SANDY B. PRIMROSE

BIOMIMETICS

NATURE-INSPIRED DESIGN AND INNOVATION

WILEY Blackwell

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The Beginnings of Biomimetics

It's not what you look at that matters, it is what you see.

Henry David Thoreau

At its simplest, biomimetics is the design and production of materials, structures, and systems that are modelled on biological entities and processes. The concept of biomimetics stems from the realization that microbes, plants, and animals have been continuously evolving to cope with environmental and other challenges. The design challenges associated with vision, movement in diverse environments, temperature control, and detection of predators and/or prey have already been solved in a myriad ways over millions of years of evolution, providing rich opportunities for development of biomimetic and bioinspired materials. The diversity in form and function of living things is such that they have evolved solutions to most of the challenges that face humans today. We just have to look for those solutions! Janine Benyus pioneered this approach to problem solving in her 1997 book entitled *Biomimicry: Innovation Inspired by Nature* – biomimicry being an alternative name for biomimetics.

The term biomimetics was devised over 40 years ago by American physicist Otto Schmitt. For him, biomimetics represented a biological approach to engineering in contrast to 'biophysics', which describes an engineering and physical approach to biology. A related term is 'bionics' but, following the 1974 television series *The Six Million Dollar Man*, this has come to mean electronically operated artificial body parts. In 2015, George Whitesides of Harvard University pointed out that scientists often take inspiration from the capabilities of plants and animals and attempt to mimic some of their functionality using simplified and probably different mechanisms. He calls this 'bioinspiration' and defines it as 'using phenomena in biology to stimulate research in non-biological research and technology'. The subject matter covered in this book is a mixture of bioinspiration and biomimetics. The novice reader might be interested to know that there is a journal that covers these two topics and, unsurprisingly, it is called *Bioinspiration and Biomimetics*.

Benyus has pointed out that there are two types of biomimetics: forward and reverse (Figure 1.1). In forward biomimetics, we see an innovation that has evolved in nature and wonder how we might use it. A good example of this is the invention of Velcro® (see Section 1.2). In reverse biomimetics, we are faced with a problem and turn to nature for a solution (Figure 1.2). Many examples of this approach are presented in the chapters that follow including the design of the Japanese 'bullet trains' (Chapter 2) and glass that prevents bird strikes (Chapter 3).

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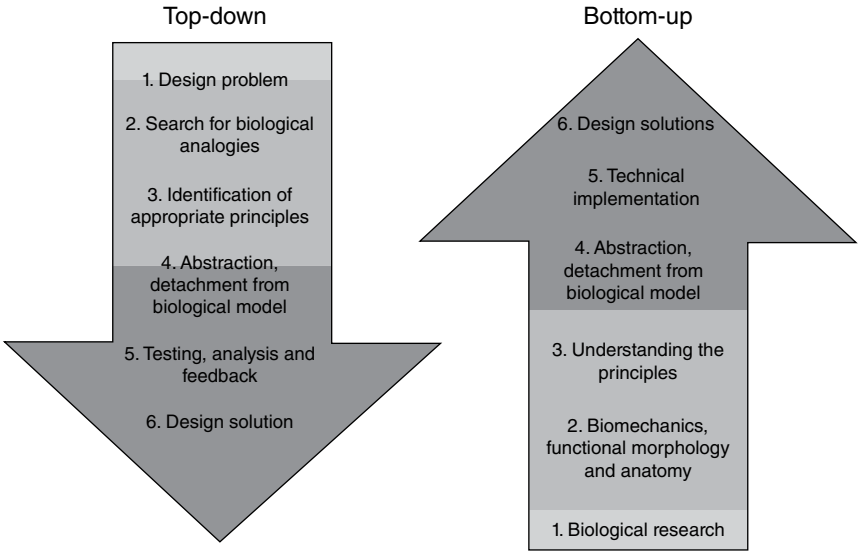

Figure 1.1 Biomimetics approaches. *Source:* Reproduced courtesy of the Biomimicry Institute.

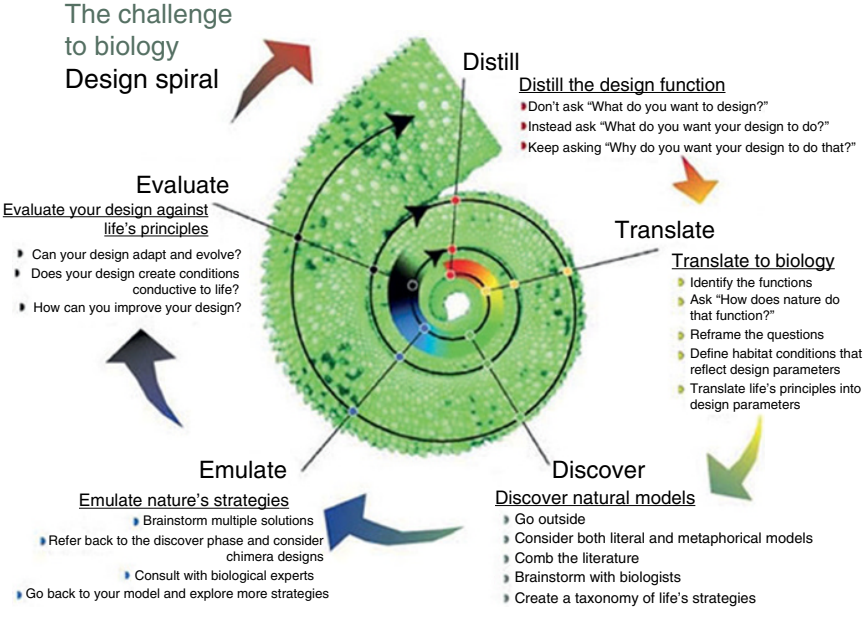

Figure 1.2 How to use reverse biomimicry in product design. *Source:* Reproduced courtesy of the Biomimicry Institute.

1.1 Early Attempts at Biomimicry: The Influence of Birds on the Development of Aircraft

The earliest recorded attempts at biomimicry relate to manned flight. The ninth century poet Abbas ibn Firnas and the eleventh century monk Eilmer of Malmesbury attempted to fly by flapping wings that were attached to their arms. In 1485, Leonardo da Vinci began to study the flight of birds. He realized that humans are too heavy, and not strong enough, to fly using wings attached to their arms. He drew sketches of an ornithopter – an aircraft that flies by flapping its wings. The drawings show an aviator lying on a plank of wood and working two large membranous wings using hand levers, foot pedals, and a system of pulleys. There is no record of da Vinci constructing and testing such a device but, in 1841, a man called Manojlo did just that. He took off from the roof of the Dumrukhana (Import Tax Office) in Belgrade and fortuitously survived as he landed in a heap of snow. We will return to the concept of ornithopters in Chapter 2.

The first person to make well-documented, repeated, successful flights was Otto Lilienthal. A German pioneer of aviation, he became known as the 'flying man'. Initially he tried, like others before him, to fly by flapping wings he had strapped to his arms. After training as an engineer, he began to study the flight of birds, especially storks, and described the aerodynamics of their wings. Based on this research on bird flight, he developed a glider in which he could change the centre of gravity by shifting his body, much as hang gliders do today. Unfortunately, his gliders were difficult to manoeuvre and tended to pitch down, leading to loss of flight. One reason for this was that he held the glider by his shoulders rather than hanging from it like a modern hang glider. Only his legs and lower body could be moved and this limited the amount of weight shift that could be achieved. Nevertheless, in 1893 he achieved flight distances of up to 820 feet (250 m). He had a total flying time of five hours by the time he died in a gliding crash in 1896.

Across the Atlantic in Dayton, Ohio (USA), brothers Orville and Wilbur Wright were reading about the exploits of Otto Lilienthal and his flights in gliders. They later said that Lilienthal's death was the catalyst for their own work on manned flight. Soon they were reading everything they could find about aeronautics, including the work of the 'father of aviation', Sir George Cayley. Cayley identified the four forces that act on a heavier-than-air flying vehicle: weight, lift, drag, and thrust. Modern aeroplane design is based on these discoveries and on the importance of having a curvature of the upper surface of the wings (Chapter 2, Some basic fluid dynamics box). In 1799, long before Lilienthal, Caley may have designed the first glider to carry a human aloft but this has not been verified.

One advantage the Wright brothers had over their predecessors who were attempting flight was the recent invention of the internal combustion engine. This could be used to generate the thrust that was clearly not possible using flapping wings. Despite Lilienthal's fate, the Wright brothers practised gliding so they could master the art of control before attempting motor-driven flight. They realized that Lilienthal's use of shifting body weight to change direction was inadequate. Wilbur had spent a lot of time observing birds and he noted that they changed the angle of the ends of their wings to make their bodies turn left or right. The brothers puzzled over how this could be achieved and eventually came up with wing distortion or 'wing-warping'. In July 1899 the concept of wing warping was put to the test

in a biplane kite with a five-foot wingspan. When the wings were twisted in opposite directions, the unequal lift made the kite turn in the direction of the lower end.

