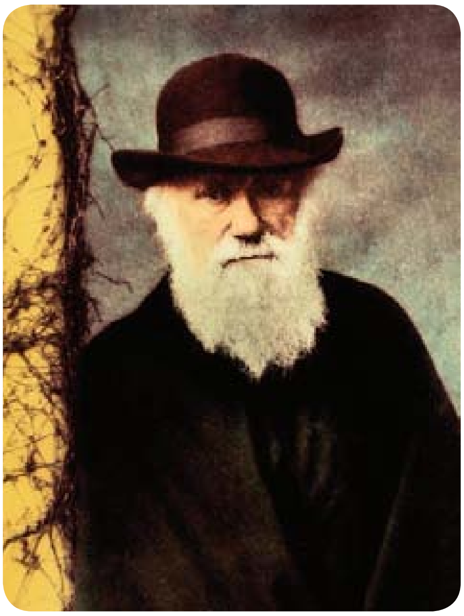
Charles Darwin – still changing the way we think about our world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Charles Darwin

One hundred and fifty years ago Charles Darwin published the theory of evolution by natural selection in 'On the Origin of Species'. From its first publication the theory stirred controversy, perhaps not surprisingly for a theory that not only revolutionised biology, but had far-reaching implications for many aspects of our lives.

Today, Darwin's theory influences many areas, from language and engineering to medicine and economics. Darwinian thinking has opened up new lines of research and exciting approaches to making new products.

The evidence for evolution by natural selection is overwhelming, but debate about the theory continues, especially about its wider application (for example in studies of societies and cultures) and what it means for our understanding of ourselves.

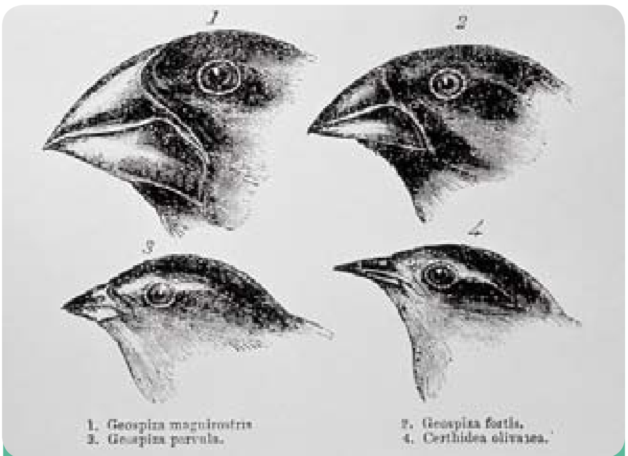
Understanding how evolution works

Darwin described how evolution – the change, over generations, in the characteristics of individuals in a population – is driven by 'natural selection'.

The idea of evolution – or changes to organisms – was not new in Darwin's day. It was Darwin's theory of natural selection, explaining how it happened, that was revolutionary. This new idea has found applications far beyond Darwin's original description of its role in biological evolution.

Darwin knew, from his extensive studies of animals and plants, that there were differences between the individuals in a population. He recognised that these variations meant some individuals would be less likely to survive in a particular environment than others. These less well adapted individuals would be less likely to reproduce and less likely to pass on their characteristics to future generations.

Darwin's insight was that if variations that affected survival (and hence reproductive success) were inherited, then over time the environment would eliminate (select out) the individuals who were least successful in reproducing. This 'natural selection' or differential survival would ensure the 'survival of the fittest'; those best adapted to their environment. A changing environment would select for individuals with characteristics that increased their chance of survival in the new conditions.



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A classic illustration of evolutionary theory, made by Charles Darwin in his book "A Naturalist's Voyage", London 1889. The drawing shows the beaks of four species of finches found in the Galapagos Islands. Darwin drew the conclusion that they all probably came from a common ancestor, but had diversified and evolved to adapt to local food supplies on the different islands.

