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Marine bacteria and the plastisphere



Robyn Wright

It is estimated that over 8 million tonnes of plastics are being added to the oceans each year. PhD student Robyn Wright explores potential microbiological solutions to the problem

AQA: 3.5.4 Nutrient cycles

Edexcel A: 4.15 Replacement of oil-based plastics; 5 On the wild side

Edexcel B: 10.4 Human effects on ecosystems

OCR A: 4.2.1(i) Conservation agreements; 6.3.2 Populations and sustainability

OCR B: 4.3.2(b) Impact of the rise in human population on ecosystems

WJEC Eduqas: 2.1.6 Human impact on the environment

Key words

Microplastics
Biodegradation
Marine biology
Microbiology

Recently the Ellen MacArthur Foundation stated, 'By 2050 there will be, by weight, more plastics than fish in the oceans!' Plastic, from the Latin 'plasticus' or Greek 'plastikos', means 'able to be moulded' and is the term we use for the materials we derive from oil. Plastics are hydrocarbon **polymers**, predominantly

made up of carbon and hydrogen, sometimes with other functional groups including esters. Many plastics are derivatives of very long chains of alkanes (see Figure 1).

We have been making plastics since the end of the nineteenth century and production is now hundreds of millions of tonnes annually. Unfortunately, the properties that make plastics so widely used underlie the reasons they are so hard to break down. This difficulty in breaking down plastics is heard in the phrase 'it will take hundreds of years for plastics to break down in the ocean'. In reality, hundreds of years have not passed since the mass production of plastics began in the 1950s, so we do not know how long they will remain in the oceans. Current research suggests that plastics

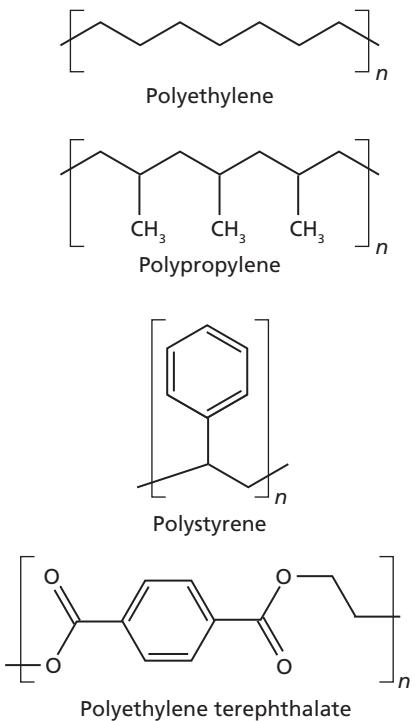


Figure 1 Chemical structures of some plastic polymers made predominantly from long chains of alkanes

simply fragment into smaller and smaller pieces but never truly disappear. The Marine Debris Working Group in the USA estimates that over 8 billion tonnes of plastics have been produced since the 1950s — and almost half of this in the last 13 years. About 80% of the waste ends up in landfill or the environment.

Where are the plastics in the oceans?

Wherever we have looked in our oceans, we have found plastics. From coastal areas to the deep sea. From the Arctic to other unpopulated areas, such as the Chagos Archipelago in the Indian Ocean. Some plastics, such as polyethylene (PE), polypropylene (PP) and expanded polystyrene (PS), are less dense than seawater, so they float and are carried by ocean currents. These have a tendency to accumulate in **gyres** in the middle of the oceans, often termed ‘garbage patches’. Other plastics, including polyethylene terephthalate (PET) and polyvinyl chloride (PVC), are denser than seawater and so sink.

Floating plastics might also sink from the surface of the sea following colonisation by bacteria and the larvae of larger organisms. Scientists from the Woods Hole Oceanographic Institution in Massachusetts termed these colonising organisms the **‘plastisphere’**, a **microbiome** for plastics. These bacterial communities are distinct from the surrounding seawater and from those that colonise natural surfaces in the ocean.

Unfortunately, plastics are also removed from the surface seawater by animals that ingest them, and are found in the faeces of animals including zooplankton, fish, seals and whales, which also sink.

How do plastics get into the oceans?

Plastics end up in the ocean by a number of different routes, such as fibres that are released each time we wash our clothes, or through **microbeads** in cosmetics such as face washes. Microbeads have now been widely banned in the UK, but there are loopholes allowing them in ‘leave on’ products, including makeup and sun cream. Other routes for plastic pollution include lost fishing gear such as nets and traps, or items lost from ships. The largest quantity of plastic pollution comes from the mismanagement of waste originating from land. Much rubbish enters the oceans from developing coastal countries that lack adequate sewage treatment or waste collections.

Why does it matter that plastics are in the oceans?

The effects of plastics on marine organisms can be both direct and indirect. The direct effects are usually through entanglement or ingestion. For example, fish will often seek out plastics to eat because when they have been colonised by the plastisphere they smell like food. When plastics are either manufactured to be **microplastics** or break down into small pieces from

Box 1 | A youth-driven challenge

‘Bye Bye Plastic Bags’ was founded in 2013 by Melati and Isabel Wijsen. Melati was 12 and Isabel just 10 years old. They had grown up on the Indonesian island of Bali, and seeing the pollution there inspired the sisters to act. Together, they collected over 77 000 signatures supporting a ban on plastic bags in Bali, which local government has enforced since January 2018. This was not the end of their journey, and they continue to campaign for ‘a world free of plastic bags and where the young generation are empowered to take action’. Speaking in March 2018 at the International Marine Debris Conference in San Diego, Melati stated, ‘youth are 25% of the population, but 100% of the future’. They continue to win awards and attend international conferences to publicise this youth-driven challenge.





Terms explained



Gyres A large system of circular ocean currents formed by global wind patterns and forces created by the Earth's rotation. The largest ones are found in the middle of oceans.

Microbeads Microplastics found in cosmetics and toiletries.

Microbiome All of the microorganisms in a particular environment.

Microplastics Plastics below 5 mm in size.

Plastisphere The microorganisms colonising the outside of plastic marine debris. It is usually distinct from the surrounding seawater and includes bacteria that could degrade plastics as well as potential pathogens.

Polymers Materials with a molecular structure primarily made of a large number of the same units (monomers) bonded together.

Sequencing DNA sequencing is the process of determining the order of nucleotides in a DNA molecule. This is used for whole communities of microorganisms in order to identify what is there, even when we cannot see it.

larger plastics, they become accessible to more organisms. Indeed, plastics bioaccumulate and thus have a greater effect on animals at the top of food chains. Often, ingested plastics pass through digestive systems, but many microplastics in the oceans are fibres and can clump together, becoming obstructive.

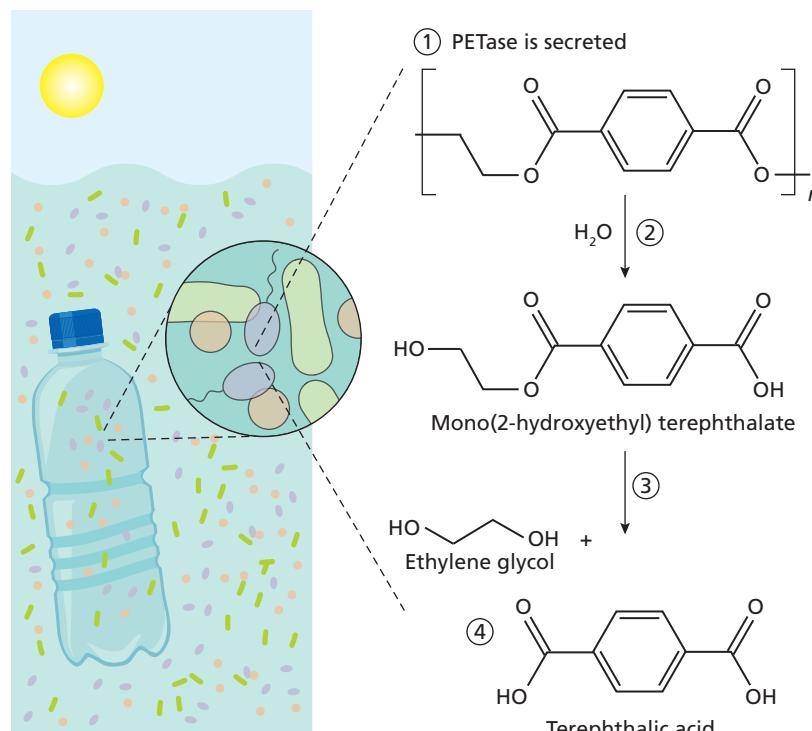


Figure 2 Degradation of PET by microbes. 1, Extracellular enzymes secreted, 2, enzymes attach to the surface and cleave the PET polymer, 3, intermediates assimilated into cells, 4, short degradation intermediates dissolved into the water

Plastics are manufactured with chemical additives — many are toxic, and other poisonous hydrophobic chemicals have been found on plastics at concentrations a million times higher than the surrounding sea water. This can lead to indirect effects via transfer to animals either when they are eaten or through contact. Because plastics are able to travel large distances in the oceans, the biological accessibility of the associated toxin is increased. Such chemical effects can potentially include reproductive failure, hormonal defects, growth of tumours and even death.

What are we doing to clean up the oceans?

Many scientists are researching the main sources of plastics in the oceans, where they end up, and what the effects of these plastics are. This will help to advise policy makers on strategies for cutting down the plastic waste that reaches the ocean, which areas need to be targeted for clean-up, and how we can improve our efficiency in removing plastics before they reach the oceans.

Importantly, some bacteria and fungi in landfills and soils have been shown to be capable of degrading plastics. Could these organisms also be present in the ocean? The terrestrial microorganisms tend to be relatively slow at degrading plastics, generally taking months for a noticeable difference in plastic mass to be observed. Additionally, the process only takes place at relatively high temperatures (optimum temperature of these microbial enzymes

is typically above 60°C). So, can we do anything to speed up these processes?

How do bacteria break down plastics?

A group of Japanese scientists discovered a bacterium (*Ideonella sakaiensis*) that can break down PET, the polymer from which most plastic bottles are made, and characterised the enzymes that the bacterium used (see Figure 2). The bacteria were found to attach to the plastic and then release an enzyme called PETase, which breaks the PET into monomers (mono(2-hydroxyethyl) terephthalate, ethylene glycol and terephthalic acid). These monomers are taken up through bacterial membranes. The bacteria are able to break down these monomers and use them as an energy source, producing carbon dioxide and water. In April 2018, a team of scientists at the University of Portsmouth, UK, managed to engineer this enzyme to increase its efficiency. While this is significant, it will realistically still take many months for there to be a noticeable change in plastics degraded by this enzyme.

The ocean is too cold...

The enzymes so far found to break down plastics in a terrestrial environment have relatively high optimum temperatures. At the surface of the ocean, the average global temperature is approximately 16°C, but the average depth of the ocean is 3500 metres. Sunlight only reaches down to approximately 200 metres and the majority of the oceans are therefore cold, about 0–3°C. It is difficult to find enzymes that are active at these temperatures. Further, plastics are challenging to degrade. Their breakdown requires several steps using several different enzymes. It has therefore

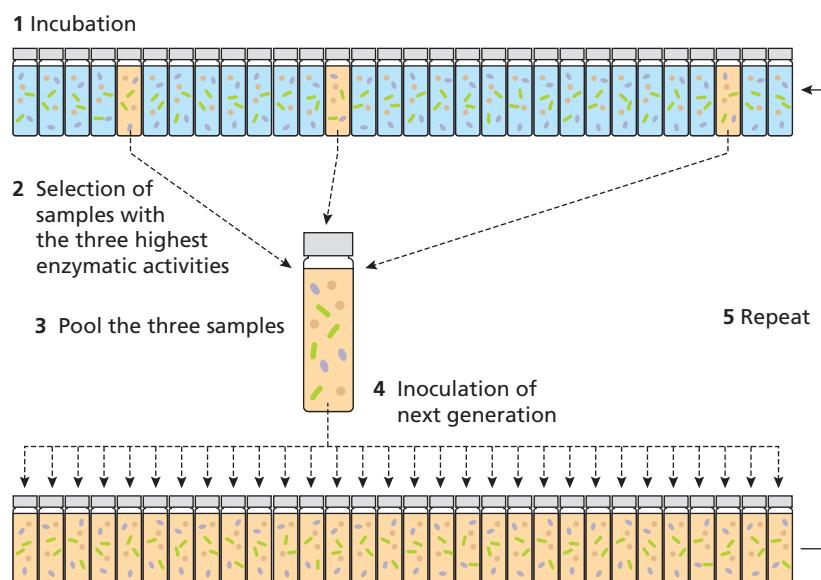


Figure 3 Workflow for the artificial selection of communities of microorganisms for polymer degradation

been suggested that a community of microorganisms may be more able to degrade plastics than an individual species or a single enzyme.

My research group at The University of Warwick, UK, is currently trying to select plastic degrading communities of microorganisms. In the laboratory we are testing microorganisms that colonise plastics from coastal waters around the UK. First, using an ‘enrichment experiment’: communities are left with the plastics as the only carbon source to see if any survive. Second, we take many replicate communities and test the activity of enzymes that could be involved with plastic degradation (see Figure 3). Subsequently, communities with the highest activities are mixed. This is carried out over 20 times to select communities that can become better at degrading plastics over time. This technique is reminiscent of selective breeding of animals and plants but is far more complex.

Currently the technique has been used to find microbial communities able to degrade chitin, the natural polymer present in the shells of crustaceans. We have demonstrated that, within 1 month of growth, a community could be selected to have increased chitinase activity up to 90 fold. Analysis of this community by DNA sequencing shows that thousands of different species are present. These include bacteria able to degrade chitin, bacteria able to use the products of chitin degradation, and eukaryotes, including protists, that feed on the bacteria. Now we know the technique works, investigations using PET are in progress. Microbial communities may help us in the future to finally degrade the plastics with which we pollute our oceans.

Robyn Wright is currently a PhD student at The University of Warwick, developing the community selection methodology to identify plastic-eating microbes that can survive in our oceans. She is an active blogger on marine biology: robynw371.wixsite.com/mainlymarine

Further reading



Keep up to date and learn more about the group that Robyn is working with at The University of Warwick: www.christieoleza-lab.com

Read about the Ellen MacArthur Foundation proposals for sustainable ‘circular economies’: <https://tinyurl.com/y7sbsvxz>

‘Our campaign to ban plastic bags in Bali’, TED talk by Melati and Isabel Wijsen: <https://tinyurl.com/jgfgkhe>

‘Bye Bye Plastic Bags’, a movement powered by youth around the world to say ‘no’ to plastic bags: www.byebyeplasticbags.org

New plastic-munching bacteria could fuel a recycling revolution’, a news article about *Ideonella sakaiensis*: <https://tinyurl.com/zjqp2yz>

‘Recycling hope for plastic-hungry enzyme’, a news article about engineered PETase: <https://tinyurl.com/ydgettak>

Key points



- Plastics are key polluters of the marine environment.
- Plastics, and the molecules associated with them, are toxic to a wide range of organisms, both physically and chemically.
- Biodegradation of plastics by single species of microbes is at best slow.
- Microbial communities are likely to be more efficient at plastic removal than an individual species or a single enzyme.

Tackling cancer

Getting personal



Histological examination of biopsied cancerous cells can lead to better, more targeted, treatments

Bioethicist Chris Willmott explains that understanding the diversity of cancer is crucial to the application of personalised treatments, tailored to challenging the characteristics of the specific cancer

Current estimates suggest that half of the UK population will be diagnosed with cancer at some point in their lives. Cancers can vary considerably in both the underlying cause (the aetiology) and the likelihood of recovery (the prognosis).

DNA damage

All cancers involve a loss of control of cell division and an accumulation of genetic errors. Although some inherited mutations make it more likely to develop cancer, these are relatively uncommon. Instead, it is DNA damage in the tissues of the body over the course of our lives that has the most important role in cancer development.

Mutations in two classes of gene are especially significant. The first are oncogenes. These genes encode proteins normally involved in promoting cell division. In cancers, one or more genetic change leaves oncogenes permanently switched on. The second class of genes are tumour suppressors. The proteins encoded by these genes normally act

Key words

Cancer
Genomics
Next generation sequencing
Oncogene
Personalised medicine

as gatekeepers. Mutations that stop tumour suppressors working allow for unrestrained cell division.

Mutations

Genetic changes can result from exposure to environmental factors, including ultraviolet radiation and **carcinogenic** substances — for example, those found in cigarette smoke. They can also arise from mistakes made during DNA replication. Some of those changes play a major role in cancer development while others have little or no effect. As we try to understand more about cancers, we need to be able to distinguish between the significant mutations that cause the cancer, known as driver mutations, and those that are less important, referred to as passenger mutations.

Changes to the DNA associated with development of cancer can take a variety of forms. There may be alteration of the sequence of a gene, and the corresponding amino acid sequence of the protein it encodes, as a result of base substitutions (a single nucleotide polymorphism), or by

insertion or deletion of larger sections of DNA ('indels'). Alternatively, there may be more radical structural changes, with whole chunks of DNA swapped between different chromosomes (translocations).