Two further modifications were made to the early gliders. To protect the pilot from a nosedive and crash like the one that killed Lilienthal, the Wright brothers mounted an elevator at the front of the glider. By moving the elevator, they could make the craft go up or down as they wished. In early flights, they noticed that wing warping created a differential drag at the wingtips. Greater lift at one end of the wing also increased drag. This slowed that end of the wing, making the glider swivel so that the nose pointed away from the turn ('yawing'). This was corrected by adding a rear rudder. Once they had mastered flying in their gliders, the Wright brothers added engine-powered propellers and made the first ever powered, manned flight in December 1903.

In mid-1910, the Wright brothers made a further change to the design of their aeroplanes. They moved the horizontal elevator from the front to the back because this made the aeroplane easier to control. Control became increasingly important as higher speeds grew more common. The Wright brothers found out about elevators and their optimum positioning by trial and error. Similarly, they mounted the rudder on a tailfin. Had they studied whales or dolphins in the same way as they had studied birds in flight, then they might have reached the optimum design sooner. Both animals have a dorsal fin that acts as a stabilizer or rudder and they move up or down in the water by means of their tails or flukes.

1.2 The Fathers of Modern Biomimetics: Percy Shaw and George de Mestral

Ask 1000 people in the UK what Percy Shaw invented and it is likely that none of them will know. This is somewhat surprising given that his invention of the reflective road studs, more commonly known as 'catseyes™', has saved the lives of thousands of road users by lighting the way along roads in the dark. There are several stories about how he came up with the idea. The most relevant in the context of biomimicry may be apocryphal but it perfectly illustrates the principle of copying function from nature. It involves a drive that Shaw did one night in 1934 along a very dangerous road in Yorkshire that had a very steep drop on one side. At one point he would have driven off the road if it were not for a cat sitting on a fence. The eyes of the cat reflected his headlights and he was able to take corrective action. Soon he had set up a company called Reflecting Roadstuds Ltd and sales of his products took off during the blackout enforced during the Second World War.

There are other versions of how Shaw came up with the idea of 'catseyes' and some of them have no relation to biomimetics. However, an early commercial product that truly was inspired by nature is the hook and loop fastener. The inventor was the Swiss engineer George de Mestral. In 1941, he had been out hunting with his dog Milka and on his return home noted that burdock burrs (seeds) had stuck to his clothes and the fur of the dog. Curious about the attachment mechanism, he examined the burrs using a microscope and noted that they were covered with hundreds of tiny hooks (Figure 1.3). A burr is spherical to maximize the angles by which it might attach to a passing animal and thus be dispersed. What de Mestral conceived was a linear piece of material with hooks that would stick to any rough material. That is, a simple fastener that, unlike a zip fastener or 'hooks and eyes',

Figure 1.3 Close-up photo of a burr showing the microscopic hooks. *Source:* https://commons.wikimedia.org/wiki/File:Bur_Macro_BlackBg.jpg.

did not require two surfaces to be lined up precisely. Subsequently he modified his fastener concept so that one surface had the hooks and the other surface had the loops with which the hooks would engage.

Like many inventors before and after him, de Mestral discovered that turning his idea into reality was much more difficult than he at first realized. Initially he went to Lyon (France) where a weaver made him cotton strips with hooks and loops. These worked as he envisaged but cotton is soft and the fastener wore out quickly with repeated use. So, de Mestral decided to try nylon, a tough synthetic fibre that had been invented in 1937. He found that nylon thread, when woven in loops and heat-treated, retains its shape and is resilient but he still need to create the hooks. He was about to abandon his invention when he came up with the solution: he trimmed the top off the loops with a pair of shears, thus creating hooks that would match up perfectly with the loops (Figure 1.4). But de Mestral's problems were not over because he had to find a way of mechanizing the manufacturing process. That took until 1951, 10 years after he first conceived of 'Velcro'[1], as he called his hook and loop fasteners.

Once the problem of mass manufacturing Velcro had been solved, de Mestral expected that there would be a high demand for his 'zipperless zipper'. It was not to be. Early versions of the product looked like they had been manufactured from left-over bits of cheap fabric and so were of little interest to clothing manufacturers. It was the 1960s before there was a commercial breakthrough: Velcro was used to help astronauts manoeuvre in and out of bulky spacesuits. This was followed by its use in ski clothing, which can also be bulky, and then in diving gear. Today, the use of hook and loop fasteners is widespread.

The story of Velcro illustrates perfectly the different stages in developing a new product from concept to commercialization. First, one must show the feasibility of the concept, and

Figure 1.4 The structure of hook and loop fasteners.

for Velcro this was achieved with the early cotton versions. Next, it is necessary to show practicability: can a version be made that functions reliably and reproducibly? The nylon versions of Velcro did this. Finally, it should be possible to develop a reproducible and cost-effective manufacturing process. For de Mestral, this turned out to be the hardest part of the development process. What might not be realized is that de Mestral was a pioneer in new product development and it is not surprising that it took 10 years to get Velcro ready for the market. Today, most product development is carried out by companies and not by individuals, there is a wealth of literature on the subject, and also specialist consultancies to provide help.

De Mestral was disappointed by the initial lack of demand for his revolutionary new product and this problem still haunts inventors today. Essentially, he had a solution in search of a problem because his product did not fit the needs of his perceived market (fashion clothing). Once feasibility has been established, the smart inventor will undertake market research to establish the real needs of the marketplace and then develop a version of the product that meets these needs. But, de Mestral was a pioneer who cannot be criticized for what he did given the period when he carried out his development and the fact that he did it as an individual.

Relevant Innovations Described in Other Chapters

The new generation of ornithopters (Chapter 2, Section 2.11).

Note

1 Velcro is a portmanteau of the French words velours (velvet) and crochet (hook). The name Velcro is covered by trademarks and should only be applied to material manufactured and sold by the Velcro Company. Similar materials made by other companies should be called hook and loop fasteners but in the minds of the public they are synonymous with Velcro.

Suggested Reading

Khan, A. (2017). *Adapt: How We Can Learn from Nature's Strangest Inventions*. London: Atlantic Books. This title is scientifically incorrect. Nature does not invent things, for invention requires conscious thought, but generates them through evolution and selection.

Müller, R., Abaid, N., Boreyko, J.B. et al. (2018). Biodiversifying bioinspiration. *Bioinspiration and Biomimetics* https://doi.org/10.1088/1748-3190/aac96a.

Whitesides, G.M. (2015). Bioinspiration: something for everyone. *Interface Focus* https://doi.org/10.1098/rsfs.2015.0031.

2

Transport, Motion, and Energy

When Nature has work to be done, she creates a genius to do it.

Ralph Waldo Emerson

2.1 Birds and Bullet Trains

Almost everyone reading this book will have heard of the Shinkansen. The word in Japanese means 'new trunkline', which is what it was when constructed to speed up the train journeys people made during the Tokyo Olympic Games in 1964. Outside of Japan it is colloquially known as the 'bullet train'. Initially, trains on the Shinkansen travelled at speeds of 217 km h^{-1} when trains in Europe and the rest of the world rarely reached 161 km h^{-1}. Later the speed of the bullet trains increased significantly and today up to 13 trains per hour in each direction run at 240–320 km h^{-1}. The speed of these trains has so caught the imagination of the public that, if asked, any new visitor to Japan will say that they want to ride a bullet train. Europe, particularly France with its *Trains à Grand Vitesse* (TGV), and China have now caught up with Japan in the use of high-speed trains but it is Japan that has flagship status.

Not just tourists appreciate the bullet trains. For business people, bullet trains provide a quick and efficient way of travelling between the major cities in Japan that is more convenient than domestic flights. Despite the obvious advantages of bullet trains, the loud noise they generate is a major downside that has affected people living up to 450 m from the track. In a country as heavily populated as Japan, this was a major issue and led to laws that prohibited trains from producing noise levels of more than 70 dB (Figure 2.1) when travelling through populated areas.

Any high-speed train generates noise from three sources: the interaction of the wheels with the track, the interaction of the pantograph with the overhead electric wires (all high-speed trains are electric-powered), and the sonic booms created when travelling in confined spaces. The first of these problems is relatively easy to solve by modifying the track bed so that it absorbs most of the sound. Solving the other two problems has proved more difficult but studying birds has provided the answers.