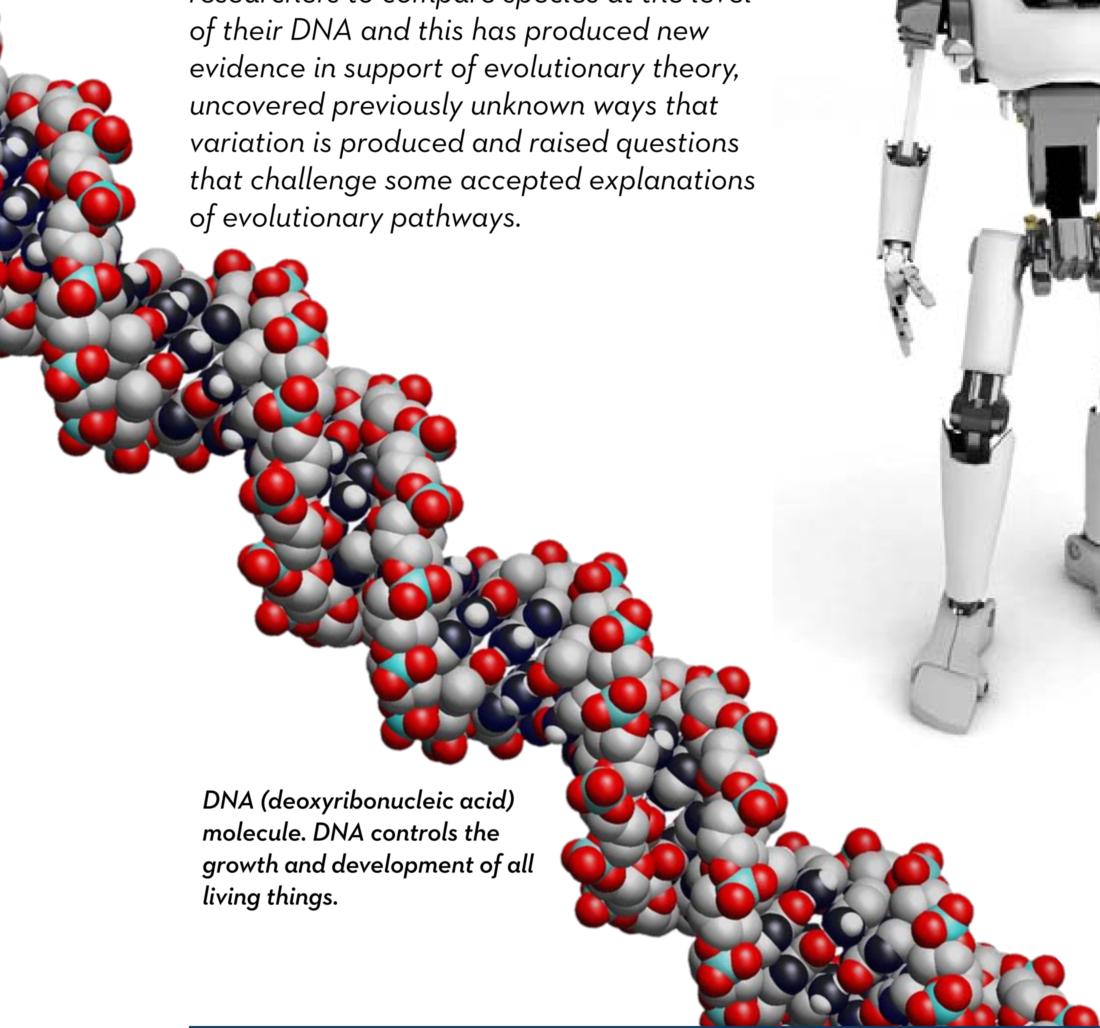
He realised that, given enough time, this process could result in large changes and that populations could eventually evolve into new species.

An explanation of how variations are inherited followed shortly (in 1850), when Gregor Mendel published his studies on inheritance of parental characteristics by their offspring. However, it was nearly a 100 years before DNA and genes were identified as the basis of inheritance, the physical carriers of the information that was passed from one generation to the next, and that DNA mutations, and other genetic changes, caused the variation between individual organisms on which evolution depends.

Recent advances in biotechnology enable researchers to compare species at the level of their DNA and this has produced new evidence in support of evolutionary theory, uncovered previously unknown ways that variation is produced and raised questions that challenge some accepted explanations of evolutionary pathways.

Evolution by natural selection is not restricted to living organisms. (Darwin may have realised this; he refers to parallels between the evidence for the development of languages and evolution by natural selection). Any population of 'things' that vary in ways that affects their ability to survive can be subject to selection by their 'environment', resulting in better adaption to that environment. Researchers are using this general application of evolution by natural selection in a wide range of social studies and to develop new computer software, robots and molecules.

Read more at http://www.darwin.rcuk.ac.uk



DNA (deoxyribonucleic acid) molecule. DNA controls the growth and development of all living things.