Other cancers are associated not so much with a change in the DNA sequence of the gene itself but a change in the amount of protein being produced. This in turn may be due to having more copies of the gene within the chromosomes (copy number alterations) or higher levels of expression of the existing genes.

The power of sequencing

Our understanding of cancers has been progressed by the development of new technologies that allow us to rapidly acquire the DNA sequence of entire genomes. Although the original human genome project, first drafted in 2001, was an amazing achievement, it took over 10 years to complete and cost more than \$2 billion. To make **genomics** useful for personalising cancer diagnosis and treatment, a radically different, and very much cheaper, approach was needed.

Creative minds have come up with several new methods to sequence DNA more quickly, and for a tiny fraction of the cost. By 2010, it was possible to sequence DNA 50 000 times faster than it had been a decade earlier, and the latest methods are faster still. These techniques, sometimes collectively referred to as 'next generation sequencing' (NGS) share the fact that they achieve 'massively parallel sequencing', allowing millions of sequencing reactions to be carried out simultaneously.

Comparison is the key

Crucially for cancer genomics the faster and cheaper methods allow us to make three different sorts of comparison.

- Comparing the DNA sequence in tumour cells with that of normal cells from the same patient reveals specific changes that have happened as the cancer developed.
- Comparing variations within a tumour as it develops. These can be changes over time, e.g. as the cancer becomes a more **malignant** form, or differences — heterogeneity — between cells within a particular tumour. This is why taking only one **biopsy** sample may provide an inaccurate or incomplete picture of the genetic alterations that have been taking place.
- Comparing mutations in the 'same' cancer in different patients lets you see whether the underlying causes really are identical. If you looked at the DNA in only one cancerous cell, you would not be able to tell which changes were crucial driver mutations and which were passengers. But if you look at the DNA in hundreds of cells with the same cancerous morphology, you can start to see which changes are shared across a wide variety of the cancers tested.

There will be distinct patterns of mutations — many will have the same genetic alterations, but others share a different set of characteristic changes. It is this third type of comparison that offers the greatest potential for cancer treatments to become more tailored to the individual patient.

When the 'same' cancers are actually different

Until the advent of genomics, people generally described cancers based on the tissue within which the disease was found, for example bowel cancer or brain cancer. Doctors might also talk about the type of cell that had become mutated (e.g. **carcinomas** originate in epithelial cells, sarcomas develop in connective tissues, and leukaemias affect leukocytes). Discussing the tissue and the type of cell involved remains useful, but genomics allows a closer look at the underlying cause of the cancer in a particular patient.

It has long been known that some patients respond well to a specific drug, while others do not. A major part of this different response stems from the fact that cancers that appear similar may actually have quite different genetic changes.

Breast cancer, for example, can be diagnosed histologically, by examining biopsied cells under a microscope. Traditional treatment options were then a combination of surgery, chemotherapy and/or radiotherapy. But now, we can offer more refined treatments.

Even before genomics had become established, it was known from genetic studies that breast carcinoma was associated with **upregulation** of two proteins — oestrogen receptor and human epidermal growth factor receptor 2 (HER2). Patients with high blood concentrations of the latter, roughly a quarter of all breast cancers, are said to be HER2-positive and this was associated with poor survival rates.

Trastuzumab, better known as Herceptin, is a **monoclonal antibody** that targets the HER2 protein. This drug significantly improves outcomes but only for patients overproducing HER2. 'HER2-negative' women do not benefit from Herceptin. This was among the earliest examples of tailored treatment based on genetic information.

NGS allows deeper analysis of the molecular causes of cancers and more specific classification of disease types. There are at least ten subtypes of breast cancer, with associated differences in prognosis and responsiveness to particular therapies. Armed with this information, doctors can pick the most appropriate treatment for the individual.

Terms explained



Biopsy A sample taken from a patient to look for the presence, cause or extent of a disease.

Carcinogenic A substance or agent that has the potential to cause cancer.

Carcinoma A cancer originating from epithelial cells in the skin or the lining of an internal organ.

Genomics Broadly, the study of the structure and function of the genome, but particularly used to mean sequencing of multiple genes in an organism simultaneously.

Malignant A tumour that is capable of spreading to other tissues in the body.

Metastasis The spread of a cancer from the original site (the primary tumour) to a different region of the body (a secondary tumour), possibly a long way apart.

Monoclonal antibody Purpose-made antibody that recognises a specific target molecule (e.g. a protein found on the surface of a cancerous cell).

Oncology The study and treatment of cancers.

Upregulation A protein (e.g. a cell surface receptor) is said to be upregulated if there is an increase in the number of copies of that protein (due to there being more copies of the gene for that protein, and/or the gene being transcribed more frequently than usual).

Cancer is all about loss of control of cell division. If we compare cell development to driving a car, a mutation in an oncogene is like the accelerator of the car getting stuck in the 'on' position. A mutation in a tumour suppressor is like the brakes failing to work



Ethics

The ability to identify differences in cancers that would previously have been grouped together (and treated the same) is one of the most important outcomes of cancer genomics, and is the cornerstone of personalised **oncology**. This means both that the right treatment goes to the patients who will benefit from it, and that time is not wasted giving patients a drug that would not work for them.

Genomics is also leading to other fundamental changes in both the diagnosis and treatment of cancer. At its most radical, this could lead to a shift from reactive approaches (treating an existing cancer) to a proactive model, in which genetic knowledge facilitates prediction and prevention of cancers. An early example of this would be the choice of women, most famously the actor Angelina Jolie, to have an elective mastectomy based on the fact they have a mutated copy of a BRCA gene, known to give a high chance of breast cancer.

Particular excitement is focused on the emerging use of a simple blood test that can reveal whether someone is developing cancer. The test — a liquid biopsy — relies on the fact that tumours release fragments of DNA into the blood. With NGS approaches it is possible to pick out these

genetic signals. Most of these tests are not currently accurate enough to be rolled out into the clinic but, once validated, will offer several advantages over existing biopsies.

1 They are less invasive than taking tissue samples from a patient, meaning less pain and less risk of accidentally dislodging cancerous material, which might cause spread to other locations.

2 They can reveal signs of cancer development much earlier, meaning that the disease can be tackled in a more timely fashion, ideally before **metastasis**. The test can look for the presence of specific changes associated with certain stages of the disease, giving useful information about prognosis and the likely success of treatment.

3 Ongoing blood testing after treatment will be an easy way to monitor whether there has been any return of the cancer.

Working together

The key to the success of cancer genomics is comparison of normal versus tumour DNA for an individual patient, of tumour development over time, and of molecular differences in the 'same' cancer. The more available data, the better. This has driven large collaborations such as The Cancer Genome Atlas and the International Cancer Genome Consortium (ICGC). The ICGC is well on the way to fulfilling its ambition to complete a comprehensive description of 500 genomes from each of 50 different types of cancer. The pooling of this information is an example of the potential for 'big data' projects to maximise their impact.

However, there are some difficulties with cancer genomics. One concern about a shift to personalised oncology is the expense. The price of sequencing has fallen rapidly but remains costly. The medicines used for tackling a specified cancer tend to be far more expensive than traditional therapies. Bodies such as the National Health Service have finite resources, so decisions about costs versus benefits have to be made. Money spent here cannot be used for other treatments.

On balance, however, the opportunity that genomics offers to make earlier, more accurate diagnosis of the molecular basis of an individual's cancer, and to follow this up with medicine tailored to tackling their specific disease, means that cancer genomics is going to become an ever more important tool in the battle against 'the big C'.

Things to do

- Watch one of the short videos listed in Further reading (or, if you are particularly interested in the topic, the longer more detailed one).
- What are the main ethical issues with cancer genomics? What advantages does cancer genomics bring? What are the potential downsides?

Chris Willmott is an associate professor in the Department of Molecular and Cell Biology at the University of Leicester. He is co-author of the award-winning book *Where science and ethics meet: dilemmas at the frontiers of medicine and biology*.

Further reading and viewing



Cancer Genomics Overview (from the website of the US National Cancer Institute, introductory):

<https://tinyurl.com/yb3gj5gl>

Video: 'Genomics and personalised medicine', NHS Alliance (4.5 min, introductory): <https://youtu.be/X8eNFA6fpLs>

Video: 'Personalised medicine could lead to a breakthrough in cancer in 2017' (3 min, introductory): <https://youtu.be/JGk2k1mWMk8>

Video: 'Personalized medicine in cancer: what does it mean and how is it done?' (6 min, introductory): <https://youtu.be/5iNV8Fuc8pk>

Video: 'Introduction to cancer genomics' (90 min, advanced):
<https://youtu.be/9mKkQ0f1Qxs>

Snake venom

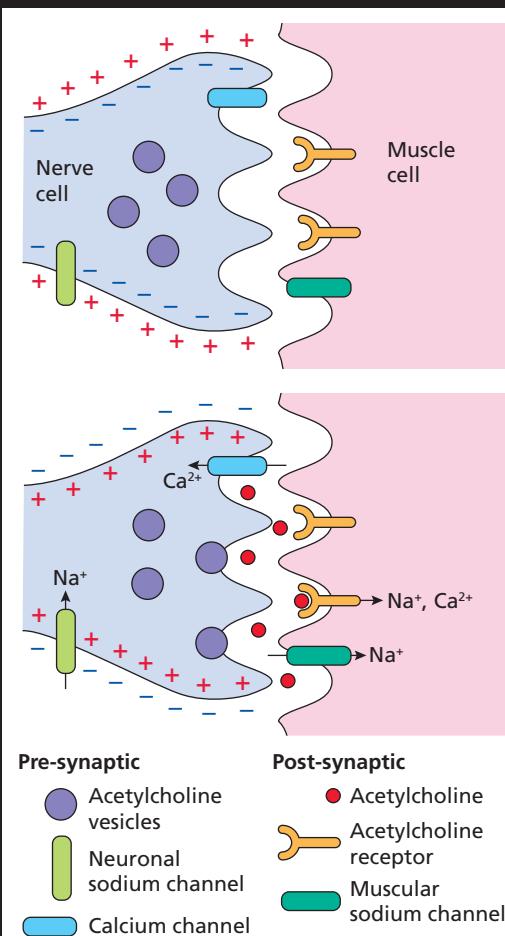


Figure 1 Neuromuscular junction showing transmission from nerve cell to muscle cell. At rest (**top**), the cytoplasm of the neurone has a negative charge relative to the extracellular fluid — the resting membrane potential. During a nerve impulse (**bottom**), this potential is briefly reversed, resulting in a positive charge inside. This leads to events that ultimately trigger muscle contraction

Of the 2340 known species of snake, approximately 420 are venomous. Around 5 million snake bites are recorded globally each year, and at least 125 000 victims die. Snake venom can contain many different toxins. Those that target the nervous system are called neurotoxins. Many venoms contain several neurotoxins that work together to prevent the nervous system from functioning, thus immobilising prey.

Many neurotoxins disrupt the transmission of impulses that make muscles work, by affecting events within the neuromuscular junction (see Figure 1). Electrical impulses travel along the length of a motor neurone until they reach a junction with a muscle cell. Impulses reaching the terminal of the neurone cause an influx of positive ions, including sodium and calcium (see BIOLOGICAL SCIENCES REVIEW, Vol. 31, No. 3, pp. 2–6). This stimulates the vesicles containing the neurotransmitter acetylcholine to fuse with the surface membrane of the neurone. As a result, the vesicles release their acetylcholine, which diffuses across the gap and binds to specific receptors on the muscle cell, leading to influx of calcium ions from the sarcoplasmic reticulum. These ions fuse with troponin, exposing the binding sites of actin molecules, which triggers contraction.

Pre-synaptic neurotoxins block neurotransmission by affecting release of acetylcholine from the neurone. Post-synaptic neurotoxins block binding of acetylcholine to the receptors in the muscle cell membrane. Together these neurotoxins effectively block transmission of nerve impulses to muscles, thus paralysing the muscle. Muscle contraction is required to keep animals alive, so suffocation, caused by paralysis of muscles involved in breathing, is a common cause of death after snake bite.

If you are travelling in areas known to be frequented by snakes, without appropriate protective gear (why?), take a smart phone. That way, if you are bitten, you can call the emergency services and take a picture of the snake to show them so that they can bring the appropriate anti-venom (see this for more: <https://tinyurl.com/8p7scd>).

Max Drakeley and Liz Sheffield, University of Liverpool; Catherine McCrohan, The University of Manchester

The measure of a monkey

Speciation and hybrids

Duncan Wright

What can the evolution of two macaque species tell us about speciation? Science writer Duncan Wright examines this question



AQA: 3.4.4 Genetic diversity and adaptation; 3.4.5 Species and taxonomy; 3.7.3 Evolution may lead to speciation

Edexcel A: 4.4 Natural selection can lead to adaptation; 4.6(i) Species concept; 5.19 Allopatric and sympatric speciation

Edexcel B: 3.1 Classification; 3.2 Natural selection

OCR A: 4.2.2 Classification and evolution; 6.1.2(g) Allopatric and sympatric speciation

OCR B: 3.1.3 The development of species; 5.1.2(e) Geographical and reproductive isolation

WJEC Eduqas: 2.2.1(f) The concept of species; 2.2.6(i) Isolation and speciation

At last! After an hour's hike up the Tianmu Historic Trail in the unforgiving Taiwanese heat, I'd found them. To the left of the trail, on a raised patch of earth overlooking a sheer drop down the mountain, was a group of infant Formosan rock macaques. I crept forward to try to get a better shot with my camera, when suddenly — whump! The space between me and the infants was now occupied by an imposing male macaque, and the quiet mountain was suddenly filled with the sound of monkey chatter. Outmanoeuvred and out of my natural habitat, I began to think perhaps I had made a mistake. Eager to avoid a face full of macaque teeth, I broke eye contact and started to step slowly away, backwards. I didn't get my photo, but at least my face was still intact.

The Formosan rock macaque (*Macaca cyclopis*) is one of two primate species native to Taiwan, the other species being humans. Rock macaques primarily inhabit mountainous regions, where they forage for plant matter, insects

Key words

Speciation
Vicariance
Hybridisation
Reproductive isolation

and small vertebrates. Much like a hamster, the macaques store food in cheek pouches for later consumption. They are closely related to both rhesus macaques (*Macaca mulatta*), after which the Rhesus blood group is named, and Japanese macaques (*Macaca fuscata*).

Allopatric speciation

While rhesus macaques are broadly distributed across the Asian mainland, both Formosan rock macaques and Japanese macaques are **insular species**, restricted to Taiwan and the Japanese islands, respectively. How did these non-seafaring animals find themselves confined to these islands? The answer lies in their DNA and the Earth's history.

Taiwan and Japan have not always been islands: lower sea levels during **glacial periods** meant that Taiwan and Japan were connected to the mainland by **land bridges**. Comparison of **mitochondrial DNA** implies that an ancestral rhesus macaque population split between 380 000 and 440 000 years ago, and suggests that rhesus macaques migrated to Taiwan and Japan. A subsequent rise in sea levels cut off these islands from the mainland, causing the resident macaques to become isolated from the rest of the gene pool.

These island macaques evolved to become separate species with distinct physical characteristics. Japanese macaques have stump tails and distinctive red faces, while Formosan rock macaques have long tails and less colourful faces.

Terms explained



Allele A variant of a given gene.

Allopatric speciation The process whereby new species evolve from geographically isolated populations of a single species.

Courtship Behaviour and rituals used to attract a mate.

Gene flow The transfer of genes from one population to another.

Glacial period A time period associated with glacial advance.

Insular species A species with an island distribution.

Land bridge A connecting strip of land between two larger land areas.

Mitochondrial DNA The 16569 bp of circular DNA found in mitochondria, encoding 37 genes.



Japanese macaques, famous for their enjoyment of hot springs, relaxing in Onsen Jigokudan Park, 130km northwest of Tokyo

The emergence of these species is an example of **allopatric speciation**. The first step in this process is the geographical isolation (also known as vicariance) of populations of the same species. In our example, the macaques were isolated by rising sea levels. The isolated populations are unable to breed with one another, and there is thus no exchange of genetic material between them (i.e. there is no **gene flow**). The populations then slowly undergo genetic divergence, through various mechanisms (see Box 1). The gradual accumulation of genetic changes may ultimately result in reproductive isolation, meaning that, were the two populations to encounter one another again, they would be unable to exchange genes (see Figure 1). Reproductive isolation can be caused by several factors, as shown in Box 2.

Box 1 Genetic divergence

The gene pools of isolated populations can diverge through the following processes.