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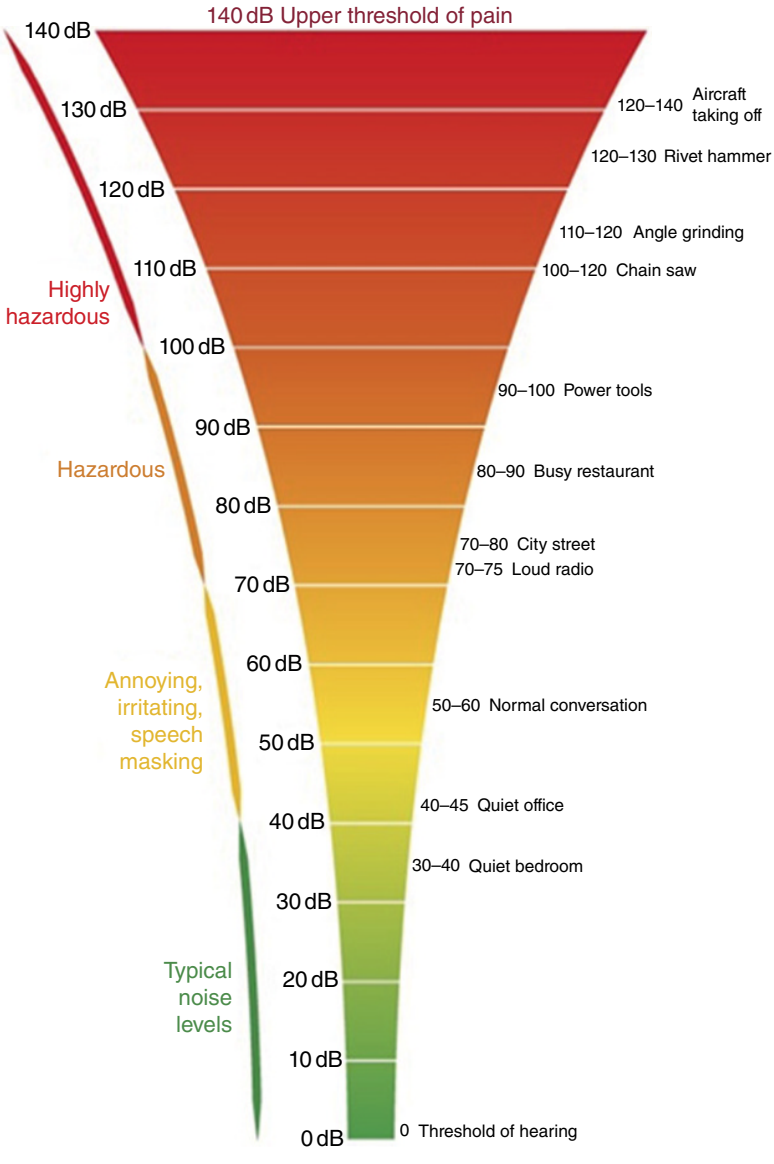


Figure 2.1 Noise produced by various activities.

When a vehicle is moving through open country, the air in front of it is pushed in all directions: sideways and upwards. When the vehicle enters a tunnel, the air is confined by the tunnel walls and is pushed in front of it. In effect, the vehicle is analogous to a piston moving in a cylinder (the tunnel). This piston effect is very pronounced in railway tunnels because the cross-sectional area of the train is large and often almost fills the tunnel cross-section. Anyone who has stood on an underground railway platform that does not have platform screen doors will have noticed the blast of air that precedes the arrival of the train.

This is the piston effect. The piston effect does not occur when cars enter road tunnels because here the cars have a small cross-sectional area compared to that of the tunnel.

One consequence of the piston effect is that the air in front of a moving train is compressed into a shock wave. The strength of this wave is proportional to the cube of the speed of the train. When a high-speed train exits a tunnel, the compressed air is free to expand and the expansion creates a loud noise known as *tunnel boom*: a shotgun-like thunderclap that can be heard over long distances. The perception of it by humans is analogous to the sonic boom from supersonic aircraft when they exceed the speed of sound. Tunnel boom also occurs when trains come out of railway cuttings at high speed and the problem is exacerbated in mountain valleys where sounds can echo. The principal limitation to increased train speeds in Japan was tunnel boom because the mountainous terrain requires frequent tunnels: half of the Shinkansen Line from Osaka to Hakata runs through tunnel sections. Eiji Nakatsu was the general manager responsible for technical development at the Japanese rail company JR-West. He knew that the secret to getting the company's trains to run faster was to make them quieter. The breakthrough for him came in 1990 when he attended a lecture on bird flight given by aircraft design engineer Seiichi Yajima. From Yajima he learned how much of current aircraft technology has been based on studies of the structures of birds and the function of these structures.

Nakatsu was a birdwatcher and he had observed that a kingfisher can dive at high speed from one fluid (air) into another that is 800 times denser (water) with barely a splash. He surmised that the shape of its beak was what allowed the kingfisher to enter the water so cleanly. The JR-West team analysed the kingfisher's beak to determine its cross-section and its length relative to the size of the bird. The design team then developed various nose shapes for the bullet trains using this information and tested their properties in wind tunnels. These tests confirmed that the kingfisher bill was the most efficient of all those tested – and by a wide margin. Prototypes were built and tested on trains and the final version selected was a nose that is 15 m long and resembles a kingfisher's beak (Figure 2.2). In operation, this nose greatly reduces tunnel boom because it has 30% less air resistance than its predecessor. This in turn has led to a 13% reduction in power consumption to maintain the same speed as its predecessor. Passenger satisfaction also increased.

Figure 2.2 A kingfisher's beak inspired the nose of the bullet train. *Source:* https://www.flickr.com/photos/48975388@N07/42189044932.

However, the main reason for the bullet trains exceeding the 70 dB noise limit was the noise from the pantographs. The cause of the noise was air rushing over the struts and linkages and forming what is known as a Karman vortex street. Karman vortices form whenever a single body breaks up the flow of air (Figure 2.3). Alternate and opposite air eddies swirl downstream of the obstruction, swinging back and forth as the force of one and then the other dominates. Karman vortices are created at all scales, from islands in the ocean to car aerials and are responsible for the 'singing' of telephone wires. Nakatsu's solution to the problem of Karman vortices came from studying the flight of owls.

Most birds in flight generate high-frequency sound that is heard by humans and other animals. Owls are the exception. They are silent predators capable of flying very close to their prey without being detected. Owls can fly silently because of the structure of their wings. Usually, when air rushes over a bird's wing, it creates a 'gushing' noise because large areas of air turbulence build up. The leading edge of an owl's wing is serrated and the serrations break up the air flow into smaller flows that are less turbulent. This reduces the noise of the flowing air, particularly when the wing is at a steep angle as it would be when the owl is coming in to strike its prey.

Nakatsu's team spent four years redesigning the pantograph to try and mimic an owl's wings. Eventually serrations were inscribed on the main part of the pantograph and this succeeded in reducing the noise enough to meet the 70 dB limit. This technology is known as a 'vortex generator' and it has been applied in diverse areas such as aircraft wings and the boots of professional skaters.

There was yet another bird-inspired modification. The body of the Adelie penguin is shaped like a spindle and this allows it to move effortlessly through water to catch fish. So, the pantograph was modified further by re-shaping the supporting shaft to make it look like a penguin's body (Figure 2.4). This modification lowered its wind resistance as well as the noise it produced and it will have given some energy savings.

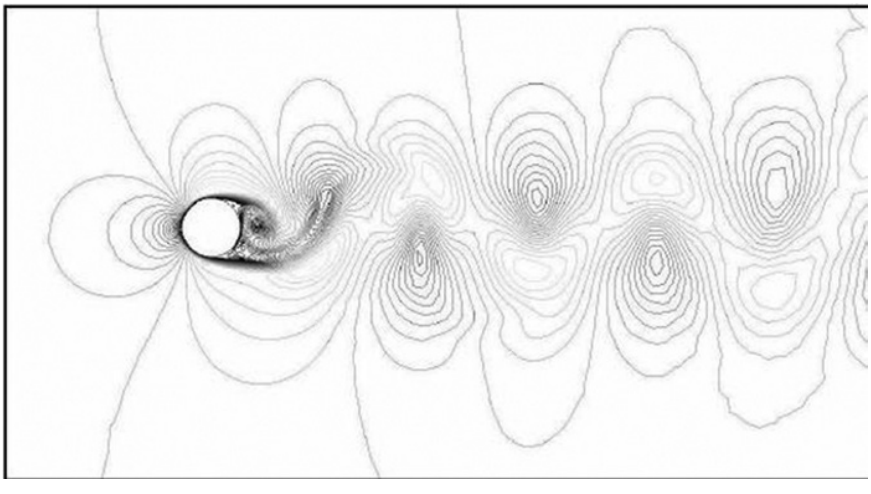


Figure 2.3 Karman vortex caused by a tower. *Source:* Reproduced courtesy of NASA.