***Darwin Today** is raising awareness of the importance of Darwin's theory of evolution by natural selection, in current research and innovation across many disciplines. **Darwin Today** is targeting general audiences around the UK. It is led by the Biotechnology and Biological Sciences Research Council on behalf of the UK Research Councils.*

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Darwin, biodiversity and a changing world

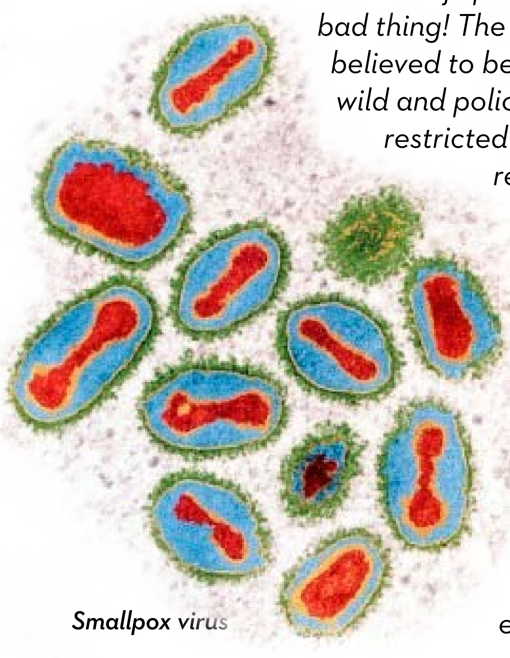
Darwin's theory of evolution by natural selection describes how species emerge, change and become extinct in response to changes in the environment. At several points in Earth's history, rapid environmental change has caused mass extinctions when up to 95% of Earth's species were wiped out. But, these "disasters" have been followed by a blossoming of biodiversity, as a rich variety of new species evolved.

If natural selection is changing species and ecosystems, in response to environmental change, then what should be our attitude to the management and conservation of biodiversity and how important, in the long term, is the extinction of species? Some estimates suggest half of the species alive today will be extinct by 2100; what should we do?

Biodiversity – who needs it?

Human activities such as habitat destruction, pollution and over-harvesting are threatening many species with extinction. Even feeding the birds can put species in danger of extinction. On the Galapagos Islands, two diverging populations of Darwin's finches are collapsing back into one because of the local practice of feeding finches with rice. The abundant supply of one food type has removed the selection for different beak types adapted to different food sources. What should we do about it?

Extinction of species may not be a bad thing! The smallpox virus is believed to be extinct in the wild and polio virus is now restricted to a few small regions. The serious cattle disease, Rinderpest, was almost certainly wiped out in 2000; making it the first virus of non-human animals to be eradicated.



Smallpox virus

It has been suggested that the planned extinction of 30 species of mosquito, which spread diseases that kill one million people annually, would be morally and economically justified.

But what of the majority of species that contribute to the planet's biodiversity? We have poor estimates of how many species are going extinct and little idea of how quickly new species are appearing; almost certainly the overall diversity of the Earth's ecosystems is being reduced. We know that less diverse ecosystems are less productive and less stable, so loss of biodiversity may weaken ecosystems and make them more fragile.

Biodiversity loss certainly reduces the natural resources available to us. Fourteen animal species account for 90% of the livestock we raise and around 30 crop species supply 90% of the calories in our diet. This is a tiny slice of the 1.5 million known plant and animal species. In a constantly, changing world, dependence on so few plants and animals makes us very vulnerable to crop and livestock diseases and the effects of climate change. Natural selection allows species to adapt to changing environments, whether in the wild or on farms, and understanding how pests and pathogens evolve in different environments is increasingly important in the fight to protect our livestock and crops.

While sudden changes can be catastrophic, as seen with mass extinctions, we know they can also be extremely effective in selecting for individuals that can survive under new conditions. Natural systems can respond very quickly to changes in their environment. A recent example is the effect of a deadly bacterial disease on populations of Blue Moon butterflies on South Pacific islands. The arrival of the disease was a sudden and harsh selection pressure that killed off nearly all male Blue Moon butterflies. A few males carried a particular gene mutation that enabled them to fight off the bacterial infection; as only these males lived to reproduce, the resistance gene spread rapidly through the butterfly population; the population evolved in response to the new selection pressure.

Climate change is changing evolution

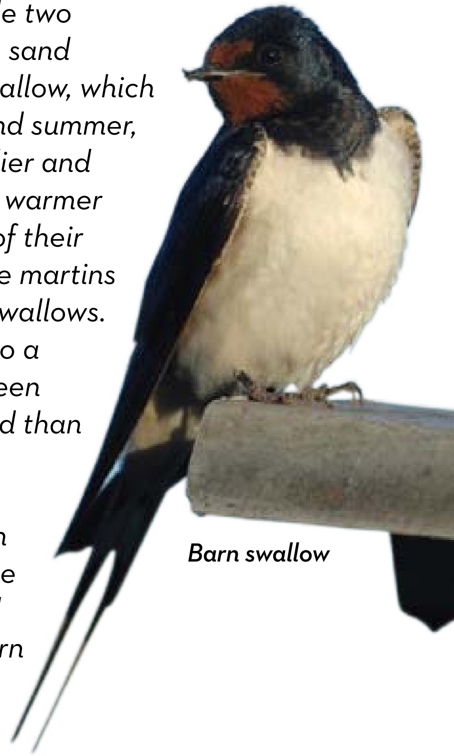
The reality of climate change is no longer seriously questioned. What is debated is how quickly changes will occur, how extreme they might be and what their impact will be on wild and farmed ecosystems and human activity. We can expect that species that cannot adapt will go extinct, while new species may evolve to fill niches in changed ecosystems. There will be winners and losers.