- **Mutation:** random genetic mutations occur in each population, resulting in distinct gene pools. Some of these mutations do not affect an organism's ability to survive and reproduce (they are 'neutral') but may still be passed on by chance (see 'genetic drift' below).
- **Natural selection:** other mutations may enhance an organism's ability to reproduce in a particular environment. Organisms with such mutations are thus more likely to pass their favourable **alleles** of genes to more offspring. For example, mutations that increase the chance of survival in Taiwan's subtropical heat would be more likely to be retained in Formosan rock macaques.
- **Genetic drift:** it is not always the fittest organisms that survive and pass on their genes — there is also an element of chance involved. If organisms fail to mate through bad luck (say, an encounter with a human hunter), their alleles may be lost from the gene pool. Such a random change in the frequencies of alleles is called genetic drift.

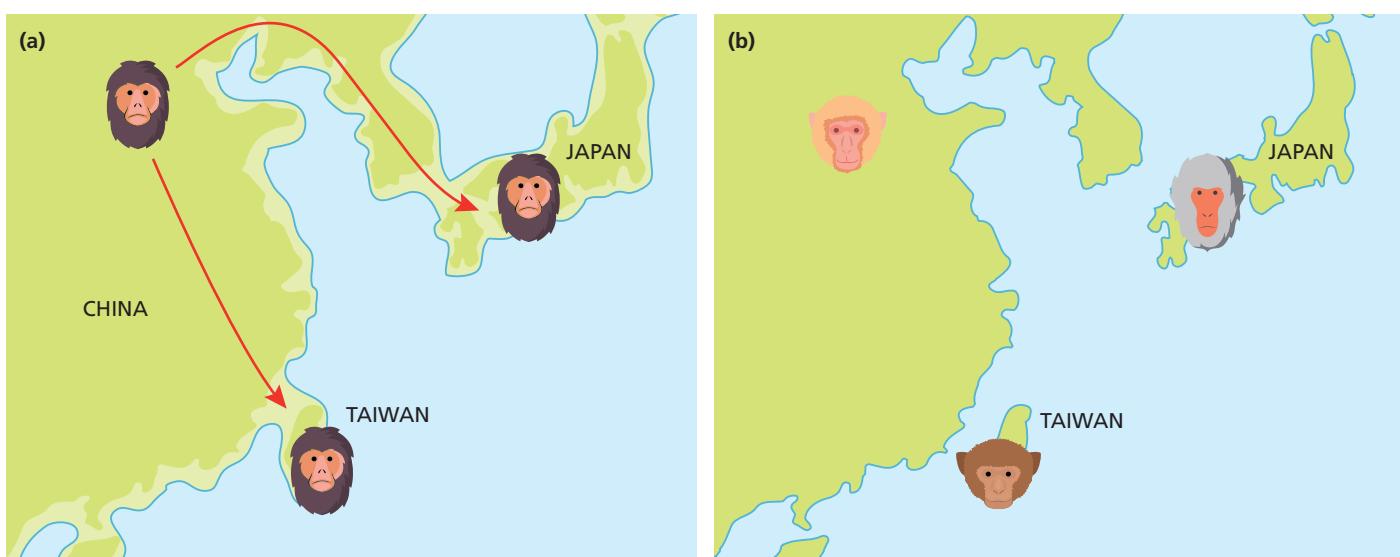


Figure 1 Speciation in macaques. (a) During earlier glacial periods, rhesus macaques migrated from the Asian mainland to Taiwan and Japan via land bridges. (b) Taiwan and Japan later became islands, isolating their resident macaque populations from the wider population. Subsequent genetic divergence caused distinct species to form in Taiwan, Japan and continental Asia



Formosan rock macaque in Taipei, Taiwan. Formosan rock macaques have long tails and less colourful faces than Japanese macaques, which have stumpy tails and distinctive red faces (see page 11)

Hybridisation

Although Formosan rock macaques can swim, it is unlikely they would have the stamina to swim over 1000 kilometres from Taiwan to Japan. Even if a macaque clung on to a piece of wood that was washed out to sea, and that wood just happened to float all the way to Japan, the macaque would be unlikely to find enough food to survive in the open ocean. The bottom line is that Formosan rock macaques and Japanese macaques would probably not have encountered one another had it not been for human intervention.

Formosan rock macaques were taken to zoos and research centres in Japan and some of them managed to escape. Indeed, enough macaques escaped from a private zoo in Wakayama City to set up their own breeding population (see Figure 2). This particular group has been known to mate with Japanese macaques, producing fertile hybrids between the two species.

But wait. We tend to think that different species cannot interbreed and even if they can, the offspring tend to be sterile. Matings between donkeys and horses produce (usually) sterile mules or hinnies. If Japanese macaques and Formosan rock macaques can produce fertile offspring, can they really be considered two different species?



Figure 2 Sites of *Macaca cyclopis* breeding populations in Japan

Box 2 Reproductive isolation

Reproductive isolation can occur at two main levels — pre-zygotic (before fertilisation or mating) and post-zygotic (after fertilisation).

Pre-zygotic barriers

- Behavioural isolation: two populations will not interbreed because of differences in **courtship** behaviour.
- Mechanical isolation: differences in the size, shape, and/or location of genitals prevent mating.
- Gametic isolation: the sperm and egg (or pollen and ovule) are incompatible for fertilisation.

Post-zygotic barriers

- Non-viable hybrid: the egg is fertilised but the embryo fails to develop normally.
- Hybrid sterility: the hybrid develops normally but has low fertility or is completely sterile.

Definition of species

This brings us to ‘the species problem’ — how does one define species? The biologist Ernst Mayr defined a species as:

‘groups of actually or potentially interbreeding natural populations, which are reproductively isolated from other such groups’

In other words, organisms can interbreed with members of the same species, but not with members of other species. However, there are several problems with this definition (see Box 3). One problem is that it does not account for hybridisation between closely related species, such as our macaques. Although Formosan rock macaques and Japanese macaques exhibit distinctive physical and genetic properties, they have not yet undergone complete reproductive isolation. This is also true for coyotes and wolves — canines that meet and mate where their territories overlap, creating hybrid zones in which ‘coywolves’ are common.

Hybrid success

Often, hybrids are less fertile and less adapted to their environment than their parents, meaning they are less likely to pass on their genes. In

Further reading



Read about the Formosan rock macaque here: www.arkive.org/formosan-rock-macaque/macaca-cyclopis

And more about the Japanese macaque here: www.arkive.org/japanese-macaque/macaca-fuscata

Read Richard Dawkins' book on evolution — *The Blind Watchmaker*.

Box 3 Defining species

The Mayr definition of species is challenged by the following situations.

- Asexual reproduction: members of asexually reproducing species (such as bacteria) cannot be defined based on their ability to interbreed.
- Ring species: sometimes it is not clear where one species ends and another begins. Ring species (such as the *Larus* gull, see p. 25, this issue) consist of a long chain of populations (say, 'ABCDEFGH') — neighbouring populations can interbreed (for example, members of A can breed with members of B), but the two ends are reproductively isolated from one another (members of A do not breed with H).
- Hybridisation: sometimes reproductive isolation between two related species is not complete, and members of distinct populations can interbreed to produce hybrids (e.g. macaques).



The European bison is an example of successful hybridisation

Wakayama Prefectural Government launched a campaign to exterminate hybrids of these two species, as part of a wider movement to limit damage to ecosystems caused by invasive alien species. Sadly, the greatest threat facing macaques is not hybridisation, but rather destruction of their environment by human encroachment. While a group of macaques may be able to scare off one human, they are defenceless against the destructive force that is human society.

Dr Duncan Wright completed a PhD in molecular genetics at The University of Warwick and subsequently worked as a postdoctoral researcher in Taiwan. He currently works in scientific publishing.

Key points



- Rising sea levels caused the ancestors of Japanese macaques and Formosan rock macaques to become separated from each other.
- Geographical separation prevented interbreeding between the two groups, causing them to slowly undergo genetic divergence.
- Genetic divergence may eventually result in reproductive isolation, preventing organisms of two species from producing fertile offspring.
- Formosan rock macaques and Japanese macaques can still mate and produce fertile offspring, and so do not exhibit complete reproductive isolation.

Francis Crick Institute exhibition

Craft & Graft: Making Science Happen, Francis Crick Institute, 1 Midland Rd, London NW1 1ST (near Kings Cross Station) until 30 November 2019

A new exhibition from the Francis Crick Institute offers visitors the chance to go behind the scenes and see the work of five specialist departments which support the institute's ground-breaking research. They include:

- Glass Wash, which cleans 750 000 items of glassware a year
- Fly Facility, which nurtures over 1.5 million flies
- Cell Services (or 'Librarians of life-forms'), which grows around 100 billion cells a month

BIOLOGICAL SCIENCES REVIEW has a link with the institute: its director Sir Paul Nurse is on our advisory panel and articles from Sir Paul and other authors from the institute regularly appear in the magazine (e.g. 'Cancer stem cells: the seeds of a tumour', Vol. 30, No. 4).

Opening hours:

Wednesday 10 a.m.–8 p.m.

Thursday, Friday, Saturday 10 a.m.–4 p.m.

Admission is free



The Fly Facility

Feeding the future

Plant scientist Joseph Moughan has long been obsessed with the challenge of feeding the world's predicted 9.7 billion people by 2050. Now an agricultural development worker for One Acre Fund — a non-profit, social enterprise in sub-Saharan Africa — he shares his story

My first year studying biology at The University of Manchester was truly inspirational. It became clear to me that plant science held huge potential to make the world a better place. In our generation, biologists need to ensure that there will be enough healthy and nutritious food for everyone to eat. Food production must increase sustainably, with increased resilience to environmental extremes predicted to result from climate change. This all needs to happen in the coming 20–30 years to ensure that mass starvation events are not a part of our future. Whether you are interested in science, arts, or humanities, there is a role for everyone in the dynamic field of plant science and agriculture. Farming is no longer just for traditional farmers. Today there are many different careers in agriculture that require people from all backgrounds.

Key words

Agriculture
Food security
Genetics
Hybrid
Nutrition
Population



The author running a farmer focus group to understand their needs and explain the benefits of best practice agriculture

Food security

Food may be something that you take for granted. The United Nations World Food Program defines people as 'food secure' when they have access to sufficient, safe and nutritious food at all times, to allow them to live healthy and active lifestyles. However, not all people have this luxury. It is currently estimated that around 10% of the world suffers from chronic hunger and is therefore food insecure. That equates to around 800 million people.

This problem is predicted to worsen as the world's population continues to rapidly expand — particularly in the developing nations

(see Figure 1). The United Nations predicts that the world's population will increase by almost 30% to 9.7 billion people over the next 30 years. During this time, the diets of people in the developing world will change dramatically, through increased diversity of food and overall consumption. This means that food production must increase substantially to meet demand. Globally, there is not enough land available to grow our food on, yet production needs to increase somewhere in the region of 50% by 2050. Being inspired to try to help alleviate this situation, using my plant sciences degree, I decided to pursue a doctorate in crop science at Rothamsted Research and the University of Exeter.

The Green Revolution

Two major scientific breakthroughs in the last two centuries enhanced the natural ability of plants to take up and use nutrients. The first was the use of fertilisers. These products enable farmers to apply the vital nutrients — nitrates, phosphates and potassium ions — that plants need to produce high yields but naturally deplete from soil. The second was the production of improved varieties of crops through selective plant breeding, which generated crops that use nutrients more efficiently than before. Some of the most amenable crops were rice and wheat, where, for example, varieties were produced with reduced height, enabling the resultant plants to spend more energy on food production than growing tall.

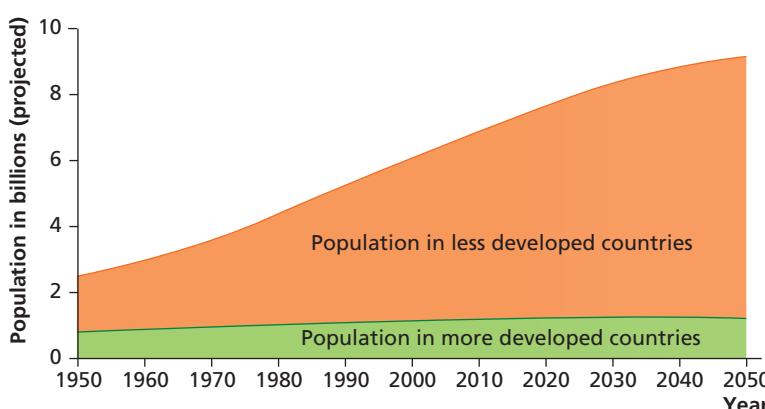


Figure 1 The world's population is increasing and is expected to reach 9.7 billion by 2050. Most of this increase will occur in the world's less developed countries (Data from UN *World Population Prospects: the 2006 revision*, 2007)

In the 1960s, 60% of the world's population in developing countries was chronically malnourished. During this time, agricultural scientists, including biologists, combined improved crop varieties with application of fertilisers for the first time. As a result of these technological advancements, rice and wheat yields doubled globally between the 1960s and the 1990s. This period is known as the Green Revolution and the technologies developed in this time are thought to have prevented starvation in around 1 billion people.

Delivering the Green Revolution to farmers most in need

While the Green Revolution in the mid-twentieth century greatly increased crop yields in many of the world's agricultural systems, large parts of Africa never achieved the same success. This is largely because the staple crop in many sub-Saharan African countries is maize.

Maize yields can be increased dramatically through the process of hybridisation. Commercially produced hybrid maize was developed in the 1940s in the USA. However, due to the high price and complexities of producing this seed, it was never introduced to many of Africa's farmers. Hybridisation involves the intentional outcrossing of two plants, with different parent plants, to create genetically diverse offspring.

To create hybrid plants, we control the reproductive process. The pollen-producing organs (stamens) are removed from their flowers, forcing the plant to outcross with pollen from a different plant. Hybrid maize plants, which are more genetically diverse, are better able to withstand environmental stress (e.g. low water availability and high temperatures) and attacks from insect pests and microbial pathogens. This makes them yield higher than maize plants produced through inbreeding.

To ensure that we can feed the expanding population, farmers in the developing world need access to high-quality fertiliser and high-yielding seed. I work for a social enterprise called One Acre Fund that provides these technologies to over 800 000 farmers in eastern and southern Africa. We enable farmers to access fertiliser and seed through the provision of small loans and a complex logistics network, delivering to within walking distance of the farmers' houses.

We also provide training on improved farming techniques, such as how to plant in well-spaced rows (see Figure 2) and microdosing fertiliser. Microdosing involves applying a small amount of fertiliser underneath each



Figure 2 Farmers can increase their maize yields by planting in rows and spacing the plants 20 cm apart (**top**), following One Acre Fund planting guidelines (**bottom**)

Terms explained



Agronomist Person concerned with the health and well-being of crops used for food production, fuel and land reclamation.

Agronomists conduct experiments to develop the best methods for increasing the quality and production of crops.

Eutrophication Excessive richness of nutrients in a lake or other body of water, frequently due to run-off from the land, which causes a dense growth of plant life.

plant, at the precise dose that the plant species needs to successfully grow (see Figure 3). In modern agriculture, fertiliser is applied to fields using inefficient spreaders or sprays. This results in fertiliser running off into the wider environment, causing **eutrophication**. Microdosing means the fertiliser is completely and effectively used by the crop. Farmers on the One Acre Fund program double their yields and greatly increase their income (see Figures 4 and 5).



Figure 3 Top: Small doses of fertiliser (microdosing) can lead to large increases in the yields of maize without damaging the environment.

Bottom: Fertiliser provides plants with the nutrients they need to grow strong and yield well, such as nitrates and phosphates

Using biology in agriculture

Agriculture is at a pivotal time where crop yields must increase with less impact on our environment than current practices (many of which are unsustainable). Biologists will play an important role in solving this issue.

Some plant species are able to withstand environmental extremes, such as heat and drought. Plant geneticists can select plant strains with desirable phenotypes, such as tolerance to drought. Plant breeders can then select for these traits through traditional crossing (inbreeding) into high-yielding plant varieties, for example as a way to encourage adaptation to a changing climate. Biologists and **agronomists** largely perform this work through in-the-field identification and selection of phenotypes,

Box 1 People working in agriculture and rural development

Sarah-Jane

Background: MSc (Hons) biology and PhD crop pathology.
Current position: Crop production systems scientist, responsible for management and data validation of crop variety and agronomy field trials throughout the UK.

Quote: 'Working in agriculture allows me to collaborate with a broad range of people, including scientific researchers, breeders, and farmers. It's an important process to effectively translate applied scientific research to the farm.'

Kaan

Background: BA in business administration and MSc in public policy. Previously worked in small business development and advisory/mentorship roles.

Current position: Program associate with One Acre Fund, focused on system innovations —using tablets in the field to improve transaction efficiency with smallholder farmers in Kenya.

Quote: 'I love that my work allows me to support families in building their way out of poverty. Being so close to the beneficiaries of the program gives us a chance to make honest assessments and design impactful interventions.'

Sam

Background: BSc agricultural science (focus on soil science).
Current position: As graduate project manager at the Australian Centre for International Agricultural Research, helps design, manage and assess research projects that benefit poor farmers in developing countries.