Figure 2.4 Conventional pantograph (top) and Shinkansen pantograph (bottom).

2.2 More Owl-Inspired Noise Reduction

Owls fly so silently that detecting them at night is very difficult even with the most sensitive microphones. Scientists have identified three features of owl wings that act to reduce noise. The first of these is the serrations on the leading edge of the wings and the best-known application is on the Shikansen pantographs as noted in the previous section. Another application comes from the world of computing. Regardless of their format, computers use a significant amount of power and so generate heat. This heat often is dissipated with the

use of in-built fans but these fans can be noisy. A traditional fan blade has a leading edge that is more or less flat. After seeing an owl in flight, an engineer from Lenovo designed a fan blade with notched leading edges for their ThinkPad and this reduced the noise by 3 dB.

The serrations on the leading edge generate smaller airflows that roll along the owl's wing towards the trailing edge which, unlike in other birds, is comprised of a flexible fringe. This fringe breaks up the air further as it flows over the trailing edge, resulting in a large reduction in aerodynamic noise, particularly at low speed. A German manufacturer of fan blades, Ziehl-Abegg, has developed a series of low-noise 'Owlet' blades that have serrations on their trailing edge to mimic the fringes on owl wings.

The third, unique feature of owl wings that leads to noise reduction is the velvet-like structure on the wing surface. As seen under a microscope, the down consists of hairs that form a structure similar to that of a forest. The hairs initially rise almost perpendicular to the feather surface and then bend over in the flow direction to form a canopy. Justin Jaworski at Lehigh University in Pennsylvania has modelled this downy canopy to understand how it might reduce the noise generated by trailing edges. He has produced a three-dimensional plastic wing attachment that reduces wind turbine noise by 10 dB, no mean achievement, without affecting aerodynamic performance. Jaworski now is working with the US Office of Naval Research to develop a similar material that could reduce submarine noise without increasing drag.

Aeroplanes generate a lot of noise in flight and even more during take-off. It would be very satisfactory if the features used by owls to reduce noise could be applied to solve the problem of aircraft noise. However, bird flight differs from the flight of aircraft in two respects. First, birds have flexible wings and use these wings for different modes of flying such as gliding flight and flapping flight. Aircraft usually have fixed wings. Second, overall size differences mean that the aerodynamics of bird flight differ significantly from that of fixed wing aeroplanes. At best, bird flight can serve as a role model for drones.

Drones need to be highly manoeuvrable so that they can navigate close to obstacles. The wing surface needs to be maximized to achieve rapid changes of direction with a small turn radius; however, wings with a large surface area are sensitive to wind-induced turbulence. Wings with a small surface generate less resistance (frictional drag) allowing an aerial vehicle to fly faster and keep a constant forward speed in comparatively stronger headwinds. Birds solve this problem by altering the shape and size of their wings. This inspired Dario Floreano from the École Polytechnique Fédérale de Lausanne and his colleagues to develop a novel morphing wing for drones that is composed of artificial feathers. In flight, the wing shape can be changed rapidly giving the modified drone the expected aerodynamic performance.

2.3 Humpback Whales and Wind Turbines

Frank Fish runs the Liquid Life Laboratory at West Chester University in Pennsylvania. One day he was visiting a gallery in Boston that featured sculptures of animals, including one of a humpback whale. 'Look at that', he said to his wife, 'the sculptor put the bumps on the wrong side of the flippers'. The shop manager quickly put him right. She told him that the sculptor had a good knowledge of humpback whales and the bumps, or tubercles as

they are correctly known, were where they should be. She showed him a photograph of a humpback and Fish realized that the artist was correct (Figure 2.5). Fish was intrigued because everyone 'knew' that the leading edge of wings and hydrofoils had to be smooth. So, what were the tubercles doing on the front of the flippers?

Fish needed a sample of a humpback whale fin in order to study the function of the tubercles. He put in a request to the Smithsonian Museum. Eventually they called him to say that a dead whale had washed ashore in New Jersey. He was welcome to come and get a flipper but he would need to cut it off himself. Fish estimated that the fin would be about 6 ft (1.83 m) long, a tight fit for his hatchback car, but it was 10 ft (3.05 m) long. It took him hours to cut the fin into three pieces, each weighing more than 100 lb (45 kg). Once all the pieces were in the car, the rear end was sagging badly. He drove back to Pennsylvania in fear of being stopped by a State Trooper for driving an overloaded vehicle. What would a trooper make of rotting body parts in black plastic bags?

Fish and his colleagues made models of the whale flippers, with and without tubercles, and tested them in air tunnels. They made a significant discovery. When an aircraft wing is tilted into an airflow the oncoming wind generates lift. Increase the angle too much and the air rushing over the top of the wing becomes turbulent, tumbling over itself in undesirable eddies – the wing stalls. The smooth model flippers stalled at an angle of 12°, whereas

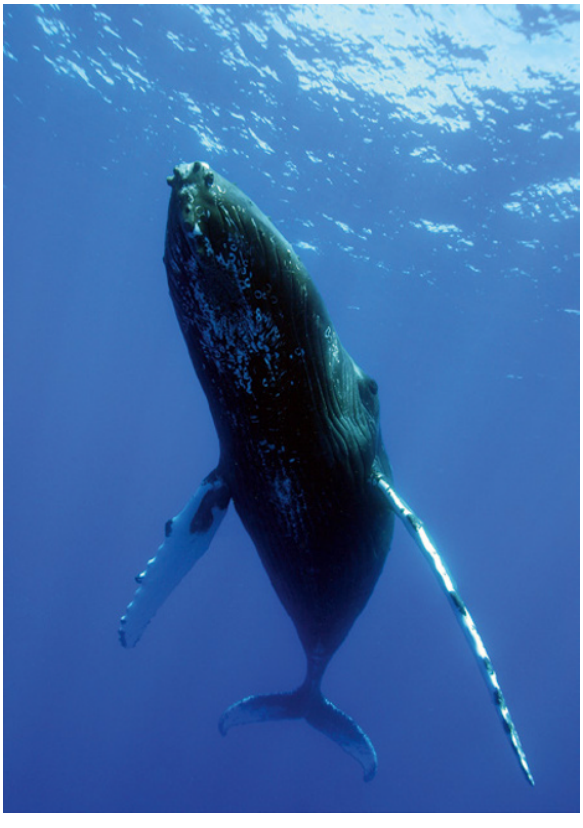


Figure 2.5 A humpback whale with tubercles on the leading edge of the flippers. *Source:* Reproduced courtesy of Ed Lyman, Hawaiian Islands Humpback Whale National Marine Sanctuary.

the ones with tubercles stalled at 16°. That is, the stalling speed increases by 40% when tubercles are present. For the humpback whale, an increase in stall speed equates to greater manoeuvrability, especially when catching fish.

Subsequent work by Fish and his colleague Phil Watts showed that tubercles on the leading edge of an aerofoil increased lift by nearly 5% and reduced the effects of air resistance (drag) by 40%. Another important finding was that when stalling did occur, aerofoils with tubercles experienced a gradual loss of lift. By contrast, aerofoils without tubercles experienced a sudden loss of lift. They also discovered that by varying the size, shape, and position of the tubercles it was possible to increase the stalling angle to 30°. Realizing that these discoveries had applications in a variety of industries, Fish and Watts teamed up with Canadian entrepreneur Stephen Dewar and founded WhalePower Corporation in 2005.

A simple application of the WhalePower technology is in industrial ventilation fans. If tubercles are added to the fan blades, the power consumption drops by 20%, they do a better job of circulating the air, and they generate less noise. A more important application is in the design of blades for wind turbines. At first sight, a wind turbine is a very simple structure but in reality the aerodynamics of power generation are very complex. The speed at which the blades rotate needs to be controlled if irreversible damage is not to occur. For example, the centrifugal force on the spinning blades increases as the square of the rotation speed. In addition, the power of the wind increases as the cube of the wind speed. This means that turbines have to be built to survive much higher wind loads (such as gusts of wind) than those from which they can practically generate power.

Modern wind turbines have been designed to produce power over a range of wind speeds. The cut-in speed is about 3–4 $m\,s^{-1}$ (8–9 $miles\,h^{-1}$) and the cut-out speed is around 25 $m\,s^{-1}$ (56 $miles\,h^{-1}$). All turbines have a maximum wind speed, known as the survival speed, which commonly is 60 $m\,s^{-1}$ (134 $miles\,h^{-1}$). By incorporating tubercle technology, the overall performance of wind turbines can be increased significantly. All wind turbines have a minimum speed of operation below which they will stop turning. They will start again only when the wind speed is sufficient to overcome the inertia of the turbine. With tubercle blades, the start-up speed is reduced meaning that power can be generated even when there is little wind and five tubercle blades can generate the same amount of electricity as 10 normal blades. A further advantage of tubercle technology is a reduction in noise. Anyone who has walked near a spinning wind turbine will have noticed the noise. This noise is caused principally by chattering of the tips of the blades. The presence of tubercles reduces this noise by 80% and, in some respects, they resemble the serrations on the wings of owls.