Soay sheep

Recent studies, on Soay sheep and migratory birds, have demonstrated how sensitive some species can be to small changes and that species respond to change in different ways.

In years with long, cold winters the Soay sheep population of the Outer Hebrides grows fastest when the flocks include many large individuals. A greater proportion of big sheep in the population increases the population growth rate. Big sheep are better adapted for harsh winters and their survival rates are higher, so hard winters select for larger sheep and this increases the population growth rate. If climate change results in milder winters, the selective advantage of large animals will decrease and this could have a significant effect on the number of sheep that are born.

In the last decade two migratory birds, the sand martin and the barn swallow, which visit the UK in spring and summer, have been arriving earlier and earlier in response to a warmer climate. But the order of their arrival has reversed; the martins now arrive before the swallows. The martins' response to a warming climate has been stronger and more rapid than that of the swallows.



Barn swallow

Bluetongue virus, which causes a serious disease in livestock, has spread from Africa into southern Europe because milder weather has allowed the African midge that spreads the virus to survive the winters of southern Europe.

As we learn more about natural selection, genetic variation and the importance of biodiversity, Darwin's theory is informing the steps we are taking to prepare for, and respond to, the effects of climate change.

Read more at http://www.darwin.rcuk.ac.uk

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Darwin's theory – no stranger to controversy?

Today, 150 years after its publication, an overwhelming body of evidence has been collected in support of Darwin's theory, but it is attracting as much, or more, controversy than ever. Discussions continue over the details of the theory and how evidence from the fossil record and (more recently) genome comparisons should be interpreted. There is debate over the extent to which the theory can be usefully applied to social and cultural subjects and the deep implications of a Darwinian view of individual and social behaviours. Finally, a fierce argument is raging between militant atheists and proponents of Creationism and Intelligent Design, over the authority of evolution versus creation accounts in sacred texts. The protagonists are adamant that their worldviews are mutually exclusive, while many people recognise that the arguments may be more subtle. What do you think?

Evolving language

Darwin's thinking on evolution may have been influenced by studies on language evolution, which pre-date his theory by at least 70 years. Darwin noted that, although languages have changed and divided at different rates, we are able to organise them in a genealogy and it should, therefore, be possible to do the same for species.

The way words are used and the meaning they are given is constantly changing. Typically, new words, variations on existing words and new meanings are created in small social groups, from which they may spread into more-or-less general use. Words and meanings also regularly fall into disuse. Increasingly, languages are intermixed, with words being shared directly, rather than translated. So words vary, reproduce and are inherited, some may not survive.

Researchers have seen startling parallels between the laws that govern evolution of language and those that govern the evolution of species. For example, the meanings of frequently used words (more critical elements in language) change more slowly than the meanings of words that are used infrequently (less critical elements).

Evolving language

*There is still debate over what is meant by 'a species'. We expect different species to look different, but contrast the following examples of species. Two 'species' of butterfly (*Heliconius himera and H. erato*) can mate and produce fertile hybrids, but the adults look completely different from one another. What was, until very recently, thought to be one species of earthworm actually includes four species. The comparison of genomes from different species is, in some cases, re-writing genealogies where the relationships were originally based on (mis-leading) similarities between physical characteristics.*

How can you tell when a new species emerges from an old one? The scientist's answer is that when two individuals can no longer mate and produce fertile offspring, then they are different species. Reproductive isolation of populations is essential for new species to develop. This isolation can be based on geography, behaviour, or a physical or genetic change, but it must minimise genetic mixing so that natural selection can operate on separate populations. The Galapagos Islands are home to related, but reproductively isolated, populations living in slightly different environments – hence their importance in the development of Darwin's theory.

Heliconius erato

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Microraptor dinosaur

Gone extinct or moved on?

One of the main bodies of evidence that supports Darwin's theory is the fossil record. However, the fossil record itself has sometimes generated controversy, both over the interpretation of individual fossil remains and the relationships between fossils. One particular area of debate has been the evolution of the birds.