Quote: 'Sustainably growing more nutritious food using less resources enables farmers to support their families, protect the environment and nourish their communities.'

Advice

My best career advice is to try lots of things, find out what you definitely don't want to do and take the opportunities that seemingly come out of nowhere — even if a risk is involved. Follow what excites you and become an expert in it. If it feels right, it probably is, even if it feels scary too. Don't obsess about 'your career' or 'what you want to be'. If you had told me when I was 18 that at 28 I would be an agronomist/plant scientist, with a PhD, working in rural development in Rwanda, I would have laughed (and wouldn't even have known what that job was).

Further reading

For career information visit these websites:

www.brightcrop.org.uk
<https://tinyurl.com/yc4pyjr3>
<https://tinyurl.com/ya46oxkr>

The United Nations World Food Program: <http://www1.wfp.org>

One Acre Fund: <https://oneacrefund.org>

Food and Agriculture Organization of the United Nations:

www.fao.org/home/en

Rothamsted Research: www.rothamsted.ac.uk



Figure 4 Joining One Acre Fund enhances farmers' maize yields



Figure 5 Increasing farmers' yields allows them to have surplus produce that they can sell to make profit and live more prosperous lives

climate-controlled glasshouse experiments, or through laboratory and computer studies of plant genetics.

Careers in agriculture and plant science

Farming is currently undergoing a technological revolution, so people from many backgrounds are now vital.

- Physicists and engineers are developing autonomous (self-driven) tractors and drones that can microdose fertilisers and other chemicals.
- Mathematicians and data scientists are using agricultural data to provide high-definition maps of the nutrients available in soils. This enables farmers to apply the exact types and amounts of fertiliser they need, resulting in little or no run-off, so reducing eutrophication.
- Chemists are inventing fertilisers and pesticides calibrated to provide nutrition and pest control for specific crop plant species. These often target a single organism, reducing effects on other organisms in the same environment.
- Biologists are breeding high-yielding crops that can grow while submerged in water or in conditions with limited water availability.

Marketing and advertising from supermarkets and advice provided by nutritionists and doctors have a huge influence on consumer habits. By encouraging healthy eating and consumption of crops from sustainable sources, we reduce our impact on our environment. Consumers' choices ultimately define which crops are grown, and where and when they are produced. The future of food will depend on young people entering this exciting sector, to ensure that all 9–10 billion people can eat healthily by 2050, with minimal impact on our environment — one of the biggest challenges currently facing humanity.

Dr Joseph Moughan is Seed Partnerships Lead for One Acre Fund in Rwanda. He is working to ensure that 250000 farmers on the program can access high-quality hybrid maize seed for the future.



Sympatric speciation

Sympatric speciation in plants frequently happens via genome duplications, but what about animals? Biologists Robert Spooner and Raksha Gohel explore the situation in grasshoppers and mechanisms occurring in other animals

Sympatric is derived from the Greek meaning 'from the same area'. Sympatric speciation occurs when populations of a species become reproductively isolated from each other in the absence of physical or geographical separation.

Plants

In plants, this often occurs through polyploidy, where some offspring have multiples of the normal number of chromosomes. If an individual is normally diploid (with two copies of each chromosome), then polyploid offspring could be tetraploid (with four copies). They themselves subsequently often perform meiosis poorly but can sometimes reproduce asexually. Even if successful in making gametes, then a mating between tetraploid and diploid individuals does not generate fertile offspring. The tetraploid becomes reproductively isolated from the parental diploid species. Sometimes the plant can self-fertilise and a new tetraploid species is created. The situation in animals is different.

European grasshoppers

It is not unusual to find pairs of closely related species that occupy the same geographical range and that do not interbreed naturally, but which can interbreed under experimental conditions. Some *Chorthippus* grasshoppers are so similar that without a microscope, it is hard for

humans to determine which species they belong to. But the grasshoppers themselves have no difficulties.

Female grasshoppers do not rely on looks when choosing a mating partner, but instead they listen. The males have courtship calls made by stridulation (the scraping of their back legs against their wing-cases), but different species stridulate at different frequencies. In the wild, females will only choose males that stridulate at the correct species frequency. This choice of courtship call is a powerful species separator. However, in captivity a female will mate with a male from a different species if she can hear the courtship call of a male from her own species, and the offspring are usually fully fertile.

The choice of frequency preferred by a female grasshopper depends on the temperature of her head. A male of any grasshopper species stridulates over a temperature-dependent range of frequencies (as the temperature rises, so does the stridulation frequency). The female's choice is temperature-sensitive, so she will pick a male of the same species no matter what the ambient temperature. Experimentally, she can be fooled. If her head is heated using a tiny thermocouple, her choice switches to higher





frequencies, and so she will mate with a male of a species with a higher frequency call.

What might be the mechanism of sympatric speciation in grasshoppers? Both stridulation frequency and female preference are variable genetic traits. In any collection of grasshopper males, some will stridulate at a slightly higher frequency than the average, and some will stridulate at a slightly lower frequency. Similarly, some females of that species will

have a genetic disposition to prefer the higher frequency range, and some the lower, with most preferring the average. Female choice thus becomes a driving force for speciation, and nowhere in this process have grasshoppers doubled their chromosome number.

Other species

Are grasshoppers the only animal species that have undergone sympatric speciation?

Studies of stridulation reveal speciation in field crickets (which scrape their wing covers) and in South American ants (which stridulate by rubbing abdominal segments against each other). Female choice as a species separator is not restricted to insects. Sympatric evolution has also been noticed in eastern Mediterranean subterranean blind mole-rats. Here, different dominant females show preference for different types of soils. Some prefer chalky soils and others prefer basalt soils, limiting gene flow and resulting in separation of species. With further animal examples now being discovered — beak differences in Santa Cruz finches, echolocation calls in bats, and prey differences in killer whale populations — it is likely that sympatric speciation is more common in animals than was previously thought.

Robert Spooner is a senior teaching fellow. **Raksha Gohel** is an undergraduate student and a curriculum advisor to the Royal Society of Biology. Both are in the School of Life Sciences, The University of Warwick.

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Protecting the pinosaur

Discovery of a plant dinosaur

The story starts in 1994, when a national parks and wildlife ranger noticed an unusual-looking tree in a remote canyon in Wollemi National Park in the Blue Mountains of New South Wales, Australia. He took a sample to a plant expert, who was excited to confirm that it was a conifer that was thought to have died out at least 2 million years ago. These trees can reach over 30 m in height and were very successful up to and including the Cretaceous period (along with many species of dinosaur). Although they are not pines (they are most closely related to monkey puzzle — *Araucaria* — species), these beautiful trees are affectionately referred to as pinosaurs (and Wollemi pines).



Pinsaur bark — an attractive feature likened to CocoPops or bubbling chocolate



Pinsaur cones. Left is a male cone, releasing a cloud of pollen. Right is a female cone, which, when pollinated, will produce seeds

Vulnerability

The discovery triggered massive media interest and intensive research, which quickly showed that there were only 100 or so individuals in one area of the park, and that they were genetically identical. This means that the species must have gone through a severe genetic bottleneck (see Box 1). The researchers realised that this made the plants extremely vulnerable, as a disease that affected one tree would necessarily affect them all. They kept the location of these rarities secret, took extensive measures to avoid transporting in pathogens, and did something completely unprecedented. Using cuttings and seeds, they cultivated new plants just as fast and furiously as they were able. They hoped that, by making the plants commercially available, the original trees would avoid unwanted attention, especially from plant poachers.

Biological Sciences Review Extras



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The Wollemi pine

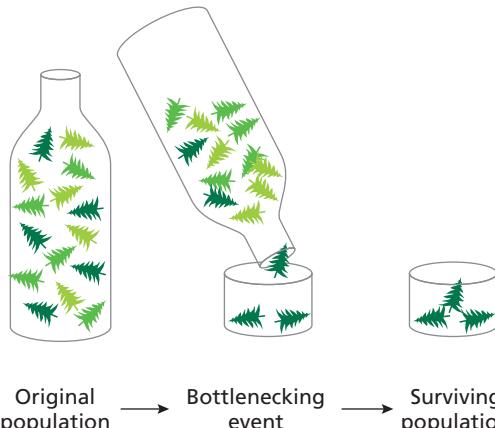




Box 1 Genetic bottlenecks

The first bottle in Figure 1.1 represents a population of individuals, such as the dinosaurs alive in Cretaceous times. The different colours represent individuals with alleles that differ from those of other members of the population. The second illustration shows the population being subjected to an influence, such as a pathogen or an environmental catastrophe, which kills many individuals. Such events will remove some genetic variation, and in the case of the dinosaur, this was so severe that only a single genotype survived.

Figure 1.1



Disaster averted

Sadly, in 2005, it became clear that the original trees were infected with *Phytophthora* (see also BIOLOGICAL SCIENCES REVIEW, Vol. 31, No. 3, pp. 20–21). It is not known how the pathogen arrived, but suspicion fell on unauthorised visitors who failed to take the precautions necessary to avoid contamination.

Happily, the foresight of the conservationists had paid off and trees were growing all over the world in parks and gardens by then. Now an 'insurance population' of 191 trees is thriving at a secret Australian location. This area is sufficiently distant from the original site that it should avoid fire, predators or disease striking the other grove. This insurance population is growing 'like Weetabix kids', at 30 cm per year instead of the 1 cm of those in the original (much darker) location, according to Dr Heidi Zimmer, a senior scientist with NSW Environment. This year, for the first time, some of this population has produced fertile seeds, so the future of this iconic living fossil looks bright.



Young pinosaurs growing in a commercial glasshouse. When planted out, the trees are tolerant of full sun and deep shade, below freezing to 40°C, so are popular with gardeners all over the world

Further reading

For more on this story see: www.youtube.com/watch?v=LQuhXLDXI-0

For more about living fossils, including animals, see: www.youtube.com/watch?v=uX1Qbztryds



Liz Sheffield, University of Liverpool



Lampreys

Lampreys form a group of around 40 highly successful species, both freshwater and marine.

Neurobiologist Catherine McCrohan describes how these apparently primitive fish live, and how they are helping scientists unravel some of the mysteries of body function in all vertebrates, including humans

Lampreys have been called '**living fossils**'. They belong to a group of vertebrates called the jawless fish or agnathans. They are so called because they lack the hinged jaw characteristic of all other vertebrates (the gnathostomes: from the Greek *gnathos*, jaw + *stoma*, mouth). Fossil evidence shows that the ancestors of lampreys and of modern jawed vertebrates split around 550 million years ago (see Figure 1). Apart from **hagfish**, other agnathan fish that are present in the fossil record have been extinct for at least 200 million years.

Lampreys have a non-mineralised skeleton made of cartilage — like that of elasmobranch fish (sharks and rays). Other differences from jawed fish are a lack of scales and paired fins, and a single, unpaired nostril. Adult lampreys have an eel-like body and range in length from 10 to 100 cm, depending on the species. The circular mouth acts as a sucker, by which the lamprey attaches itself to stones in order to rest, or to its prey (see Figure 2).

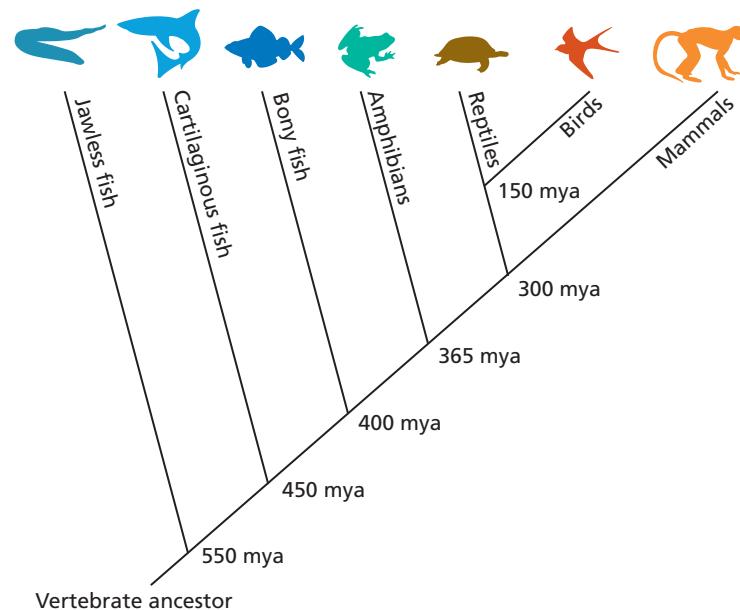


Figure 1 Simplified phylogenetic tree of vertebrates (mya = million years ago)



Key words

Lamprey
Vertebrate
Specific immune system
Spinal cord
Invasive species

Lifestyle and feeding habits

Lampreys are found in **temperate** regions in both marine and fresh water, although all species migrate into rivers to spawn. After hatching, lampreys enter the larval stage, which may last up to 7 years, and is spent in freshwater. The larvae burrow into the silt at the bottom of the river and feed on tiny organisms and food particles, which they filter from the water that they pump through their **pharynx**. Eventually, the larvae **metamorphose** into adults, with a very different lifestyle.

The adults are free swimming and many species are parasitic. They feed on the blood of their prey — usually other fish. The circular mouth contains many keratinised

Terms explained

Hagfish Jawless, marine, eel-like fish, often called slime eels because of their ability to produce copious amounts of slime (mucus) — up to 20 dm³ — when threatened or captured.

Interneurone (or relay neurone) A neurone that conveys signals from one neurone to another and is usually confined to the central nervous system.

Intrinsic A natural or built-in component.

Invasive species A non-native or introduced species that causes harm to an ecosystem.

Living fossil An organism that has remained unchanged over a long geological period and that resembles other species that are only known in the fossil record.

Metamorphose To change physical form and enter a different stage of life.

Pharynx The part of the alimentary canal that links mouth and oesophagus.

Pheromone A chemical signal released by an individual that influences the behaviour and/or physiology of others from the same species.

Specific immune response Response of the immune system that generates immunity to a specific pathogen or antigen.

Temperate Parts of the world with a mild climate, occurring between tropical and polar regions.

Box 1 Lampreys in history

Perhaps the best-known historical reference to lampreys relates to Henry I, King of England (1068–1135), who is said to have died from ‘a surfeit of lampreys’. Although apparently healthy, Henry became ill and died just a few days after eating a large helping of his favourite dish — lampreys. The lampreys have been blamed ever since.

A more sinister event relates to Vedius Pollio, who was a high-ranking Roman during the first century BCE. He was renowned for his cruelty. Lampreys were a culinary delicacy for the Romans and Vedius kept a fish pond stocked with them. The story goes that, when one of his slaves broke a crystal goblet, Vedius ordered him to be put to death by being thrown to the lampreys, which would quickly attack and devour him — a horrible end. The slave was rescued by the Roman leader, Augustus, who was so horrified by the cruelty of the punishment that he ordered all of Vedius’ crystal glasses to be smashed.

Nowadays, lampreys are still regarded as a delicacy in many cuisines — for example, in France, Spain, Portugal and the Baltic States. In the UK, they are used more as bait to catch predatory fish such as pike.



A dish of lampreys

teeth (see Figure 2). These teeth are made of a similar protein to mammalian hair and nails, and rhino horn. Once the mouth has attached to the body of the prey, the hard teeth rasp through its skin and body wall and then suck out blood and other body fluids. This can lead to significant injury, or even death of the prey fish. Stories of lampreys attacking humans are rare and this probably only happens when the lamprey is starving (see Box 1). Adult lampreys have a shorter lifespan than their larvae, living only around 2 years.

Evolution of the immune system

Lampreys have had a chequered history with regard to their relationship with humans (see Box 1). However, because of their position in the evolutionary tree as ‘living fossils’, they can help us understand the evolution of body functions in vertebrates.



Figure 2 Mouth of a lamprey, showing the sucker around the edge, surrounding numerous sharp, rasping teeth

One example of this is the immune system. The **specific immune response** of jawed vertebrates, such as fish, birds and mammals, involves two main types of white blood cells (lymphocytes), called B and T cells. B cells are produced in the bone marrow, whereas T cells develop in the thymus — a gland located in the chest. These two cell types work together to launch effective responses to invading pathogens such as bacteria and viruses. They also enable the body to produce a much more rapid response to re-infection with a pathogen that has been encountered previously, providing the basis for immunity to infection and for immunisation by vaccination (see BIOLOGICAL SCIENCES REVIEW, Vol. 31, No. 2, pp. 38–41 and No. 3, pp. 38–41).

Recent research has found that lampreys have a similarly sophisticated specific immune system involving two main types of white blood cell, which have roles similar to the B and T cells of jawed vertebrates. In lampreys, these cells are produced in two different locations. The B-like cells develop in an organ adjacent to the intestine called the typhlosole, and the T-like cells in specialised tissue, called thymoid tissue, located at the tips of the gill filaments.