2.4 Fish Shoals and Wind Farms

Conventional wind turbines are like giant pinwheels with propeller-like blades. Their proper name is horizontal-axis wind turbines (HAWT). Many people consider HAWT to be eyesores, especially when they are located in areas of natural beauty. There are two other problems. First, each turbine in a wind farm needs to be some distance from its neighbours so that the wind field of one does not negatively affect the others. This means that an onshore wind farm requires a lot of land area. The second problem, as noted in the previous section, is the noise that wind farms generate.

Figure 2.6 Swirling pattern produced by shoals of fish. *Source:* Reproduced courtesy of Timothy Schaerf.

John Dabiri is a professor of aeronautics and bioengineering at Caltech in Southern California. Back in 2009, he was intrigued by the pattern of spinning vortices created by shoals of fish (Figure 2.6). When fish swim in a shoal, each individual fish uses the swirling currents generated by the other fish to swim more efficiently. Dabiri wondered what would happen to the output of a wind farm if its turbines were spaced like those of fishy vortices. In simulations, the energy output increased by a factor of 10.

Dabiri and his students then built a small wind farm of 24 turbines in the California desert (Figure 2.7). They showed that placing the turbines in a particular orientation in relation to one another profoundly improves their efficiency of energy generation. More important, their turbines look like eggbeaters (more correctly called Darrieus rotors) and the drive shaft is vertical. They are known as vertical-axis wind turbines (VAWTs). Compared with HAWTs, VAWTs require much less space and do not need to be as tall making the overall environmental impact much less.

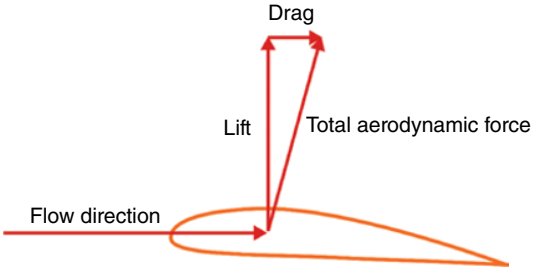
One organization that is very interested in Dabiri's ideas for wind farms is the US Department of Defense. They are one of the largest users of electricity in the world and want to make more use of renewable sources such as wind energy; however, large HAWTs can interfere with helicopter operations and radar signatures whereas VAWTs do so to a much lesser extent.

2.5 Liquid Movement in Nature: The Importance of Spirals

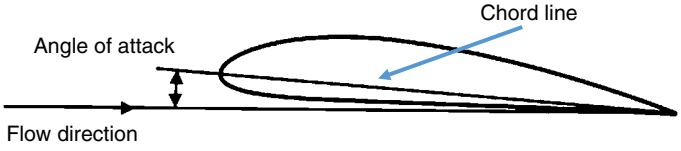
When engineers design systems to move liquids or gases, they use pumps that generate linear flow. Nature, on the other hand, moves fluids in three-dimensional logarithmic spirals: think of blood flow in the vascular system or air movement in tornados. Jay Harman, a keen naturalist, first noticed this as a boy and he reasoned that spiral flow must be more efficient than linear flow. This led him to found PAX Scientific as a means of exploiting the benefits of spiral flow. The company's air cooling fans are 15–50% more efficient than

Some Basic Fluid Dynamics

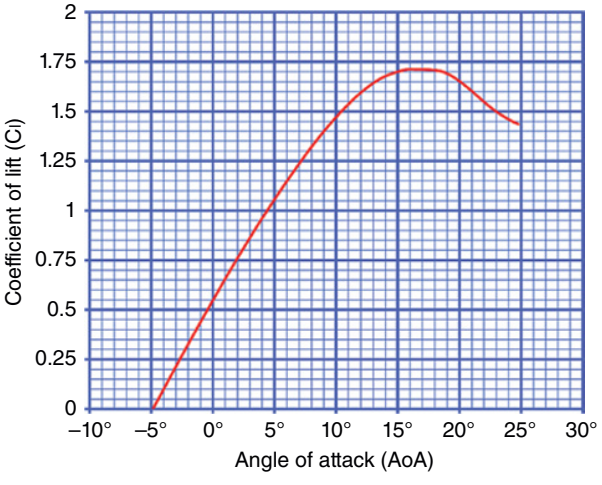
A fluid flowing past the surface of a body exerts a force on it. It makes no difference whether the fluid is flowing past a stationary body or the body is moving through a stationary volume of fluid. *Lift* is the component of this force that is perpendicular to the oncoming flow direction. Lift is always accompanied by a drag force, which is the component of the surface force parallel to the flow direction.



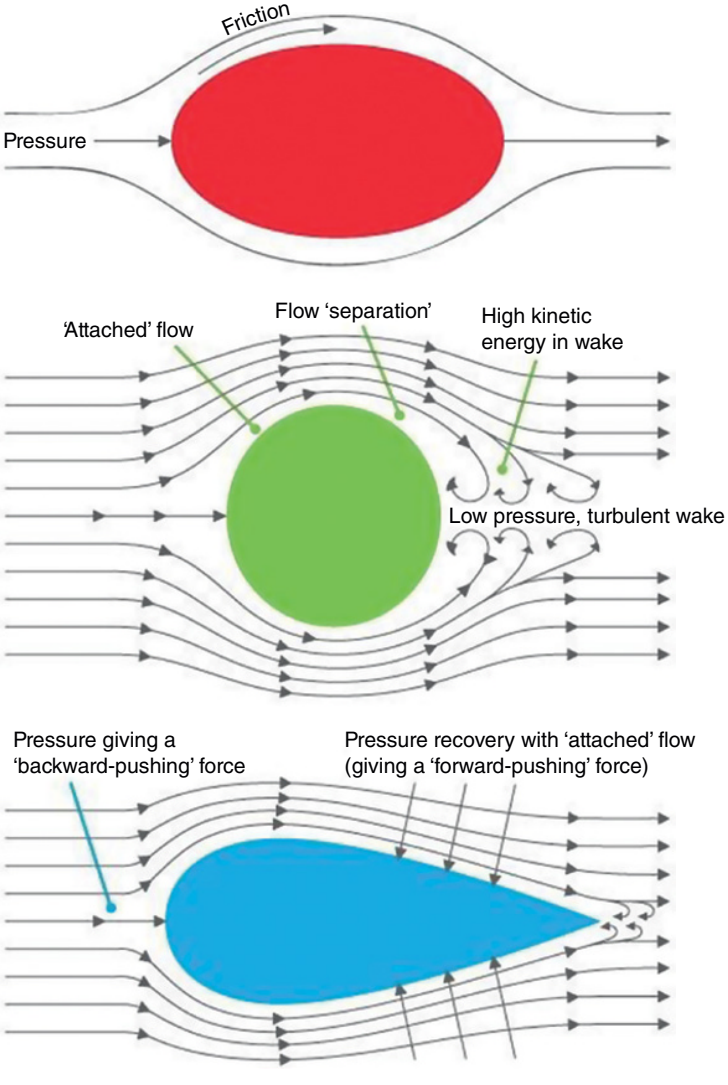
The amount of lift generated by a fixed-wing aircraft varies with the angle of attack. The latter is the angle between the chord line of the wing and the relative air direction. This typically is around 2° in cruising flight.



Increasing angle of attack is associated with increasing lift coefficient up to the maximum lift coefficient, after which lift coefficient decreases. The critical angle of attack is the angle of attack that produces the maximum lift coefficient. This also is known as the stall angle of attack. Readers will recall that there were two crashes of the newly introduced Boeing 737 MAX aircraft in 2018 and 2019. These aircraft were fitted with an automated system called Manoeuvring Characteristics Augmentation System (MCAS). This was supposed to automatically force down the nose of the plane if it was approaching the stall angle. A malfunction in the MCAS put the planes into unrecoverable dives and the pilots had not been shown how to override the system.



There are two types of drag acting on a moving object: pressure drag and friction drag. Pressure drag is caused by fluid (air, water) particles being more compressed on the front-facing surfaces and more spaced out on the back surfaces. Turbulent flow occurs when the layers of fluid separate away from the surface and begin to swirl. This increases the pressure drag. The shape of the moving object can have a significant impact on the magnitude of the drag.