Epidexipteryx *is a recently discovered very bird-like, pigeon-sized dinosaur that may be a clue to why feathers first evolved. The feathers of this dinosaur were useless for flying, but its four long and elaborate tail feathers probably made a striking display. Fossils of feathery, but flightless, dinosaurs are quite common and it may be that feathers first evolved as an insulating layer or for ornamentation. Variations in these early feathers, acted on by natural selection, eventually led to groups of dinosaurs with feathers suited to gliding and flight. The squirrel-sized* Microraptor *may represent an important step in this story as scientists believe that it used long feathers on its arms and its legs to glide from tree to tree. So not all the dinosaurs went extinct – as some were the ancestors of birds and their descendants are still with us today.*

The development of DNA technology allows us to make detailed comparisons between the genomes of different species and this has added to the supporting evidence for evolution. The structure of the genome is an internal record of a species' evolutionary history, its 'fossil' record written in its DNA.

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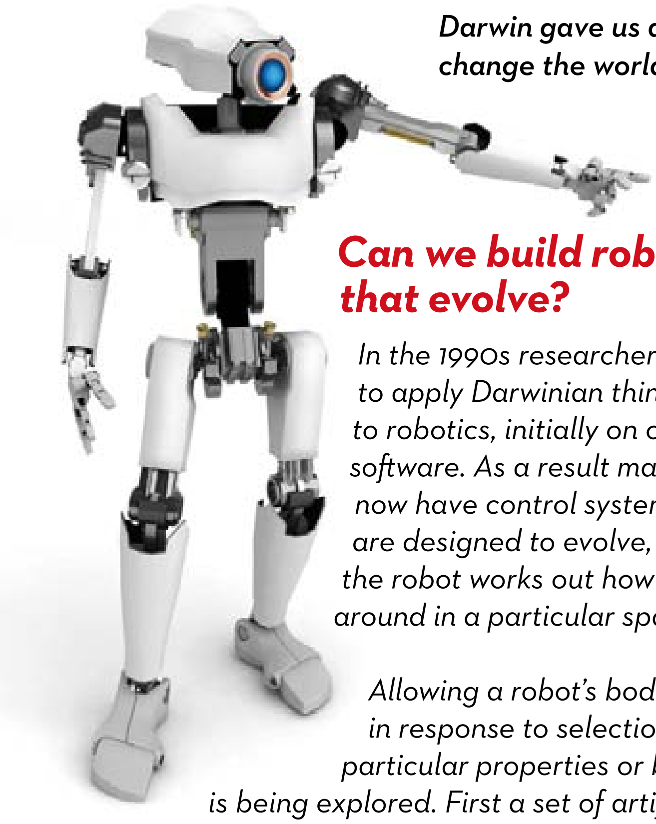
Darwin Today showcases a range of research intended to illustrate a diversity of views. Individual pieces of text have been checked by researchers for accuracy.

Putting evolution to work

Darwin gave us a powerful tool to understand and change the world we live in.



Can we build robots that evolve?

In the 1990s researchers began to apply Darwinian thinking to robotics, initially on control software. As a result many robots now have control systems that are designed to evolve, e.g. as the robot works out how to move around in a particular space.

Allowing a robot's body to evolve in response to selection for particular properties or behaviour, is being explored. First a set of artificial 'genes', describing control systems, body layout or behaviour are produced along with a way to create variants of these 'genes'. The 'genes' are then shuffled and the 'fitness' of different combinations is tested and the best are selected and maintained.

Bug wars!

Natural selection generally works against us in our fight against disease. Disease organisms reproduce (and so can evolve) much more quickly than humans; they can quickly evolve around any genetic resistance to infection that humans might develop. High reproductive rates and very large population sizes also give bacteria (and other disease organisms) an evolutionary advantage when humans use antibiotics and other therapies. Widespread treatment of bacterial infections with a particular antibiotic is a powerful selection for naturally-occurring variants of the bacteria, which carry genes that make them resistant to the antibiotic. Antibiotics may become ineffective as these resistance genes spread through the bacterial population.

