig. 8. When exposed to the pesticide DDT, over 200 species of insects evolved resistance to it, including the bed bug, diamond-backed moth, granary weevil, housefly and malaria mosquito.

Viruses, because they reproduce very rapidly, are ‘moving targets’ for those attempting to produce therapies. Not only does an individual particle of the HIV virus produce in excess of 10,000 new virus particles within 24 hours of infecting a human white blood cell, but in addition the mutation rate of this organism is such that each of the new particles can carry at least one mutation. Since it first came to attention in the 1980s, the HIV virus has produced many different strains with different properties. Because a small proportion of the mutations contributes towards resistance to anti-viral drugs, we can observe a loss of effectiveness in therapies within three weeks of the drug’s first administration. There could be no clearer proof of the power of the modification by descent so eloquently described by Darwin.



Teaching evolution in the classroom

Good education is at the core of personal development and of civilization. In today's technological society, it is more important than ever that scientific education in particular is of the highest quality. The school science curriculum should encourage children to assess how the material they are being taught has been challenged and tested by observation and experiment.

In this context, evolution should appear on the syllabus in terms of the scientific evidence for Darwinian natural selection described in this document. It should be set in the context of applying evolutionary principles to solve agricultural, medical, and other real-world problems such as those outlined on pages 14 to 17.

Other, non-scientific, explanations for the world's biodiversity should not be part of the science curriculum.

Critical inquiry is essential to science, and children should be encouraged to question methods of arriving at conclusions, as a way of learning more. However, if a student argues that there is a better explanation for the diversity of life on Earth – such as 'creationism' or 'intelligent design' – teachers should aim to explain why evolution by natural selection is the only known way of understanding all of the available evidence. They should be confident in teaching why natural selection is a scientific explanation – arguing from evidence, observation and experiment – and why other explanations do not stand up to these criteria.

The future

What of our future? Understanding the past is the key to moving on wisely. Some feel that evolution is a sterile and comfortless explanation for our existence, and so are inclined to reject it on moral grounds. The answer to such concerns is that despite the role of evolution in giving rise to the human species, we should not see our inheritance as the whole story. For all of us, our genes are our beginnings, but not our ends. Our natures, our very selves, are shaped also by our experiences and by our own thoughts. Like other animals we have instincts, but we need not be constrained by them, and we are free to construct the moral codes that we need for survival, happiness and social harmony. Acceptance of the fact of evolution does not require us to subscribe to a deterministic view of human society. On the contrary, these findings of what has shaped our present existence enable us to think clearly about our future – a future in which we will have ever increasing powers, to be used not lightly but responsibly, to make the world a better place. The Royal Society aims to expand the frontiers of knowledge by championing the development and use of science for the benefit of humanity and the good of the planet. The study of evolutionary principles and their application is a crucial part of that mission.

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