As the layers of fluid move over a rough surface, the particles in the layer closest to the surface collide with the surface. This makes the particles slow down (friction drag) and right at the surface they stop completely. These particles then collide with fluid in layers further out and make them slow down as well. The speed of the particles is not affected further away from the surface. The region of fluid where the speed of the particles has been changed is called the *boundary layer*.

Figure 2.7 A vertical-axis wind turbine installation. *Source:* Reproduced courtesy of Professor Richard Cochrane, University of Exeter.

conventional fans and cut fan noise by up to 50%. Their water mixers are modelled on the calla lily (*Zantedeschia aethiopica*) that replicates nature's spiral flow pattern.

Intimal hyperplasia is the deposition of fatty substances that is the leading cause of failure of the arterial stents and bypass grafts used to treat cardiovascular disease. Recognizing that flow in nature is helical, Colin Caro at London's Imperial College wondered what would happen if conventional straight stents were replaced with helical ones. Experimentally, it was found that conventional straight stents reduced arterial curvature and disturbed blood flow, creating areas of low wall shear where intimal hyperplasia predominantly developed. By contrast, a helical geometry maintained or imparted arterial curvature, promoted laminar swirling blood flow, and elevated wall shear to protect against the recurrence of abnormal narrowing of arteries and valves after corrective surgery (restenosis).

2.6 A Tree-Inspired Wind Turbine

In 2011, Jérôme Michaud-Larivière was sitting in the Luxembourg Gardens in Paris when he noticed that even though there was no wind, the leaves on the trees were shaking on their stems. Although the movement of each leaf was small, the total number of leaves on each tree is very large and so the total amount of energy involved must be great. How might this energy be captured? The answer is the Wind Tree, an aesthetic structure that can be located in urban areas and generate electricity for local use.

The key to the success of the Wind Tree is its multitudes of Aeroleafs. Each Aeroleaf is a micro wind turbine (Figure 2.8) which is mounted vertically (i.e. a VAWT) thereby minimizing space requirements and reducing noise. The Aeroleafs can take wind from any direction and because they are light and almost without inertia, their starting threshold is wind of $2\,m\,s^{-1}$ ($4.5\,miles\,h^{-1}$) versus $5\,m\,s^{-1}$ ($11\,miles^{-1}\,h$) for conventional turbines. This means that they can generate electricity with only the slightest breath of wind and will be active for 300 days versus 120–140 days for wind farms.

A Wind Tree (Figure 2.9) fitted with 54 Aeroleafs is about 10 m high and 8 m wide and can generate 5.4 kW of electricity. For each wind speed there is a corresponding optimum leaf rotation speed that provides the maximum power generation. In urban areas the wind speed can be extremely variable over very short distances. So, to leverage on each available

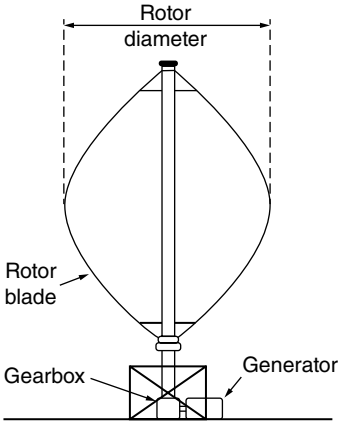


Figure 2.8 Design of a microturbine for a wind tree. *Source:* Reproduced courtesy of New World Wind.

Figure 2.9 A wind tree installation. *Source:* Reproduced courtesy of New World Wind.

Watt of energy, there is an electronic card with a micro-processor that keeps each Aeroleaf autonomous such that it rotates at the optimum speed for its own exposure. In practice, the maximum energy generated reaches a plateau at 18 m s^{-1} (40 miles h^{-1}).

2.7 More Fishy Developments

John Dabiri has spent a lot of time studying the design features in jellyfish and fish-like lampreys to see if they can provide solutions to engineering problems. Jellyfish are surprisingly efficient swimmers, more so than ordinary fish. Part of their efficiency comes from the way in which they generate a forward motion. They push off their own wake by generating vortex rings that resemble the smoke rings that cigar and cigarette smokers sometimes blow. They do this by squeezing their bodies which results in the expulsion of a jet of water. Based on this discovery, Dabiri has developed an underwater vehicle that is 50% more efficient than conventional propeller driven vehicles. The key operating principle was that the propellers were modified to generate vortex rings just like a jellyfish. This is of great interest to marine engineers given that much of the energy expended in moving a boat is overcoming the resistance of the water through which it is passing.

Fish still have a lot to teach us. Dabiri, working with Brad Gemmell at the University of Southern Florida, found yet another form of energy saving when studying lampreys in a water tank. They added many tiny glass beads to the water and illuminated them with a laser. With the aid of high-speed cameras, they could record the disturbance pattern of the beads caused by the swimming activities of the lampreys. They found that the undulating motion of the lampreys created a pocket of low pressure inside each bend in their bodies. Water ahead of the lampreys rushed to fill the low-pressure pockets and the lampreys were pulled ahead by a form of suction. Even more surprising, a similar effect was seen with jellyfish even though they have a different shape and swimming motion. This discovery had not been used in man-made objects at the time of writing.

2.8 A Fishy Failure: The Boxfish Car

In the mid-1990s, Mercedes Benz set out to build a vehicle that was aerodynamic, safe, efficient, and manoeuvrable based on a single design principle. The engineers turned to nature for inspiration and eventually discovered the boxfish (Figure 2.10). This is a species of fish found around tropical reefs and, as the name suggests, it is box-shaped, i.e. not unlike a car. The external skeleton, the carapace, is made of rigid, fused scales and the edges are called keels. What interested the engineers was, that despite its blocky shape, the boxfish has exceptionally low drag and can dart in and out of reefs. Also, the carapace supposedly had unique self-correcting stabilization properties directing the flow of water in such a way that fish is kept on course even in turbulent water. This stabilization was thought to come from vortices forming around the keels. At the same time, destabilizing forces generated by the boxy front gave it an instability that facilitated agile turns. This combination of spacious body, low drag and high stability and manoeuvrability made the boxfish an obvious model for a new car.

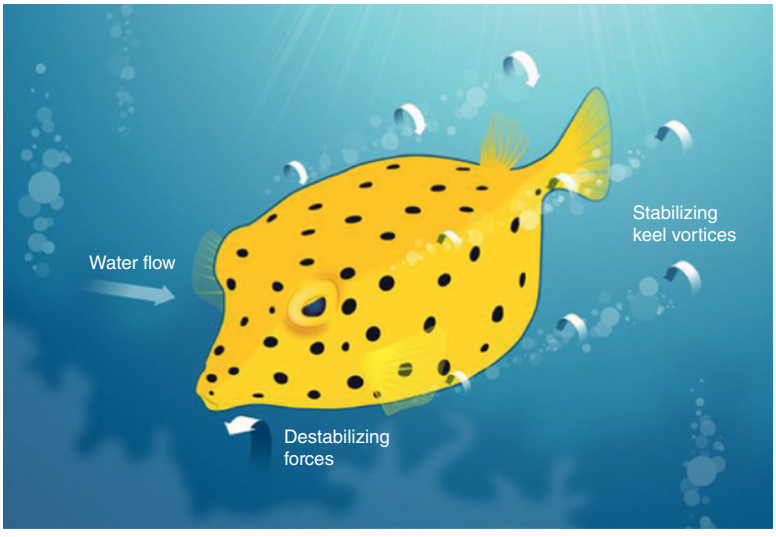


Figure 2.10 Schematic representation of a boxfish.

Figure 2.11 A car modelled on the boxfish by Mercedes Benz. *Source:* https://commons.wikimedia.org/wiki/File:Bioniccar_11.jpg.

In 2005, Mercedes Benz unveiled the Bionic (Figure 2.11), the car that was designed to resemble the boxfish. The new design generated a lot of attention and was touted as an outstanding example of biomimicry. However, it did not perform as expected. Unfortunately, the engineers at Mercedes Benz had not understood the fundamental hydrodynamic principles that govern boxfish movement. Research done 10 years later showed that the carapace promotes instability while swimming rather than minimizing it. Also, stability and manoeuvrability have competing requirements, i.e. body designs that are adapted for stable movement are not suitable for high manoeuvrability and vice versa. What the engineers had missed was the importance of the apparently insignificant fins on the tail and sides of the boxfish: they promote the stability in motion. The tail functions as a hyperflexible rudder allowing the fish to turn through 180° in its own length.

2.9 Fuel Efficiency Inspired by Sharks

Nothing induces more fear in a swimmer or surfer than the thought that they might be attacked by a shark. The sight of a dorsal fin of a shark off an Australian beach will catalyse the rapid evacuation of the water – and rightly so. Sharks have evolved to move very fast, reaching speeds up to 50 mph, and silently through the water. They are the ultimate speed machine. Many structural features of the shark contribute to its ability to swim very fast but it is its skin that has been of greatest interest.