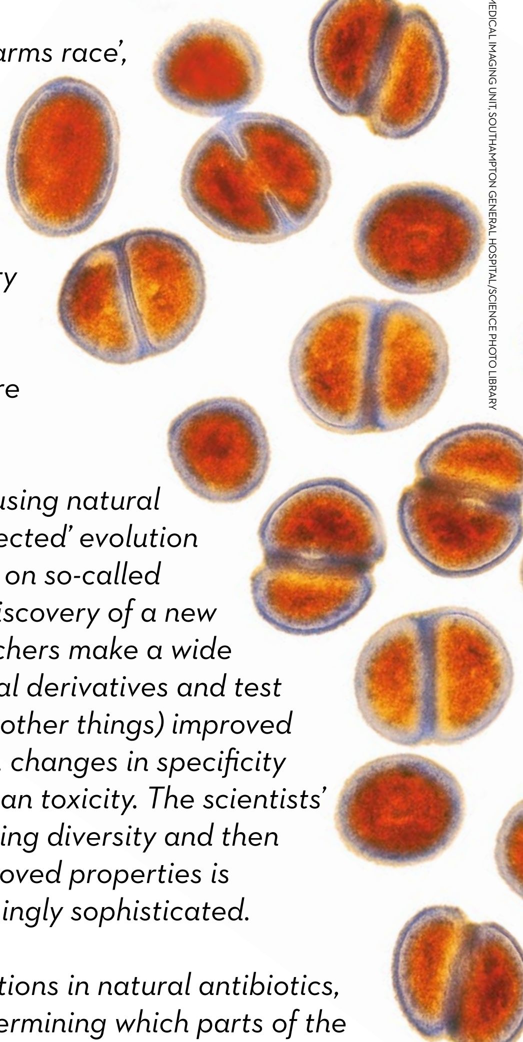
This leads to an 'arms race', with researchers constantly searching for new antibiotics to control bacteria that carry genes that make them resistant to antibiotics that are already in use.

Researchers are using natural selection and 'directed' evolution to turn the tables on so-called 'superbugs'. On discovery of a new antibiotic, researchers make a wide variety of chemical derivatives and test these for (among other things) improved antibiotic activity, changes in specificity and reduced human toxicity. The scientists' strategy for creating diversity and then selecting for improved properties is becoming increasingly sophisticated.

By studying variations in natural antibiotics, scientists are determining which parts of the antibiotics are essential for their antibacterial activity. Varying the other parts of the molecule allows them to design new antibiotics with better activity and fewer side effects.

Scientists are now trying to develop antibiotics that target genes essential to bacteria's ability to cause infection. For example, from genetic studies of many different strains of Staphylococcus aureus *(a bacterium closely related to MSRA) several genes have been identified that help the bug to infect humans. As these genes are essential for infectivity they may be good targets for disruption by new types of antibiotics. Any gene variants that might make the bacterium antibiotic resistant might also disrupt its ability to infect humans.*

Staphylococcus aureus



Directed evolution

As with antibiotic development, scientists working in agriculture, medicine and industry are also using directed evolution - creating many chemical variants of existing molecules and then selecting for variants that have new or improved properties. This can be repeated over and over again; selecting over several 'generations' for desired changes in properties. Scientists have used directed evolution to increase the efficiency of enzymes that are used as catalysts to make sialic acid. The variant enzymes produce new types of sialic acid molecules - including some used as antiviral drugs. Directed evolution of proteins that inhibit plant enzymes is being used to increase their ability to fight nematode infections, which cause devastating crop diseases.

Taming the wild

The earliest farmers collected seeds from the wild plants that they liked to eat and planted them in their fields. Each year they

sowed seed from plants that in the previous year had produced higher or more reliable yields, better tasting food or were easier to process. Unwittingly, they were selecting for plants that carried the individual genes and gene combinations that determined the characteristics they wanted in their crops. Crop cultivation brought plants close together, encouraging hybridisation, which created new gene combinations and, in extreme cases, new species (eg modern wheat). The qualities farmers value in crop plants are often the opposite of the characteristics that make a plant competitive in the wild; as farmers selected for (and against) particular qualities crop plants quickly became very different from their wild ancestors.

About 100 years ago, plant and animal breeding became much more efficient when breeders were able to combine the understanding from Darwin's theory of natural selection with Mendel's theories of genetic inheritance.

In the future will our understanding of genetics and inheritance allow us to make more use of the natural resources around us? Fourteen animal and 30 plant species account for most of the human diet. Compare this with the estimated 1.5 million known species (this ignores vast numbers of unidentified species and many microorganism). In a constantly changing world, dependence on so few plants and animals makes us very vulnerable to crop and livestock diseases and the effects of climate change.

One solution is to try to use this natural diversity. Recent advances in understanding chromosome pairing in cereal plants has important implications for wheat breeding as it may allow breeders to hybridise modern bread wheat with many of its wild relatives. This will give breeders access to a larger pool of desirable traits, such as salt tolerance, drought resistance and disease resistance, that would be otherwise unavailable.

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Questioning evolution?
Evolving answers!

The evolution revolution

One hundred and fifty years ago Charles Darwin published his theory of evolution by natural selection in 'On the Origin of Species'.

Darwin had observed that there were differences among the individuals in many of the animal and plant populations he had studied. He recognised that these variations meant some individuals would be less well adapted to a particular environment than others and, therefore, less likely to survive, less likely to reproduce and less likely to pass on their characteristics to future generations. If variations that affected reproductive success were inherited, then over time the environment would eliminate (select out) the individuals who were least successful in reproducing. A changing environment could select for (and against) individuals with particular characteristics - 'natural selection'. He realised that, given enough time, this could result in dramatic changes and that populations could evolve into distinct new species.