Although the two cell types in lampreys have similar functions to B and T cells, molecular analysis shows that their surface receptors are unrelated to those of jawed vertebrates. This indicates that the specific immune systems, involving two main cell types that develop in separate locations in the body, evolved in parallel, rather than that of jawless vertebrates being ancestral to that of jawed vertebrates. Scientists can now investigate what might be the advantages of an immune system organised in this way that have led to it evolving in parallel in two separate arms of the vertebrate lineage.

Neural circuits in the spinal cord

Lampreys have played a key role in neuroscience research — in particular, helping us to unravel the circuitry of the spinal cord. The spinal cord of vertebrates can be thought of as an extension of the brain. As well as the tracts of nerve fibres that connect the brain to more distant body parts, it contains nerve cells that are connected together by synapses to form functional circuits. One of these is the circuit that generates the

Further reading

Read about control of sea lampreys by the Great Lakes Fishery Commission:
www.glfcc.org/sea-lamprey.php

Lampreys are returning to British rivers: <https://tinyurl.com/hg9gnsm>

Spinal stimulation therapy for paralysed patients: <https://tinyurl.com/yaltdrl2>



rhythmic movements of locomotion — swimming in fish, flying in birds and bats, and walking and running in mammals.

Like many other fish, lampreys swim by alternately contracting body wall muscles on the left and right sides, producing a bending movement that travels like a wave along the length of the fish (see Figure 3). In the 1970s, the Swedish neuroscientist Sten Grillner and colleagues pioneered the study of neurones in the spinal cord of lampreys. They found and recorded electrical activity (action potentials) from motor neurones in the right and left sides of each segment of the cord. These motor neurones connect directly to, and excite, the muscle on the same side. The left- and right-hand motor neurones fire action potentials alternately to produce bending of the body.

Grillner showed that the motor neurones would still fire alternately even when the cord was severed from the brain and removed entirely

from the body. Their experiments confirmed that neuronal circuitry in the spinal cord could generate the activity rhythm for swimming entirely on its own. This finding was a major breakthrough in our understanding of how locomotion is controlled in vertebrates. The circuit for generating the rhythmical pattern for locomotion is hard-wired and **intrinsic** to the spinal cord — though, of course, this does not mean that this circuit is not influenced by input from sensory neurones and from the brain.

Scientists in several laboratories across the world went on to unravel the circuit that controls firing in the motor neurones (see Figure 3). Rhythm-generating circuits in successive segments along the spinal cord are connected to each other to provide the wave of contraction along the length of the body. Similar circuits have since been described in the spinal cords of many other animals. It is now believed that circuitry for walking is located in the spinal cord of humans. This raised the intriguing possibility that paraplegic patients, whose spinal cords have been severed from the brain through injury, might be able to walk if their spinal circuits could be reactivated in some way. This possibility is the subject of intense research.

Lampreys as pests

Lampreys have only limited economic importance as food, and they have become significant pests in some parts of the world. In the Great Lakes of North America, sea lampreys are an **invasive species** and have had a huge negative impact on fisheries and associated employment, threatening a total economy worth \$7 billion a year. They probably arrived in the Lakes through improved man-made canals that were built in the late nineteenth and early twentieth centuries to create better passage for ships from the Atlantic Ocean and between the Lakes. Once in the Lakes, and free from predators, lamprey numbers exploded, and they had a devastating effect on fish stocks. Fish are parasitised to the point where they die.

Over the last 50 years, the Great Lakes Fishery Commission has worked hard to reduce the lamprey population using a combination of approaches. These include:

- chemical pesticides targeted on the larvae located in nursery sites in the lakes' tributaries
- physical barriers to prevent adults reaching their spawning sites
- artificial application of the lampreys' own **pheromones** and chemical alarm signals to lure adults towards traps and away from spawning sites

In combination, these methods have led to a 90% reduction in lamprey numbers in some areas. However, it is essential to remain vigilant and maintain control where needed.

Catherine McCrohan is professor of comparative neurobiology at The University of Manchester. She is interested in how neural circuits carry out sensory and motor functions in 'simple' animals including flies, snails and fish.

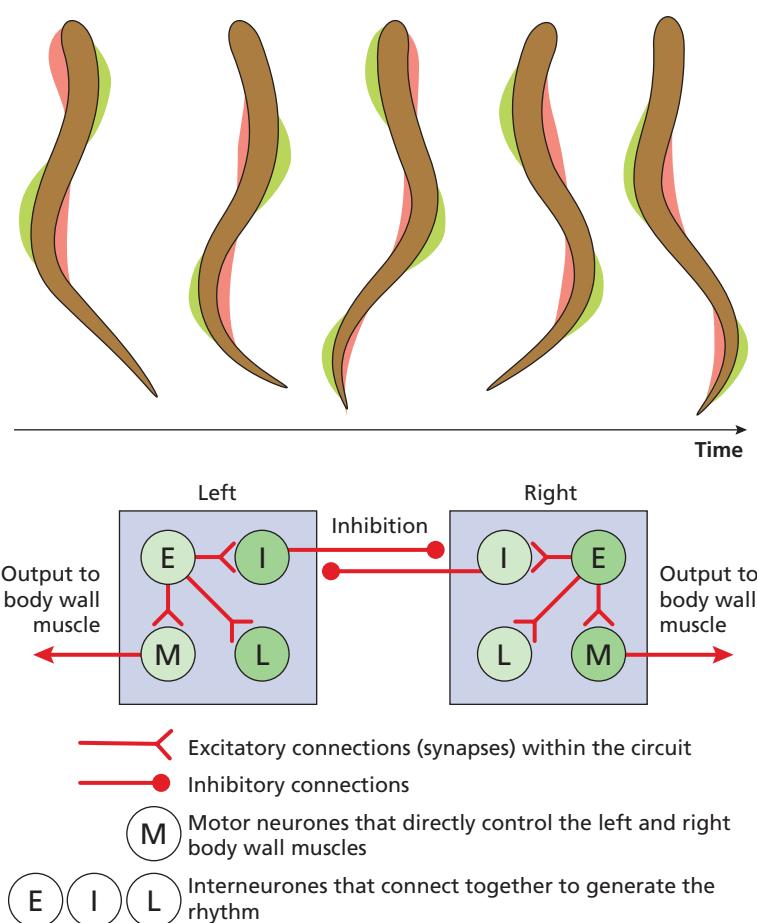


Figure 3 Top: lamprey swimming. Alternate contraction (red) and relaxation (green) of left and right body wall muscles passes along the length of the animal. Bottom: simplified diagram of the neural circuit for swimming in a single segment of the lamprey spinal cord. The mutual inhibitory connection from I interneurones on the two sides ensures that when one side is firing, the other is inhibited and unable to fire



A ring species

A species can be defined as a group of individuals that can interbreed in the wild. What mechanisms might cause speciation — the generation of new species from an ancestral species? Biologists Robert Spooner and Raksha Gohel examine the concept of a ring species

Speciation, the generation of new species from an ancestral species, requires reproductive isolation. If the geographical area that a species occupies is larger than the average life-time travel of any individual, then although the population is continuous, gene flow will be restricted to geographic neighbours. Could collections of genetic changes at the extremes of a geographic range of a population result in speciation?

Salamanders

This has been observed in ring species, where an ancestral species encountered a geographical barrier, migrated around it in two directions and the populations then met again.

The classic example is that of multi-coloured *Ensatina escholtzii* salamanders in the Central Valley of California. This dry grassy valley acts as a geographical barrier to gene flow for salamanders, which require moist habitats. A population at the north of the valley migrated south down both the east and west flanks of the valley, evolving on the way into 19 different subspecies. A subspecies can be considered somewhat physically and genetically different from the rest of the species, but still similar enough to interbreed. Indeed, individual salamanders in adjacent subspecies appear to mate freely. However, where the eastern and western populations meet at the southern end of the Valley (where the 'ring' closes), the two populations look distinctly different and do not mate with each other, so they have become two different species.

Gulls

You don't need to travel to California to see an example of a ring species. If you are in the northern hemisphere, just look up (although the closer you are to a coast, the more likely you are to see it).

There is a circumpolar ring of *Larus* gull subspecies (see Figure 1), with the Arctic ice acting as a physical gene flow barrier. Where the ring closes above Britain and Scandinavia, the physical differences between the gulls are extreme, as in the salamanders mentioned above. The herring gull (*Larus argentatus*) has grey feathers on the backs of its wings, pink legs, pink feet and golden/orange eye-rims. The lesser black-backed gull (*Larus fuscus*) has dark charcoal/black feathers on the backs of its wings, yellow legs, yellow feet and red eye-rims. There is no interbreeding between these gulls, so they have become different species.

Observational studies from Walney Island in northwest Lancashire, UK, showed that no hybridisation between



Figure 1 The ring species of *Larus* gulls. The numbers around the Arctic Circle are placed at the approximate geographical centre of the range of each subspecies. 1, *Larus fuscus* (lesser black-backed gull); 2, *Larus heuglini* (Heuglin's gull); 3, *Larus argentatus birulai* (Birula's gull); 4, *Larus vegae* (east Siberian herring gull); 5, *Larus smithsonianus* (American herring gull); 6, *Larus argentatus* (herring gull). The double-headed arrows show gene flow. Each subspecies can breed with its neighbour subspecies except over northern Europe where the herring gull and the lesser black-backed gull do not interbreed, and where speciation is complete

herring gulls and lesser black-backed gulls happened in the wild. However, in captive conditions, herring gulls and lesser black-backed gulls will mate and produce fully fertile hybrids. So, why don't they mate in the wild? Why do we consider them different species? Are there other factors that favour speciation? In part it appears to depend on the female's choice of mate. She likely reacts to specific cues: differences in call-notes, the colour of the back, the colour of the eye-ring, and the colour of the legs have all been suggested. Perhaps such behavioural barriers will subdivide the ring further, ultimately generating multiple species. Recent DNA studies on *Larus* gulls measuring gene flow indicate that this process is already underway and these subspecies are indeed becoming separate species.

Robert Spooner is a senior teaching fellow. **Raksha Gohel** is an undergraduate student and a curriculum advisor to the Royal Society of Biology. Both are in the School of Life Sciences, The University of Warwick.

Stillbirth

Understanding why the placenta goes wrong

Stacey Lee and Megan Sharps

PhD students Stacey Lee and Megan Sharps discuss the role of the placenta and describe research into what causes stillbirth

AQA: 3.2.4 Cell recognition and the immune system

Edexcel A: 2.15(i) Chorionic villus sampling; 6.9 B cells and T cells

Edexcel B: 2.4 Sexual reproduction in mammals; 6.7 Response to infection

OCR A: 4.1.1(h) Antibodies

OCR B: 3.2.2 The immune system; 4.2.1 Fertility and assisted reproduction; 4.2.2 The effects of ageing on the reproductive system

WJEC Eduqas: 2.2.3(d) The role of the placenta

In the UK, one in every 224 births is a stillbirth — meaning nine babies are stillborn every day. The cause of many stillbirths is unknown, often making them even more devastating for the families involved.

Stillbirth is defined as the death of a **fetus** after 24 weeks **gestation**. **Risk factors** for stillbirth include a maternal body mass index (BMI) greater than 30, a mother who is over 35 or who smokes, or when the fetus fails to reach its growth potential — known as fetal growth restriction. If a fetus stops growing and placental blood flow is compromised, the baby is at high risk of stillbirth. Doctors then intervene to deliver the baby early. Currently, the early delivery of these at-risk babies is the only intervention for stillbirth. More male babies are stillborn than female, but the reason for this is unclear.

In the UK, pregnant women undergo a routine ultrasound scan between 8 and 14 weeks gestation, and again between 18 and 21 weeks. These scans give an indication of fetal well-being and growth. If there is concern over the growth of the fetus, additional scans are performed. Scans can detect if there

Key words

Stillbirth
Placenta
Pregnancy
Reproduction
Hormones

is abnormal blood flow to the placenta, indicating that the placenta may not be functioning properly.

The placenta: providing life support

The placenta has a key role in maintaining fetal growth and development. It supplies nutrients and oxygen to the fetus and removes waste products into the maternal blood. When the placenta is not functioning correctly, the fetal growth rate may decline. When this happens, women often report episodes of reduced fetal movement, an indication that the fetus is not getting the oxygen and nutrients it needs. Women are advised to monitor their baby's movements from 22 weeks gestation and to contact a midwife if they notice any change.

The placenta is derived from the embryo (see Figure 1), so is genetically identical to the fetus, not to the mother. However, the placental tissue is attached to the maternal **endometrium** — the wall of the mother's uterus. As the function of the placenta relates directly to the outcome of pregnancy, it is the focus of much pregnancy research.

Exchange of oxygen, nutrients and waste products between fetus and mother occurs through a network of capillaries located in tree-root-like structures in the placenta, called chorionic villi. The



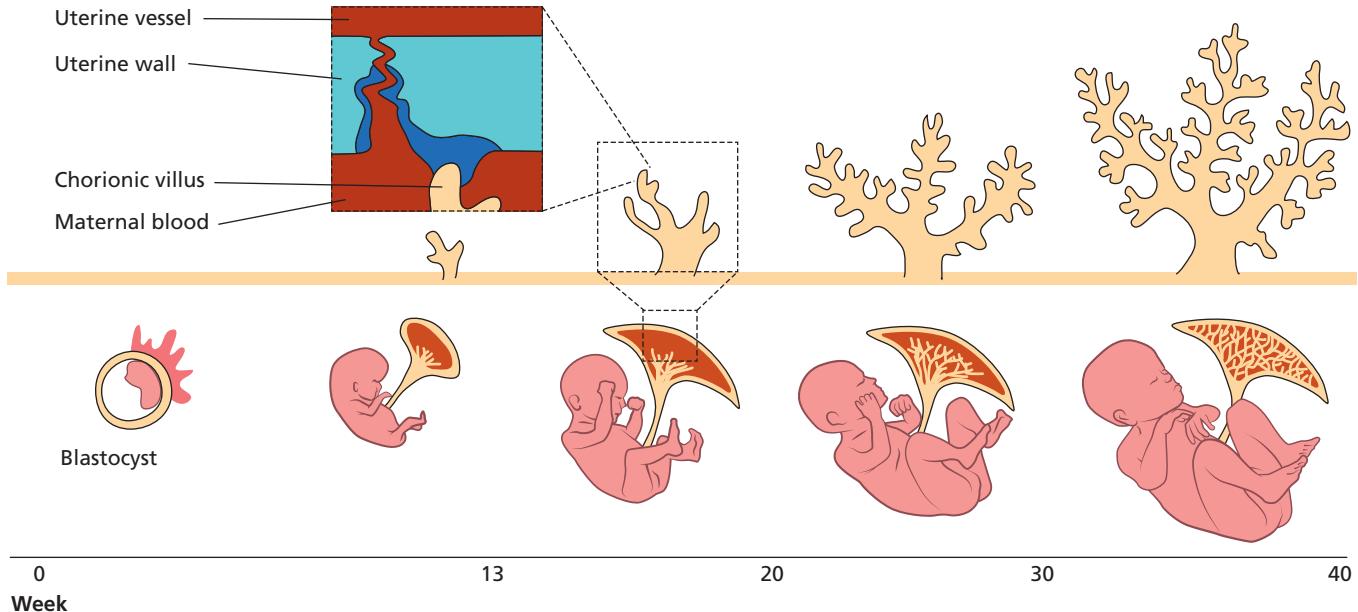


Figure 1 The development of the human placenta over 40 weeks' gestation. The placenta originates from the blastocyst and increases in size throughout pregnancy

villi are bathed in maternal blood (see Figure 2). The capillaries link the arteries and veins that form the umbilical cord, which connects the placenta to the growing fetus. Nutrients are taken up from the maternal blood into the villi via transporter proteins on the surface of the villi. These include amino acid and glucose transporters. Oxygen diffuses down an oxygen concentration gradient,

from high concentrations in the maternal blood to a lower concentration in the capillaries within the villi. An opposite gradient allows for waste carbon dioxide to diffuse back into the maternal blood.

Placental hormones

The placenta is a major source of hormones during pregnancy. These hormones are transported into the maternal blood and can be measured by blood tests run on the mother. They include human chorionic gonadotrophin (hCG), placental growth factor (PIGF), oestrogen and progesterone. hCG is produced from very early on in pregnancy and maintains the endometrium. Because hCG is produced in the early stages, its detection is used in pregnancy tests

Terms explained



Apoptosis Normal, controlled cell death that is necessary to maintain cell numbers in a tissue.

Cytokine A soluble protein molecule secreted by cells that alter the behaviour and communication of surrounding cells.

Endometrium The mucous lining of the uterus that thickens during the menstrual cycle in preparation for possible implantation of an embryo.

Fetus A baby of over 8 weeks gestation that has yet to be born.

Gestation The duration of a pregnancy. The normal gestation of a human pregnancy is between 37 and 42 weeks.

Predictive marker A substance in maternal blood that can be used to predict a condition, such as fetal growth restriction, before it occurs.