Stroke the skin of a shark from head to tail and it feels very smooth. Stroke it in the opposite direction and it feels rough like sandpaper. The reason for the different feel is that the skin is covered in tiny V-shaped scales called denticles (Figure 2.12). These denticles have riblets which are microscopic grooves running down their length in alignment with water flow. These riblets prevent the formation of the turbulent swirls of slower water responsible for frictional drag. By lowering the frictional drag, the shark can swim faster and more stealthily. According to George Lauder, Professor of Ichthyology at Harvard University, the denticles have another effect. They create a low-pressure zone, or leading-edge vortex, as the water moves over the skin. This has the effect of increasing the thrust of the swimming shark by 'sucking' it forward.

Energy consumption is a major concern in the field of transportation and so anything that reduces drag will be beneficial. With this in mind, scientists have produced artificial denticles and applied them to different surfaces. When tested in the laboratory these denticle-inspired surfaces had a drag reduction of 10% compared to smooth surfaces. If this result were repeated with a ship or an aeroplane then the cost savings would be significant. What is more interesting are the results obtained when the denticles were applied to the upper surface of aerofoils. Not only was there a reduction in drag, as expected, but there was also an increase in lift at both low and high angles of attack. Overall, the increase in lift to drag ratio was over 300%. The benefits of denticles are applicable to many systems including wind turbine blades, helicopter blades, drones, and autonomous underwater vehicles.

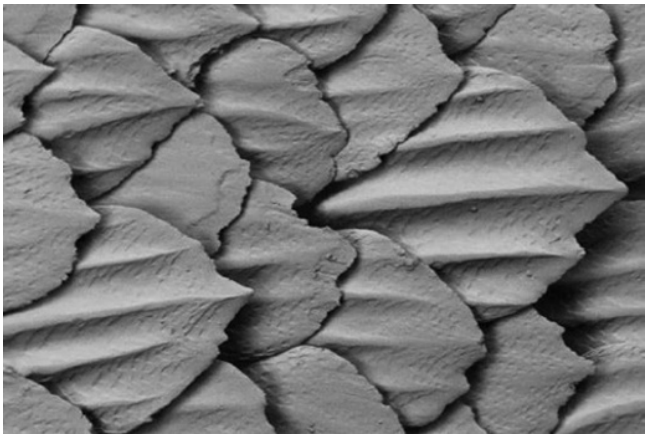


Figure 2.12 Magnified image of a shark denticle showing the riblets. *Source:* https://www.aerospace-technology.com/news/sharkskin-design-improves-aircraft-aerodynamics/.

At the time of writing, there were no reports of denticles being tested on full-sized vehicles. However, as far back as 1987, the US America's Cup team had already proven the benefits of riblets. Their yacht, *Stars and Stripes*, won 4–0 in the best of seven finals against Australia's *Kookaburra III*. A key factor in the US team's win came from technology developed by the US National Aeronautics and Space Administration (NASA) to improve fuel efficiency of aeroplanes. What NASA did was to cut V-shaped grooves, no deeper than a scratch, in the aircraft skin. These grooves, which are angled in the direction of the airflow, reduce the drag caused by the friction of turbulent airflow.

The first riblets were machined on flat aluminium sheets and tested in a NASA wind tunnel. When engineers of the 3M Company (St Paul, Minnesota) learned of the tests, they suggested moulding the riblets into a lightweight plastic film with an adhesive backing. This film (Scotchcal Brand Drag Reduction Film) could be pressed into place on an airplane, eliminating the need for welding and allowing a relatively inexpensive retrofitting to existing airplanes. NASA accepted 3M's offer to produce riblet tapes for research and used them in 1986 tests on a Learjet. In flight tests, the film riblets demonstrated a drag reduction capability of about 8%, similar to the results of wind tunnel tests using the metal sheets. The riblet technology then was applied to boats. One of the first was the US rowing shell that competed in the 1984 Summer Olympics at Los Angeles in the Four-oar-with-coxswain category. The shell's crew won a silver medal, the first US medal won in the event in many years. Another beneficiary was the racing yacht *Stars and Stripes*.

Another area of sport where riblets have made a difference is in swimming. The sportswear company Speedo designed swimsuits that were made from an artificial sharkskin material called 'Fastskin'. First introduced in 2000 for the Sydney Olympics, the suit was studded with tiny hydrofoils with V-shaped ridges like the 'dermal denticles' on sharkskin. It seemed to be a success: 83% of swimming medals at Sydney went to athletes wearing Fastskin. US swimmer Mark Phelps wore a Fastskin suit at the 2004 Olympic Games in Athens. He won six gold and two bronze medals making him the first swimmer in history to win eight medals at one Olympic Games. At the same Games, athletes wearing Fastskin suits broke 18 out of 26 Olympic swimming records. After the 2008 Olympic Games, the use of Fastskin suits was banned and this decision was supported by the medal-winning swimmers who had used them. Subsequent studies showed that wearing a Fastskin suit significantly reduced passive drag. This was associated with a decreased energy cost of submaximal swimming and an increased distance per stroke, at the same stroke rates, and reduced freestyle performance time.

Another application of sharkskin is its centuries-old use by sushi chefs in Japan. They use graters lined with sharkskin to grate wasabi root to a very fine consistency that enhances the flavour of the root.

2.10 Using Biology to Counteract Biofouling

Biofouling is the accumulation of microorganisms, algae, plants, and animals on wetted surfaces. It is a major problem in any industry with submersible equipment and it is a particular problem for shipping. Biofouling of ship's hulls (Figure 2.13) can increase both the hydrodynamic volume of a vessel and the hydrodynamic friction. The resulting increase in

Figure 2.13 Heavy biofouling of the hull of a yacht. *Source:* Reproduced courtesy of Emma Barton, Waldringfield Boatyard.

drag can be as much as 60%, which can decrease speeds by up to 10% and increase compensatory fuel consumption by up to 40%. With fuel typically making up to half of marine transport costs, effective antifouling measures would save the shipping industry around $60 billion per year worldwide. Increased fuel use due to biofouling contributes to adverse environmental effects by increasing emissions of carbon dioxide and sulphur dioxide by as much as 50%. Shipping companies historically have scheduled removal of biofouling to keep the problem manageable. However, the rate of accretion can vary widely between vessels and is accelerated in warm water, so it is difficult to predict when a ship's hull needs cleaning.

Biofouling is not just about energy consumption – it is another unintended way of introducing invasive aquatic species into an ecosystem. The US Coast Guard requires ships to have a Biofouling Management Plan on board, and the State of California established a Marine Invasive Species Program in 2003. Australia has developed several guidelines for biofouling, and in New Zealand the new Craft Risk Management Standard entered into force in May 2018.

Biofouling is nothing new. Plutarch (CE 46–120) had this to say about its impact on ship speed: 'when weeds, ooze, and filth stick upon its sides, the stroke of the ship is more obtuse and weak; and the water, coming upon this clammy matter, doth not so easily part from it; and this is the reason why they usually calk their ships.' The problem is even older

for ancient seafaring nations, such as the Phoenicians and Carthaginians (1500–300 BCE), used pitch and copper plating to prevent biofouling. In the eighteenth century, the Royal Navy solved the problem by covering the hulls of its ships with copper sheeting. On contact with salt water, the copper sheet developed a film of copper oxychloride that is toxic to living organisms. Also, the copper oxychloride slowly dissolves in water, taking any attached microorganisms with it, and the freshly exposed copper sheet quickly generates a new layer of oxychloride. The process was so successful that the term 'copper bottomed' came to mean something that was dependable or free of risk. Copper sheathing could no longer be used when wooden ships were replaced with iron ones in the nineteenth century. There was a good reason for this – when copper contacts with iron, it sets up an electrolytic cell.

One solution to biofouling is to paint the hulls of ships with compounds that are toxic to microorganisms. The most effective paint of this type contained a substance known as tributyl tin; unfortunately, this compound harms many marine organisms such as oysters and molluscs and causes gender changes in other marine creatures. The international maritime community has banned the use of tin-based antifouling coatings. Several non-toxic antifouling polymers have been developed that function by preventing the adhesion of microorganisms but these coatings do not stick well to iron hulls and wash off too quickly to be of real value. A solution to this problem came from a study of mussels (*Mytilus edulis*) and their amazing ability to remain attached to rocks and steel pilings even in stormy seas. This ability is due to their mussel adhesive proteins (see also Chapter 5, Section 5.2.1). Chemical mimics of these proteins have been made that literally 'stick like glue' to ship's hulls. The antifouling polymers can be chemically attached to the glue proteins and their functional life is being evaluated.