An explanation of how variations are inherited followed shortly (in 1865), when Gregor Mendel published his studies on inheritance of parental characteristics by their offspring.

In the middle years of the 20th century, DNA and genes were identified as the physical basis of inheritance, the carriers of the information from one generation to the next, and that DNA mutations, and other genetic changes, caused the variation on which evolution depended.

Gerbera daisy

Questioning evolution - Plant origins?

The earliest flowering plants appear in the fossil record about 180 million years ago and 144 million years ago the direct ancestors of modern flowering plants emerged. Their primitive, flower-based reproductive systems were the first steps towards the flowering species' 100 million year dominance of land plants. Today, 90% of the plant kingdom are flowering species, while algae, conifers, ferns, horsetails, mosses, liverworts, and their relatives, make up the remaining 10%.

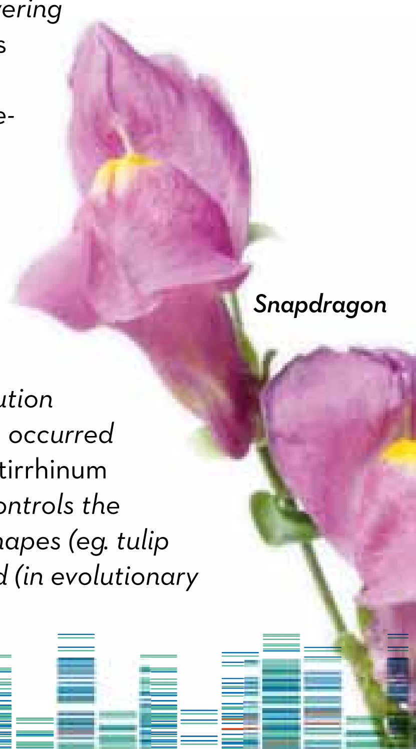
The humble origin of flowering plants is recorded in their DNA. For example, researchers have identified two genes in flowering plants that control the growth of root hairs on roots. These genes are also found in mosses, where they control growth of specialised cells that increase the surface area for water and nutrient absorption (caulonema) and provide anchorage (rhizoids). Flowering plants inherited these genes from the ancient ancestor they share with mosses, but have recruited them to perform a new, although related, role in their lifecycle.

Wood fern

Questioning evolution - Plant diversity?

Remarkably, the enormous diversity of flowering plants appears to result from natural selection acting on simple genetic control systems. Leaf, flower and inflorescence (flower spike) structures all seem to be explained by simple rules controlled by a few genes.

There are many leaf shapes, but there are only two leaf types - single-veined and net-veined leaves. Studies on two web-veined flowering plants (Thale cress, Arabidopsis thaliana and Snapdragon, Antirrhinum majus) and a single-veined club moss (Selaginella) suggest that an interaction between the same two genes controls leaf development in all three of these species. This shared genetic control system seems to contradict traditional thinking, which is that leaf evolution in club mosses and other plants occurred independently. Research on Antirrhinum has shown that a single gene controls the switch from symmetric flower shapes (eg. tulip and rose) to the more advanced (in evolutionary



Snapdragon

Rose

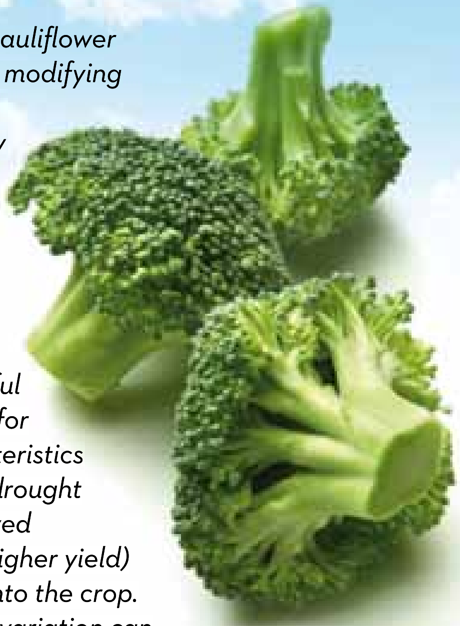
terms) asymmetric flower shapes associated with insect pollination (eg. orchids and legumes). The gene establishes a single axis of symmetry in the flower meristem. The flower parts are then able to develop and differentiate according to their position in relation to this axis.

Production of the three types of inflorescence structure found in plants is controlled by the same few genes that determine shoot tip branching and the switching of meristems (growing tips) from vegetative growth to flower production. Differences in the timing, and levels, of activity among these few genes generate the wide range of inflorescence shapes that exist.