Proliferate Division of cells leading to an increase in cell number.

Risk factors Factors that increase a person's chance of developing a disease or condition. These include lifestyle factors such as smoking.

Trimester Pregnancy is divided into three trimesters: first trimester 1–12 weeks; second trimester 13–28 weeks; third trimester 29–40 weeks.

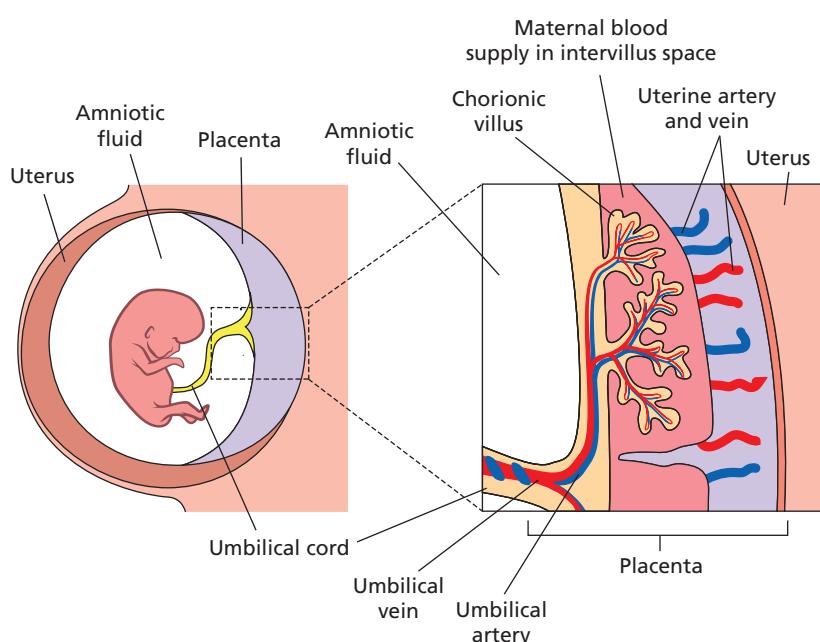


Figure 2 Structure of a healthy human placenta in the third trimester. The placenta is attached to the fetus via the umbilical cord. The expanded view shows the placental chorionic villi bathed in maternal blood, which enters the placenta through maternal arteries



The Royal College of Obstetrics and Gynaecology has issued guidelines about the care and advice that should be given to women with a BMI above 30 before and during pregnancy

Further reading

Tommy's website for information on stillbirth:
<https://tinyurl.com/y984lw89>

NHS: Pregnant women 'should avoid sleeping on back in last trimester', October 2017:
<https://tinyurl.com/y8s326rh>

NHS stillbirth prevention recommendations:
www.nhs.uk/conditions/stillbirth

(see Box 1). PIGF supports the development of the arteries, veins and capillaries in the placenta. Oestrogen and progesterone stimulate growth of the endometrium and promote maternal blood flow to the uterus, both of which are needed for fetal development. Concentrations of oestrogen and progesterone increase throughout gestation.

Placental dysfunction

Following informed parental consent, the placentas of stillborn and growth-restricted babies are examined after birth by specialist doctors. In these placentas, there is often evidence of the placenta not functioning adequately. This is known as placental dysfunction. For example, the diameters of the placental villi are smaller than those in normal placentas, and they contain fewer capillaries. This results in the placenta not being able to meet the fetal demand for oxygen and nutrients. There is also evidence that the cells involved in nutrient transport across the villi **proliferate** less and undergo more **apoptosis**, so that the placental tissue struggles to function. In addition, the placentas of stillborn babies and growth-restricted fetuses show evidence of inflammation, with increased numbers of white blood cells.

Box 1 | Measurement of hCG in a pregnancy test kit

Pregnancy tests rely on the detection of hCG. It is recommended that testing is done at least 21 days after unprotected sex. The test strip contains antibodies specific for hCG. If the woman is pregnant, hCG is detected in her urine.

Figure 1.1 shows how a pregnancy test strip works.

- At the reaction site, free antibodies bind to hCG in the urine. The other end of the antibody has a dye enzyme attached. The antibodies then move up the test strip to the next site.
- At the test site, the hCG bound to the free antibody is trapped by a second antibody, which is immobilised to the test strip. This second antibody has a dye substrate, which reacts with the dye enzyme to produce a coloured line to indicate pregnancy.
- At the control site, free antibodies that have not bound to hCG are bound by another dye substrate. This indicates whether the test kit is working. If no line appears, the kit is faulty.

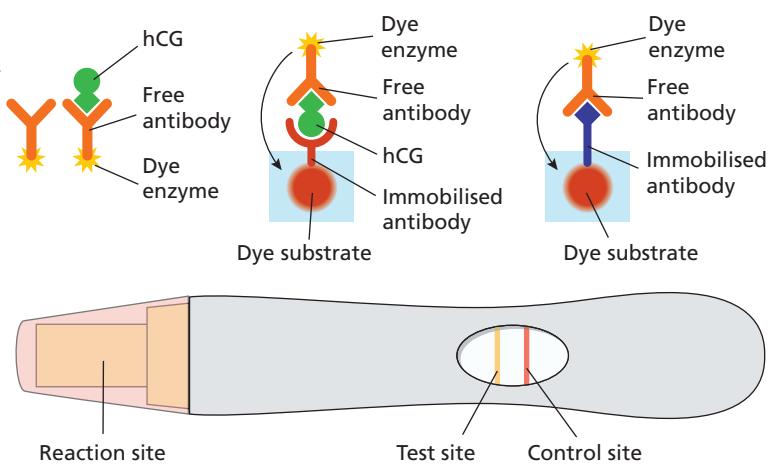


Figure 1.1 Pregnancy testing

The hormone PIGF is currently being researched for its use as a ***predictive marker*** of fetal growth restriction. Lower than normal concentrations of PIGF are present in maternal blood throughout gestation in growth-restricted pregnancies. Research is now investigating whether the concentration of PIGF in maternal blood can also be used to predict the risk of stillbirth.

Research into stillbirth

'Tommy's' is a charity that aims to save babies' lives. One of its UK centres is in Manchester, where scientists and doctors research stillbirth. Here, there are specialist antenatal clinics for women who have had a previous stillbirth (the Rainbow Clinic) or who have a pregnancy where the fetus is growth restricted (the Placenta Clinic). These women have extra ultrasound scans in addition to their standard NHS care, with the aim of detecting any problems early. After the establishment of these specialist clinics in Manchester, the rate of stillbirth in the city dropped by 19% between 2012 and 2017.

In addition to research in the clinics, scientific research is also conducted at the Tommy's centre, including investigating the effects of advanced maternal age and inflammation in the placenta. Mothers who are over 35 are more likely to have a growth-restricted baby or a stillbirth. As part of the Manchester Advanced Maternal Age Study, researchers examined placentas to try to discover the reasons for this. More than 560 women of different ages were studied. Blood and tissue samples from placentas were assessed for chemical biomarkers, which showed that placentas from older mothers age faster than those from younger mothers. These placentas had evidence of placental dysfunction as well as markers of cellular stress, which means they were less able to repair any damage. Researchers also found that placentas from older mothers showed higher levels of inflammation.

Research is also being carried out on mice. This shows a similar link between advanced maternal age and a higher rate of stillbirth. Some of the fetuses from older mice failed to form properly, and their placentas were heavier. The nutrient transporters on the chorionic villi function less effectively than those from younger mice.

Treatment

Scientists are looking at potential therapies in older mice, one of which is to treat them with melatonin. Melatonin is a naturally occurring hormone, which helps control our normal sleep/wake cycle. It may also act on maternal uterine arteries to relax them, increasing blood flow to the placenta. Melatonin treatment has led to increased fetal weights and improved placental function in mice.

Box 2 NHS-recommended sleeping position

It has been found that a woman is at increased risk of having a stillbirth if she sleeps on her back during the third trimester. This is due to increased pressure from the combined weight of the mother and the fetus on the mother's main blood vessels supplying blood to the uterus. This research resulted in a joint NHS England and Tommy's campaign called 'Sleep On Side'. Women are encouraged to go to sleep on their side, as the position in which you fall asleep is the position you will remain in for the majority of your sleep.



There is emerging evidence that the increased inflammation seen in placentas from stillbirths and fetal-growth-restricted pregnancies is mediated by chemical messengers called ***cytokines***. Scientists are looking at ways to prevent or treat this inflammation, thereby reducing placental damage and improving the outcome of pregnancies.

The public has become more aware of stillbirth and its impact, following NHS and charity campaigns such as the 'Sleep On Side' campaign (see Box 2). Although a lot is known about contributory factors, such as smoking and advanced maternal age, research into possible treatments continues. At present, women who are concerned about the risk of stillbirth are advised to visit the NHS website and consult their GP or midwife for advice.

Point for discussion

- The placenta is normally discarded after birth. Why is it necessary to obtain informed parental consent before a placenta is examined in the laboratory?

Megan Sharps and Stacey Lee are PhD students at The University of Manchester. Megan is researching the role of white blood cells in the placentas of babies that are born too small. Stacey is developing targeted delivery of therapeutic drugs to the placenta for women at high risk of stillbirth.

Key points

- Stillbirth is the death of a baby after the 24th week of pregnancy and before the baby is born. One in 224 births in the UK is a stillbirth.
- The placenta keeps the fetus alive by allowing the transfer of oxygen and nutrients from the mother to the fetus. It is thought that when the placenta starts to fail, this results in stillbirth.
- The only current treatment to prevent stillbirth is to monitor the mother and fetus closely during pregnancy and to deliver the baby early if doctors are concerned.
- Scientists are researching the possible causes of stillbirth and trying to develop new preventative treatments.



Making sense of bird bristles

Evolutionary biologist Carl Larsen describes the bristles some bird species have, and explores whether they function like the eyelashes and whiskers of mammals

Animals use a range of senses to detect and explore their environment, including vision, hearing, smell, taste and touch. Touch is highly developed in mammals. Some mammals have whiskers, which they use to explore the world. Hamsters, for example, use their whiskers to navigate their environment and avoid obstacles. Seals use their whiskers to detect the trails of fish. For many species therefore, whiskers form an important part of the sensory system.

In the bird world, similar structures are not referred to as whiskers but as bristles. Of around 10 000 known bird species, nearly 500 have bristles. These include storks, rails, flycatchers, swallows, shrikes, thrushes and nightjars. Some bird species (e.g. spiny-faced antshrike, bristlebill) and families (bristlebirds) are so named because they have bristles. Despite the prevalence of bristles in birds, we know little about their function.

What are bird bristles?

Bird bristles are modified, stiffened feathers that typically occur on the face and head, projecting beyond the plumage and the bill. They vary in structure, ranging from branched semi-bristles (see Figure 1, a–c) to bristles with branches (called barbs) near the base (see Figure 1, d and e) and barbless rictal bristles — those located around the beak (see Figure 1,

Key words

Birds
Bristles
Nocturnal
Mechanosensory

f and g). Some species have very conspicuous bristles around the eye, similar to mammalian eyelashes (see Figure 1, h), but in birds these are modified feathers, whereas in mammals they are modified hairs.

What are bristles for?

Scientists have only recently begun to examine the function of bird bristles in detail. Several hypotheses have been put forward, which are not mutually exclusive. But we still don't really know what bristles are for. We do know that nocturnal birds, which make up only 3% of all bird species, are especially bristly. This prevalence of bristles in birds that are active at night suggests that the colonisation of nocturnal foraging **niches** may have led to selection for bristles. Our research has focused on nocturnal birds in the hope that it might reveal the function of bristles in these and other groups of birds.

Bristles in nocturnal birds

At night there is a shortage of light, and many nocturnal birds have developed enhanced vision and hearing. It is likely that they also rely on other senses, including touch, to help them overcome the sensory limitations of their niche. Owls are top nocturnal predators — they prey on small vertebrates. They have highly developed hearing and vision, which they use to detect prey. Owls catch prey with their talons and the pads on the feet of owls are covered in fine bristles, which probably aid in sensing their grip. Some species of owl also have bristles around their beaks.

Nightjars and related species are also predators with rictal bristles (see Box 1), but they typically eat small and quiet flying insects, which they catch in their mouths. The possession of bristles in nightjars may be related to foraging, where they could be used to direct prey into the mouth or to detect hard surfaces while feeding near foliage in the dark. The longest facial bristles in nightjars are found in species that nest in cavities in trees and on rock ledges. The bristles probably allow them to detect the hard surfaces and help them to locate their young.

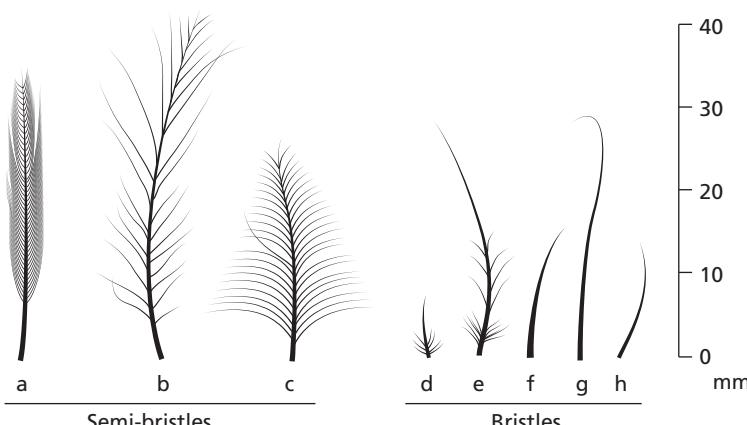


Figure 1 Sketches from museum specimens showing examples of semi-bristles and bristles

Box 1 Bristles in nightjars and related species

Nightjars and their close relatives are medium-sized nocturnal and twilight birds that feed mainly on flying insects and occur globally. The bristles of these birds range from unbranched rictal bristles, which are either (a) short, stiff and up-turned, or (b) long, semi-stiff and down-curved, to semi-bristles (branched bristles) which vary in length, are flexible and occur in various places on the head (c).



Examples of bristles on three species of nocturnal birds, highlighted by arrows

Hypotheses about the function of bristles

Four main hypotheses have been proposed to explain the function of bird bristles.

Mechanical protection hypothesis

Rictal bristles may be adaptations that protect the head from prey and hard surfaces, such as insects or foliage, when birds are feeding in flight. Much as the grill on a cricket batsman's helmet protects the batter from the ball, stiff rictal bristles could protect a bird's eyes from the legs and stings of prey such as grasshoppers and bees.

Protection from vegetation can be important. Members of one bird family — the antbirds — forage by darting into foliage, which can involve forceful contact between the head and vegetation. Bristles may also protect the eyes and nostrils of species that bore into wood — an obvious example is the woodpecker.

Terms explained



Ecological niche How an organism interacts with resources, competitors and predators and how it alters those same factors.

Herbst corpuscles Mechanosensory nerve endings found only in birds, which are associated with a highly developed sense of touch.

Histological Anatomical study of the microscopic structure of animal and plant tissues.

Mechanosensory The sensing of mechanical stimuli such as pressure or vibration.

Pacinian corpuscle Mechanoreceptor nerve ending found in mammalian skin.

Speciation Evolutionary process whereby populations have evolved to become distinct species.

Vestigial An organ or part of the body that has become functionless over the course of evolution.



**Red-legged seriema
with long rictal bristles**

Some birds of prey have very prominent bristles around their beak and face. Rictal bristles are particularly long in the predatory seriema, where they could protect the eyes from a snake writhing in the predator's beak. The secretary bird specialises in eating venomous snakes. Its flattened 'eyelashes' may protect its eyes from the venom of a spitting cobra or from the sparks from savannah fires where it feeds on fleeing or wounded prey.

Feeling hypothesis

Bristles may have a **mechanosensory** function (rather like a hamster's whiskers), giving information about the animal's immediate environment. Our **histological** studies have revealed a high density of so-called **Herbst corpuscles** in the tissue around the base of each bristle (see Figure 2). These sensory nerve endings are similar in structure to the mechanosensory **Pacinian corpuscles** found in mammalian skin and

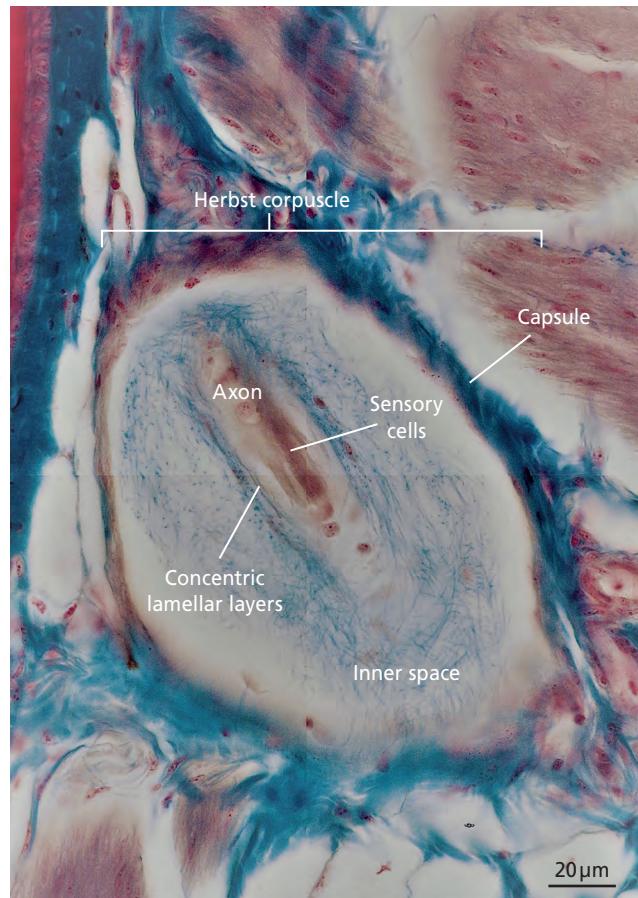


Figure 2 Section through a Herbst corpuscle, located at the base of a bristle

have been shown to respond to mechanical vibration by generating nerve impulses, which relay information to the central nervous system.