Evolution tends to retain and recycle genes so, by looking at changes in DNA, scientists are able to create detailed maps of the relationships within and between species, families and more widely. This also provides insights into how new gene functions and new developmental pathways have evolved. Of particular interest are the conflicts and contradictions that arise between DNA-based analysis and existing ideas about how species are related.

Evolving answers - Putting evolution to work!

Agriculture began about 10,000 years ago when humans first began to create crops by cultivating and domesticating wild plants. Initially through crude selection, and more recently through directed plant breeding, this process dramatically altered the characteristics of the crop plants that we grow. Changes include; creating new species (cereals), reducing the levels of natural toxins (tomato fruits and rapeseed oil), eliminating the shedding of ripe seed (cereals), altering flowering times and inflorescence (flower spike) structure (cauliflower and broccoli) and modifying nutritional and processing quality (broccoli and cereals).



Broccoli

Crucial to any breeding programme is the ability to find useful genetic variation for important characteristics (e.g. disease and drought resistance, improved nutrient uptake, higher yield) and introduce it into the crop. Potentially useful variation can be found in related species and either selectively bred into the crop, introduced by genetic modification or generated by inducing mutations in the crop's genetic code.

Scientists have developed many DNA-based technologies to analyse and modify plant genomes that supplement these established methods.

'Comparative genomics' compares the relationships between plants at the level of their DNA. This technique allows us to create genetic maps from 'model species', which then help in understanding the genetics of other species in the same family.

Tomatoes

'Tilling' is a technique that enables scientists to make targeted changes in a plant's DNA, allowing specific changes to the DNA sequence to be 'designed' into the genome.

'Marker-assisted breeding' uses the tight association between specific genes and unique DNA sequences to 'track' the presence of a particular gene by looking for its DNA 'marker' sequence.

Genetic modification, controversially, gives researchers the ability to exchange genetic information among a wide range of organisms. More importantly, it allows genes to be modified at the level of the DNA code, providing a tool for plant improvement and, most significantly, for understanding plant biology.

Evolving answers – Evolution, for us or against us!

Darwin's theory of evolution (and Mendel's theory of inheritance) dramatically changed our approach to plant improvement. Directed selection for specific inherited characteristics, which would adapt a crop to its field environment or a particular use, was a powerful idea.

In the early 1900s, this thinking was behind efforts to breed dwarf wheat varieties that would be more resistant to being beaten down by wind and rain (lodging) because of their shorter straw. This directed breeding programme led to the discovery that some dwarf wheat varieties were high-yielding because they put fewer resources into straw growth and more into grain formation. These varieties were the basis of the Green Revolution.

Crops have also been selected to suit their end-use better. The bread-making quality of wheat has been improved by selective breeding for high levels of particular proteins in the flour and ongoing research is exploring how the milling quality of the grain could be improved by directed breeding. The recent development of a 'super-broccoli' used selective breeding to boost the levels of chemicals, produced naturally by the plant, that help protect us against some cancers.

Selective breeding, in its various forms, is a proven and powerful tool for adapting crops to specific environmental conditions, management regimes and end-uses. However, it can also create or exacerbate problems.

Wheat

In particular, the genetic uniformity that ensures yield and quality can leave crop varieties vulnerable to damage by unusual climatic conditions or new races of pests and pathogens (disease-causing fungi, viruses and bacteria).

Colorado beetle, devouring leaves of a potato plant.

Pests and pathogens have co-evolved with wild plants. As we have adapted wild plants as crops, their pests and pathogens have evolved with them and continued to exploit them as a food resource. Unless breeders are careful to predict pest and disease profiles and to breed-in appropriate resistance, their new crop varieties will quickly succumb to disease. Once varieties are widely grown, natural selection ensures that pests and pathogens will, in time, evolve to defeat the crop's resistance.

Breeding resistance to pests and diseases into crop varieties is a priority for plant breeders and researchers are studying many natural and novel ways to improve disease resistance. They are especially interested in finding 'durable' types of resistance that are not easily overcome by the continuous evolution of the pathogens. Meanwhile, understanding evolution by natural selection helps when modelling how new strains of disease may arise and spread in response to new resistant varieties and in designing disease management strategies.

Read more at http://www.darwin.rcuk.ac.uk

Questioning evolution? Evolving answers! *is an initiative for Darwin Year. It is raising awareness of the importance of Darwin's theory of evolution by natural selection in current research and innovation in the plant sciences. Questioning evolution? Evolving answers! is produced for general audiences around the UK. It is funded by the BBSRC (Biotechnology and Biological Sciences Research Council; www.bbsrc.ac.uk).*

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