Some bird species that nest in burrows, tree holes or rock crevices have head bristles. One is the nocturnal burrowing kiwi. It is flightless and feeds on the ground by probing in the earth. As well as having nostrils on the tip of its beak for



**Bearded barbet with
prominent rictal
bristles**



**Southern ground hornbill
with eyelash-like bristles**

'sniffing out' its subterranean prey, research shows that the long bristles around its face provide sensory information about its prey and surroundings.

The whiskered auklet is a nocturnal seabird, which has long bristly plumes on its face and head. When scientists taped these bristles flat and placed the birds in a maze, the birds bumped their heads on obstacles in their path. This confirmed that bristles have a mechanosensory function in this species, allowing it to navigate through the rock crevices in which it nests.

Just as seal whiskers detect the trails of fish in water, bristles might act as vortex sensors, detecting changes in air currents created by flying prey. Seal whiskers have specific adaptations for this role, including an oval cross-section and an undulating geometry along their surface. However, electron microscope images show that the surface of bird bristles is smooth and cylindrical, so it is unlikely that they are used to detect changes in air pressure.

Feeding hypothesis

It has been proposed that rictal bristles may act as 'insect-catching nets', funnelling prey into the mouth. But this is not always borne out by experimental evidence. In an experiment performed on flycatchers — an insect-eating bird — small insects were blown towards birds flying in a wind tunnel. A comparison of the results from flycatchers from which the rictal bristles were removed and control flycatchers (rictal bristles intact) showed that the bristles protected the eyes but did not aid in prey capture.

Goldcrests have been seen using their rictal bristles to trap prey against a surface before eating them.

If rictal bristles are mechanosensory, providing tactile information about air flow and captured prey, they could aid aerial insect feeders in locating prey at close quarters. However, this suggestion has not been tested. If rictal bristles are indeed used as a 'net' to funnel prey into the mouth, then we would expect more species of nocturnal aerial feeding birds to have them. However, although rictal bristles are well-developed in many aerial feeding nightjars, they are either absent or too underdeveloped to be functional (*vestigial*) in nighthawks and some other nightjar species. So it is unlikely that bristles are used to capture prey in this way. We can conclude that these birds once had bristles because they have retained a special 'comb-like' claw on their middle toes, which was used to keep their bristles clean.

Cleanliness hypothesis

Stiff facial bristles are present in some birds of prey and in 'bald-headed' carrion eaters, such as vultures, where they may prevent contamination of the feathers while the bird is feeding. Some species that specialise in eating fruit also



Kiwi with long
bristles at the
base of the beak

have bristles, possibly for the same reason. The oilbird feeds exclusively on fruit. Its long stiff bristles may protect the facial plumage from fruit juices when it feeds, but this has not been tested experimentally.

Other functions

Specialised trophic functions (those related to feeding) for bristles have been suggested for other bird species. Honey buzzards raid bee nests to take their larvae. Their facial bristles are scale-like and are thought to guard against bee stings and contamination from the honey. Hummingbirds have fine bristles on their tongues that help with lapping nectar from flowers. Some species of swifts have short, stiff bristle-feathers directly in front of the eye. These are controlled by muscles and may act like the black sunblock that cricketers use to reduce glare.

There are many different types of bird bristle and their structure and location in each species is likely related to their function. We are only just beginning to understand their function and it appears that in some birds they are vestigial. Colonisation of new foraging niches, such as the nocturnal one, may have caused selection for bristles, both for protection and for sensing the environment. This in turn could have led to geographic and behavioural divergence and ultimately to *speciation*.

Things to do

- Think of possible hypotheses for the evolution of bristles in birds.
- Think of any ethical issues with attempting to test your hypotheses.
- Given that many mammals are nocturnal (including bats), why do you think so few species of bird have made this transition?

Further reading



More about bird senses:

www.thespruce.com/birds-five-senses-386441

Dr Carl Larsen is the programme director for zoology in the School of Life Sciences at the University of Liverpool. He is interested in the evolution of animal morphology and behaviour.

Water

Transport and regulation in the body

Kevin Moffat

Biologist Kevin Moffat explains the link between your blood, your brain and your kidneys and how together they control the hydration of your body

AQA: 3.1.7 Water; 3.2.3 Transport across cell membranes; 3.6.4.3 Control of blood water potential

Edexcel A: 1.2 The importance of water; 2.3 Osmosis; 8.8 Brain structure

Edexcel B: 1.7 Water; 4.2 Cell transport mechanisms; 9.9 Osmoregulation

OCR A: 2.1.2(a) Properties of water; 2.1.5(e) Osmosis; 5.1.1 Principles of homeostasis; 5.1.2(c)(i) Structure and function of the mammalian kidney; 5.1.2(d) Control of water potential of blood; 5.1.5(h) The human brain

OCR B: 2.1.2 Water and its importance; 5.3.3 Kidney functions and malfunctions

WJEC Eduqas: Core 1(b) The importance of water; Core 3(c) Osmosis and water potential; 2.3.4 Homeostasis and the kidney

By weight, the average human female is about 50% water and the average male 60%. For a 70 kg male that's around 42 dm^3 of water. Differences are due to disparities in body fat and muscle composition. But where is this water, how is it regulated and what happens when this regulation goes wrong?

Kate Mori was running her fourth marathon. Fit, experienced and a sports scientist, she was 'ahead of her thirst', well hydrated before she began. It was April 2007 and one of the hottest London marathons on record, with temperatures over 23°C . Amid frequent reminders from the race officials about dehydration, Kate made sure that she drank at every opportunity. However, as she passed the 18-mile mark, she felt ill. She knew she was in trouble. Determined to finish for her charity,

and with support from other runners, she staggered to the finish line. Shortly afterwards she collapsed and was put on a saline drip in hospital. Her problem? Over-hydration, resulting in a potentially lethal low concentration of sodium in her blood and tissues.

This condition is termed **hyponatremia**. The combination of exercise, drinking too much and inappropriate release of **anti-diuretic hormone** (ADH) resulted in Kate suffering from exercise-associated hyponatremia (EAH). This is a well-documented condition and, although it is treatable with a saline drip to replace the sodium, it can be fatal. Victims of EAH include American footballers, on-duty soldiers and policemen, canoeists, ironmen, long distance swimmers and mountain bikers. Symptoms of hyponatremia have also been linked to cases of people involved in water drinking games or those with seemingly unquenchable thirst after taking drugs such as ecstasy. They all risk death.

The UK National Health Service advises adults to drink 2 dm^3 of water a day. If we don't drink fluids we will die of dehydration in a few days. We might be lucky and last a week. However, we may die far sooner if we drink too much water too quickly. The **median lethal dose** (LD50) of water for humans is just 6 dm^3 — dangerous if drunk over a period

Key words

Water potential
Osmosis
Antidiuretic hormone
Kidney
Pituitary gland
Brain

of a few hours. To understand this, we need to consider where our body stores water and how our physiology controls it.

Where is our water?

About two-thirds of the water in our body is inside cells. The rest is extracellular. The extracellular water is divided between the plasma in the blood vessels (intravascular) and the fluid surrounding the cells and organs (interstitial) (see Figure 1). Plasma volume is normally kept at around 3 dm^3 for men and 2.3 dm^3 for women. Plasma is the main fluid compartment that interacts directly with water inputs to the body — from food and drink — and water outputs including urine, sweat, breath and secretions from the gut. To understand how water in the body is controlled, we need to consider its movement between plasma, interstitial fluid and cells. Water moves by **osmosis**, owing to differences in **water potential**.

Why does water move?

Early in our biology education we learn about osmosis, particularly in the context of plant roots taking up water, or changes in the size of cells.

Terms explained



Anti-diuretic hormone (ADH) A short, nine amino acid polypeptide hormone.

Baroreceptors Receptors that sense pressure in arteries.

Blood brain barrier Cells that normally prevent the movement of substances between the blood and the brain.

Cytokines Molecules secreted by cells that stimulate other cells, frequently found in the immune system.

Homeostasis The maintenance of a physiological state.

Hyponatraemia A concentration of sodium ions in body fluids that is below normal physiological concentration.

MDMA 3,4-Methylenedioxymethamphetamine, also known as ecstasy.

Median lethal dose (LD₅₀) The dose of a substance that will kill 50% of a sample population.

Osmoreceptors Receptors that sense changes in the water potential of arterial blood.

Osmosis The movement of a solvent across a semipermeable membrane from a dilute to a concentrated solution.

TRPV (transient receptor potential vanilloid)

channels Membrane ion channels that respond to mechanical movement, often as a result of osmotic changes to cells.

Water potential A quantitative measure of the tendency of water to move by osmosis.

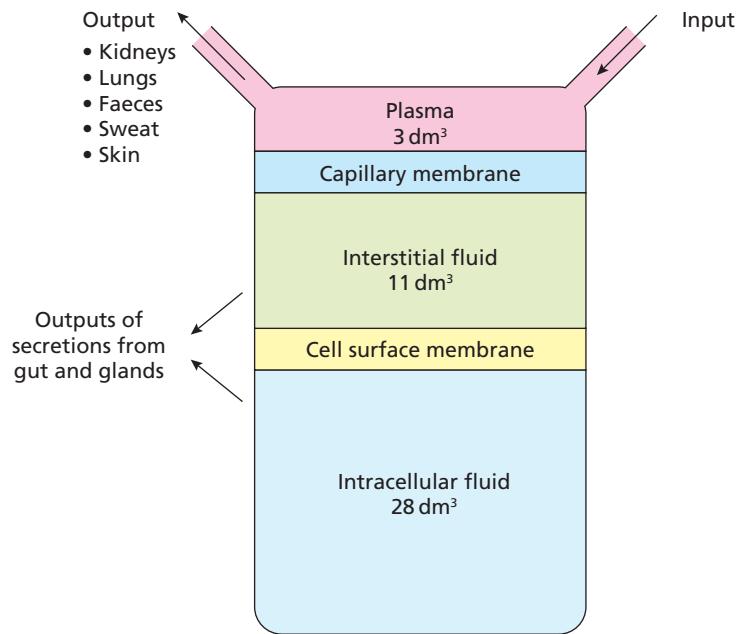


Figure 1 Fluid compartments. Our body fluids can be considered to be in three compartments separated by two partially permeable membranes. Blood plasma is responsible for the majority of exchange between the external environment and the fluid found inside our cells

Osmosis explains why water moves across a partially permeable membrane. The solvent (water) moves from the less concentrated solution to the more concentrated solution. Understanding water potential allows us to appreciate the forces underlying this movement (see Box 1).

In plant cells, the rigid cell walls contribute to the pressure component of water potential inside the cell. In animal cells, however, it is the concentrations of solutes that are the major determinants of water potential. A simple way to consider this is that the solute prevents water from moving freely by interacting with it, thus reducing the amount of free water and resulting in a lower water potential (see Box 1, Figure 1.1).

Sensing we are thirsty

When we sweat, urinate, defaecate and breathe, we lose water. The initial physiological response is the movement of water between compartments in the body owing to changes in water potential. Water loss increases solute concentration and hence decreases water potential in the plasma, resulting in the remaining water moving first from interstitial fluid and subsequently from cells (see Figure 1).

We normally maintain our water **homeostasis** by regulating thirst and urination. In severe situations, such as acute injury and blood loss, our arterioles undergo vasoconstriction in order to maintain blood pressure. This is mediated via **baroreceptors** located in the walls of blood vessels. An increase in concentration of solutes in blood plasma is sensed by **osmoreceptors**. Significant to thirst are osmoreceptors that are found in the brain, controlling the release of an important hormone, ADH.

Osmoreceptors are proteins called **TRPV channels** that are found in the cell surface membranes of neurones in brain regions where there is little or no **blood brain barrier**. Here they have close contact with blood vessels and

Biological Sciences Review Extras

Go online for a revision worksheet to test your understanding of this article at www.hoddereducation.co.uk/bioreviewextras



therefore blood plasma (see Figure 2). These neurones shrink or expand as a result of changes in the water potential of blood, and they are exquisitely sensitive.

A decrease in water potential of the blood results in thirst and concentrates urine. This process is initiated by the mechanical movement of the TRPV channels as the neurone shrinks. The TRPV channels then directly alter the flow of ions across the neuronal membrane, generating action potentials that are sent to the brain's hypothalamus. The hypothalamus controls ADH secretion into the blood from the pituitary gland (see Figure 2). ADH then regulates water retention in our kidneys and, in the brain, gives rise to the sensation of thirst.

The kidneys

The major sites of fluid regulation are the kidneys' nephrons (see Figure 3). An ultrafiltrate is produced from the blood in the capillaries of the glomerulus.

This then moves into the proximal convoluted tubules before entering the loop of Henle. The fluid moves through the distal convoluted tubule, enters the collecting ducts, and finally reaches the bladder for excretion from the body.

Human kidneys filter the blood around 20–25 times each day, producing about 1.5 dm^3 of urine, the majority of our daily water loss. The initial ultrafiltrate is similar to blood plasma, except for the proteins, which are not removed. In the proximal convoluted tubule, many ions, amino acids and vitamins are actively recovered. The descending loop of Henle is largely impermeable to ions, and water easily moves out by osmosis into the

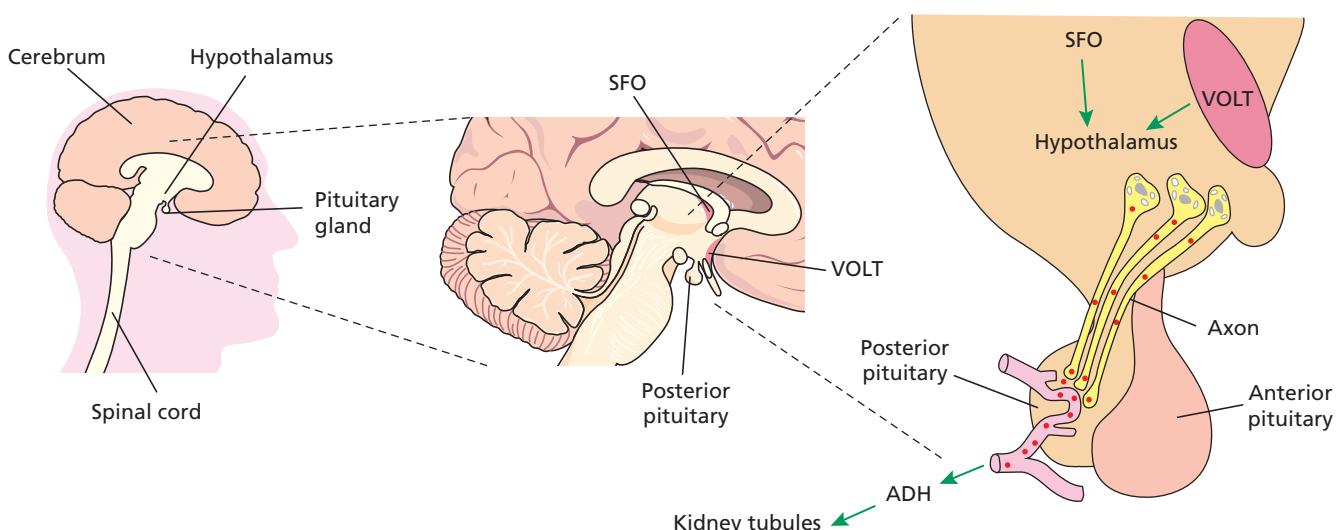


Figure 2 Osmoreception in the brain. Osmoreceptors are located in neurones in the vascular organ of lamina terminalis (VOLT) and the subfornical organ (SFO). These neurones send action potentials to hormone-producing neurosecretory cells in the hypothalamus, which regulate ADH secretion from the posterior pituitary gland

Box | Water potential

Water moves from a region of high water potential to a region of lower water potential (see Figure 1.1). Water potential is determined by two things — pressure and solute concentration. Water potential is represented by the Greek letter ψ (psi) with units of kilopascals (kPa). Water potential is effectively a measure of free water molecules in a solution. Pure water has the highest ψ of 0 kPa. The more solutes, the less free water. This is because solute interacts with water molecules so that they are not free to move. And the lower the water potential the more negative the kPa value. For example, a 0.15 M solution of sucrose has a ψ of -370 kPa.

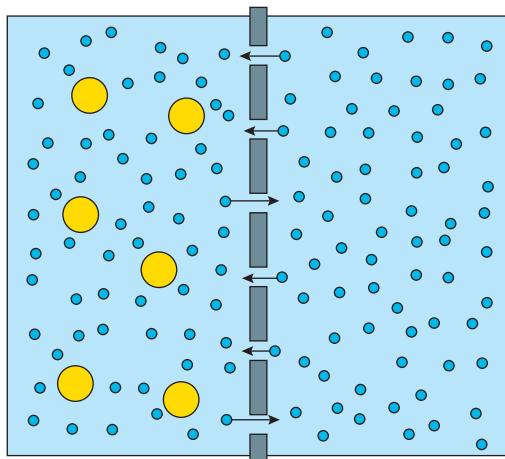


Figure 1.1 Osmosis and water potential. Yellow circles represent the solute (e.g. ions) and blue circles represent the solvent, water. The two sides are separated by a partially permeable membrane. With the solute only on the left, the higher concentration of free water is on the right, giving the right-hand side a higher water potential. The net flow of water is therefore to the left by osmosis

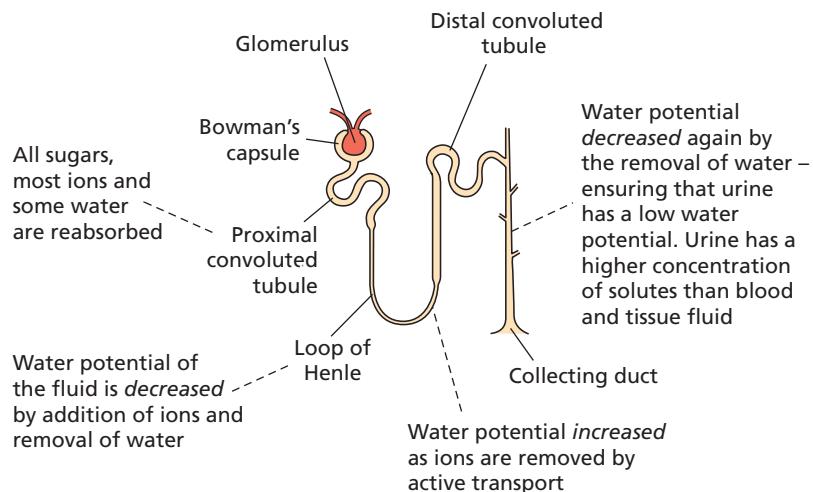


Figure 3 Water potential changes in a nephron of the kidney during production of urine

As it passes down the collecting duct, the high concentration of ions in the surrounding medulla results in a flow of water out of the duct. This results in urine that has a lower water potential — more concentrated solutes — than blood.

Importantly, the amount of water removed from the collecting duct is regulated by controlling its permeability to water. Dehydration lowers water potential in the blood, driving the thirst response via TRPV channels. The ADH subsequently released from the pituitary gland binds to receptors on the epithelial walls of the collecting ducts, stimulating an increase in the number of water channels — called aquaporins — in their cell surface membranes. This allows more water to leave the collecting duct by osmosis, resulting in further concentration of urine.

What can go wrong?

There are multiple causes of EAH: loss of sodium ions in sweat, internal production of water from metabolism, as well as a large intake of fluid through drinking. An Italian research team found that during glycogen metabolism and muscle injury — both common in intense exercise — a cytokine called IL-6 is released from muscle. This cytokine stimulates ADH release independently of osmoreceptors. Thus, during extreme exercise, even when well hydrated, ADH may continue to stimulate thirst and reduce urination, increasing water retention and therefore sodium dilution.

The causes of hyponatremia for users of ecstasy (MDMA) are different. Rather than IL-6, there is now evidence that a metabolite of MDMA can directly stimulate ADH secretion from the pituitary gland. The effect is the same as for EAH — to lower the concentration of sodium ions in body tissues. At best this is treatable with saline drips. At worst it results in death.

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Further reading

Read Kate Mori's story as reported in the *Telegraph*, 26 March 2012: <https://tinyurl.com/z36gs3j>

Watch a 4-minute documentary on the death of Jennifer Strange, after trying to win a Wii in a water drinking competition on a US radio station: www.youtube.com/watch?v=ioKdf-JvKD0

Key points

- Controlling hydration levels is important for health.
- Water moves between body compartments by osmosis owing to differences in water potential.
- The brain and pituitary hormones are critical for maintaining homeostasis.
- Water potential of blood plasma is controlled by the kidney.

Exams? You need a strategy

We usually read the pages of a novel consecutively, from the first to the last page. But is this the best way to read an A-level biology examination paper? Former A-level senior examiner Martin Rowland argues not, and suggests that students may fail to do themselves justice when they do

Invigilators were often surprised by the behaviour of my A-level biology students during examinations. As soon as it was announced, 'You may now turn over your examination papers and begin', many opened the back of the booklet. One invigilator asked me afterwards, 'Is it because, like you, they start to read a newspaper from the sports pages at the back?'. My answer was, 'No, it's because they know that the last question on this paper happens to be a high-scoring, free-response question testing AO1 and answering that first is part of their **exam strategy** for this paper'.

Let's examine why you need an exam strategy and then look at how you might develop your own.

Will you get 100%?

It is highly unlikely that you will score 100% of the raw marks in your A-level biology papers this summer. That is not because examiners don't want to reward you. It just doesn't happen.

If this is the case, the best you can hope for is to gain as many marks as you can in the time available. I call this 'harvesting marks'. Just as low-hanging apples are easier to harvest than those at the top of the tree, some marks on an exam paper are easier to harvest than others.

Which marks are easiest?

Unlike low-hanging fruit, which everyone finds easiest to harvest, the easy marks in an exam paper will depend on your own skills and on the topics that you found most interesting.

The skills that are tested are summarised in Table 1. You can read more about them, and the type of questions that test them, in *BIOLOGICAL SCIENCES REVIEW*, Vol. 30, No. 1, pp. 31–33.

After almost 2 years of studying A-level biology, you will know better than anyone else the skills and topics with which you feel most confident — i.e. your comfort zone. You are more likely to gain marks, and you will find that your confidence rises, as you answer questions that are within your comfort zone. These questions are unlikely to be the first questions in the exam paper, so you need to find them in order to answer them first.

Comfort zone

Can you predict where the questions that match your comfort zone will be? To a certain extent, yes you can. Let's take topics first. Table 2 gives information about the A-level biology examinations for students in

Key words

- Assessment objective
- Exam strategy
- Mark tariff
- Raw marks



Like the fruit on this apple tree, in an examination some marks are easier to get than others

Terms explained



Command words The part of each question that tells you what you must do; e.g. 'explain'.

Exam strategy A planned and personalised way to answer questions in an examination paper, ensuring that you gain as many marks as you can in the time available.

Mark tariff The maximum number of marks indicated for each question.

Stimulus material Information in the form of artwork, data or prose that you must use in your answers.

Synopsis The ability to present an overview of biology, by drawing together understanding and skills developed in different parts of your A-level biology course.

Table 1 The skills (called assessment objectives, or AOs) tested in A-level biology exam papers

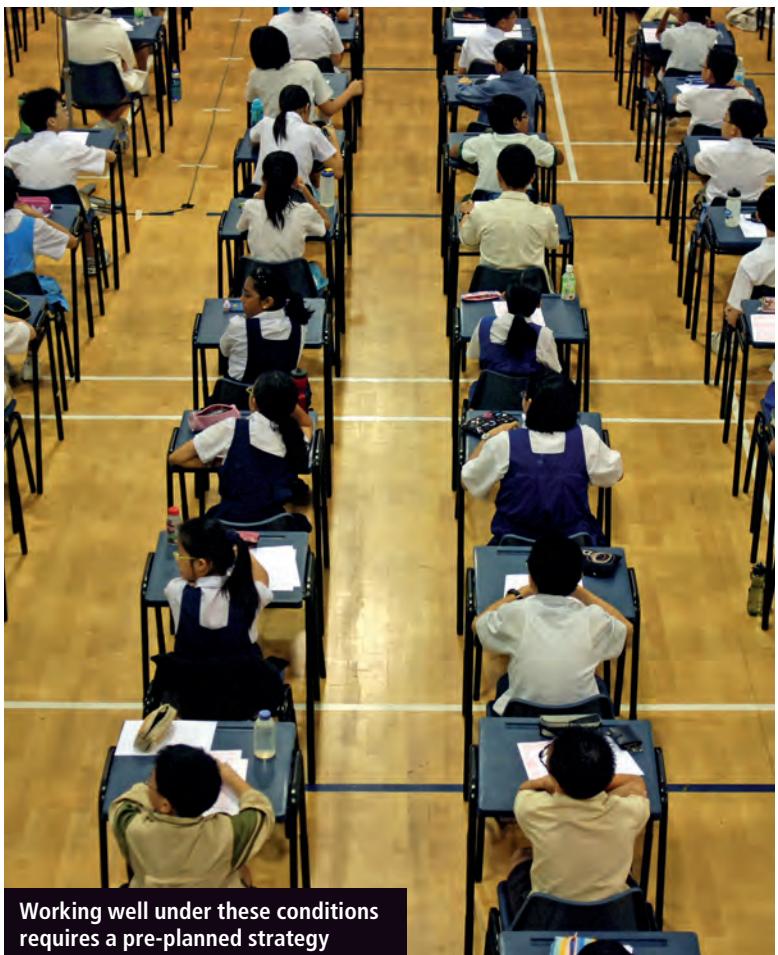
Skill	Description	Approximate overall weighting at A-level/%
AO1	Demonstrate knowledge and understanding of scientific ideas, processes, techniques and procedures	30–35
AO2	Apply knowledge and understanding of scientific ideas, processes, techniques and procedures: <ul style="list-style-type: none">• in a theoretical context• in a practical context• when handling qualitative data• when handling quantitative data	40–45
AO3	Analyse, interpret and evaluate scientific information, ideas and evidence, including in relation to issues, to: <ul style="list-style-type: none">• make judgements and reach conclusions• develop and refine practical design and procedures	25–30

Why an exam strategy?

Few of us work best under examination conditions. You will be nervous, and this can lead to you making mistakes. You need to stay calm to ensure you gain the most marks you can in the available time. Few students feel equally confident in their understanding of every skill and topic in their biology specification. A good strategy, therefore, is to ensure you gain marks that play to your strengths early on in the exam time. Knowing the subject content covered by an exam paper and the type of questions it will contain, you can plan in advance how you will go about answering it.

Table 2 Few individual exam papers test all the topics in the subject content of specifications

Exam board	Specification name (and number)	Paper number	Topics/modules/components tested	For information about question styles, see specification page
AQA	Biology (7402)	1	Topics 1 to 4	9
		2	Topics 5 to 8	
		3	All topics	
Edexcel	A (Salters–Nuffield) (9BN0)	1	Topics 1 to 6	1 to 3
		2	Topics 1 to 4 and 7 and 8	
		3	All topics	
	B (9BIO)	1	Topics 1 to 7	1 to 3
		2	Topics 1 to 4 and 8 to 10	
		3	All topics	
OCR	A (H420)	1	Modules 1, 2, 3 and 5	52
		2	Modules 1, 2, 4 and 6	
		3	All modules	
	B (Advancing Biology) (H422)	1	All modules 1 to 5	55
		2	All modules 1 to 5	
		3	All modules 1 to 5	
SQA	Higher Biology (C807 76)	1	All content	1 and 21 to 22
		2	All content	
WJEC Eduqas	Biology	1	Core concepts plus component 1	2
		2	Core concepts plus component 2	
		3	Core concepts plus component 3 and a choice of 1 of 3 options	



Working well under these conditions requires a pre-planned strategy

A topic-based approach

Suppose Question 1 on the paper is based on a topic you have always found difficult. What do you do? Do you struggle through it, determined to beat it? Or do you decide to go to the next question to see which topic that tests? Bear in mind that you hope to gain as many marks as you can in the available time. Struggling with a hard topic early in the exam paper eats away at the time before you even see the other questions.

Instead, you could spend the first few minutes of the exam skimming through all the questions, noting which topics are tested. You might find that the fifth question is based on your favourite topic and that the seventh question is based on your second favourite topic. Why wouldn't you do those questions first and leave answering Question 1 until later? If your recall is sound, you will know you are picking up marks, your confidence will grow, and your nervousness will lessen.

A skills-based approach

Suppose you perform best when answering free-response questions that test AO1. Why not answer them first? If the last question on the paper happens to be a high-scoring, free-response question testing AO1, you can start at the back of the paper, like many of my students did. Not all tests of AO1 are high-scoring, though. The early parts of longer, structured questions or, in some papers, multiple-choice questions, also test AO1. You can hop through the paper answering these, picking up a few marks with each answer.

The same applies to questions testing AO2 and AO3. If these questions test your strongest skills, answer them first. In this case, you will head for the questions with tables of data or graphs (usually testing AO2) or

questions related to practical investigations (usually testing AO3). In all cases, you will be confident that you are picking up marks fairly quickly. In addition, you will be unlikely to leave the examination hall having missed a question that you could easily have answered but failed to read because you were stuck on questions that appeared earlier in the paper. All this is reassuring and will calm your nerves.

Your exam strategy

Whatever your strategy for tackling the exam paper, you will not gain high marks unless you take the following approach to individual questions.

■ **Take note of the mark tariff.** Exam papers show the mark tariff for each question. You should use this to judge how much you need to do in order to gain those marks. Suppose a question asks, 'Name the cell organelle in which aerobic respiration occurs (1 mark)'. To gain the mark, all you need write is 'mitochondrion'. Anything else you write gains no further mark and is a waste of your precious exam time.

■ **Watch the time.** This is linked to the mark tariff. Allowing for thinking time, you should find that you have about 1 minute for each mark. If you find you are spending longer than this on an individual question, you could be answering more than is required. This might leave you too little time to answer other questions and each unanswered question will score zero marks. Watching the time is particularly important in questions with a high mark tariff. Many exam papers have questions with a tariff that is over 5 marks. Be careful to stick to the 'one mark per minute' guide when answering these questions.

■ **Analyse each question before answering.** Every year, examiners report that students failed to gain marks because they didn't answer the question that had been asked. This usually means students have not followed the **command words**.

- **Describe:** you must give an account of something you recall (AO1) or of what is shown by information (artwork or data) given as **stimulus material** (AO2).
- **Explain:** you must give reasons for something.
- **Evaluate:** you must write at least one statement that supports a given conclusion or experimental procedure and at least one statement that does not support it.
- **Use the information given:** you must refer specifically to information from the question.

Remember, you are planning how to gain marks, not how to lose them.

If you have prepared thoroughly, every question in the examination paper should be accessible to you. Your exam strategy is simply a way to focus on how you will gain the most marks you can in the time available.

Finally, a warning. Just as with revision, don't leave planning your examination strategy until the last minute.

Dr Martin Rowland taught and examined A-level biology for many years. He is the author of several biology textbooks, which you can find by visiting www.hoddereducation.co.uk

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Gannet takes the plunge



The northern gannet (*Morus bassanus*) is the UK's largest seabird. With a wing span of 1.8 m it is the largest seabird found in the North Atlantic. Vast colonies of these birds are found on the islands off Canada's east coast near the Gulf of St Lawrence. However, the biggest colonies occur in western Europe. Bass Rock in the North Sea is estimated to home around 150 000 birds. Their range spreads from the equator to northern Russia with breeding colonies largely in their northern territories. The birds are dependent on access to mackerel and herring shoals, influenced by the Gulf Stream.

Gannets breed from April to mid-June, raising just one chick a year. Pairs are monogamous and re-bond with each other each year after returning from migration. Gannets demonstrate 'differential migration'. A 2009 study of ringed birds from the Channel Islands showed that younger birds travelled further and were more likely to travel south than their older relatives.

Gannets are perhaps best known for their amazing behavioural feats of diving for fish. Typically, they dive into the sea from a height of up to 30 m, achieving reported entry speeds of 100 km h⁻¹. With the initial dive reaching up to 10 m and with additional swimming, the birds can reach depths in excess of 24 m. Fascinating adaptations allow them to achieve the dives. These include nostrils inside their bills, spongy bone plates that protect the skull, and subcutaneous air-sacs, which minimise impact.

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Further reading

BBC film exploring the adaptations of feeding in gannets and their interactions with dolphins:
https://youtu.be/1Cp1n_vPvYY

Short film of the gannet colony at Bass Rock:
<https://youtu.be/F30TFQGNFXc>

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