The structure of sharkskin and its effect on swimming speed was described earlier (Section 2.9). Tony Brennan, professor of material science and engineering at the University of Florida, realized that sharkskin is resistant to fouling and does not attract barnacles – unlike ship's hulls and structures immersed in water. This led him to develop Sharklet®, a material that has ridges and ravines at a micrometre scale (see Chapter 5, Section 5.1). When Sharklet was tested with zoospores (swimming stage) of the green alga *Ulva intestinalis*, colonization was reduced by 86% compared with the corresponding smooth surface. By making the surface more complex by using wrinkled hierarchical structures it was possible to keep the surface clean for over one year.

A European consortium known as AIRCOAT (Air Induced friction Reducing COATing) is investigating an alternative approach to preventing biofouling. Its objective is to make use of the Salvinia effect. The genus *Salvinia* comprises several species of free-floating rootless aquatic ferns. When submerged, the leaves of these ferns surround themselves with a layer of air to prevent water from touching the plant's surface. This is accomplished by tiny hydrophobic hairs that cover the leaf surfaces and that have hydrophilic tips, serving to connect the water to the plant at various intervals. This effectively attaches bubbles of air to the hydrophobic surface. The AIRCOAT consortium intends to implement this effect on a self-adhesive foil system. When applied to a ship's hull this foil should produce a thin permanent air layer that reduces the overall frictional drag while acting as a physical barrier between the water and the hull surface (Figure 2.14). This will generate two benefits, lower fuel consumption because of lower drag and minimal biofouling.

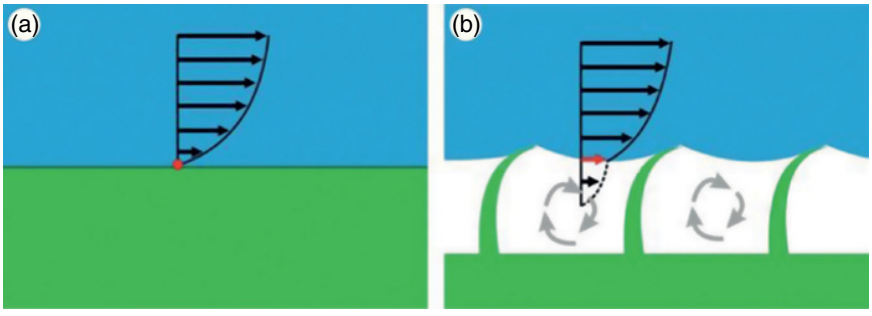


Figure 2.14 Schematic of the physical base for fluid drag reduction by air-retaining surfaces: (a) velocity profile of water on a solid surface and (b) velocity profile of water on an air-retaining surface. Owing to the 55 times lower viscosity of air compared with that of water, the air layer serves as a slip agent. *Source:* from Barthlott et al. (2016).

2.11 The New Generation of Ornithopters

Leonardo da Vinci may have been the first person to conceive of ornithopters[1] (Chapter 1) but as far as we know he never built one. One person who has is Adrian Thomas. He is professor of biomechanics at Oxford University, where he founded the Animal Flight Research Group in 1996. His research group studies the flight of insects using dragonflies, butterflies, hawkmoths, and desert locusts as models. Thomas believes the only way to understand how birds or insects fly is to build a vehicle using the same principles. His passion is flying and he was Britain's paragliding champion in 2006 and 2009. The first time he became a champion he had a wing designed to mimic the aerofoils of an albatross. In 2015, he teamed up with entrepreneur Alex Caccia and founded Animal Dynamics Limited. The mission of the company is to make small, unmanned aerial vehicles that outperform the non-military drones that are quadcopters, i.e. powered by four helicopter-style rotors.

Animal Dynamics has three vehicles in development: Stork, Skeeter, and Malolo. The most advanced of these is the Stork. It is based on powered paraglider wing technology and comprises a canopy, a vehicle with landing gear and a power unit. The Stork can carry loads of 30–100 kg up to 300 km (190 miles) at a speed of 70 km h^{-1} (45 miles h^{-1}). It is generating a lot of interest from the military because it has a low noise and radar signature and can glide silently to a target. The canopy is damage tolerant and in the event of engine failure will glide to a gentle landing.

The design of the Skeeter (Figure 2.15) is based on the body plan of a dragonfly. It is about the length of a pen, weighs less than 50 g and has flapping wing propulsion. It makes about the same noise in flight as the dragonfly on which it is modelled. This makes it of great interest to the military because it can be used for surveillance with a low probability of detection. Another key feature of the Skeeter is that it is much more tolerant of gusty conditions than conventional drones.

The Malolo project is not concerned with flight, like Stork and Skeeter, but with propulsion in water. Rather than using oars or propellers, the craft has a hydrofoil under its bow. This is flapped up and down in much the same way as a dolphin or whale swims. The advantage of this is a higher thrust coefficient over a wider range of speeds and less noise.

Figure 2.15 An ornithopter (the Skeeter) modelled on a dragonfly. *Source:* Reproduced courtesy of Animal Dynamics.

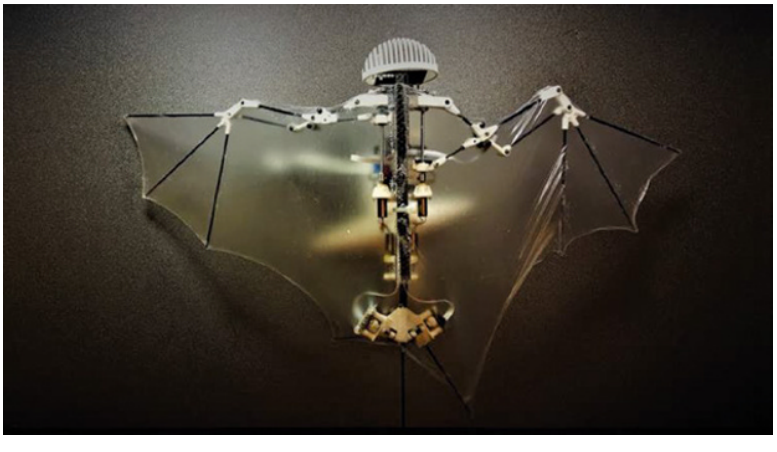


Figure 2.16 The BatBot. *Source:* Reproduced courtesy of Alireza Ramezani.

As noted above, Animal Dynamics is developing ornithopters based on insect flight. The wing structure of most insects is relatively unsophisticated being a single, unjointed structural unit. By contrast, a bat's flight mechanism is unique among flying animals as it involves several types of joints. A team at the University of Illinois at Urbana has developed a bat-inspired aerial robot called Bat Bot (B2). This has soft, pliable wings that flap at much lower frequencies (7–10 Hz) than conventional drones, i.e. quadrotors (100–300 Hz). The flight system consists of two wings (silicone membrane with elasticity properties similar to bat wing membrane) and each wing includes a forelimb and a hind limb mechanism. Each wing can move independently as can the hind limbs. One of the unique features of the Bat Bot (Figure 2.16) is that it can be flown without remote control: it has an on-board computer and multiple sensors for performing autonomous navigation. Development of this bat-inspired ornithopter is still at an early stage but it looks promising.

Relevant Innovations Described in Other Chapters

Self-cleaning materials (Chapter 4, Section 4.3).
Air trapping by insects (Chapter 6, Section 6.2).

Note

1 An ornithopter is an aircraft that flies by flapping its wings. The word is derived from Greek: *ornithos* (bird) and *pteron* (wing).

Suggested Reading

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Chatard, J.C. and Wilson, B. (2008). Effect of fastskin suits on performance, drag, and energy cost of swimming. *Medicine and Science in Sports and Exercise* 40: 1149–1154.

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3

Colour and Light

I believe in Michael Angelo, Velasquez, and Rembrandt; in the might of design, the mystery of colour, and the redemption of all things by Beauty everlasting, and the message of Art that has made these hands blessed.

George Bernard Shaw

Unless we lack vision or are colour blind, we see colour in almost everything we look at: the sky may be blue, a dress may be red, a flower could be yellow and grass is green. Subconsciously we take colour for granted and most people give little thought to the *origin* of the colours that we see. A dress will be red because it contains a red pigment. If the dress is blue rather than red then it will contain a blue pigment instead of a red one. However, a blue sky does not contain a blue pigment: the blue colour that we see is a result of light scattering. Therefore, perception of colour does not necessarily depend on the presence of a pigment and there are many instances in nature where a part of a plant or animal appears coloured and yet contains no pigments. In such instances, the perceived colour derives from light interference in an analogous manner to the colouration of the sky. Coloured objects that lack pigment have *structural* colour.

In 1665, the English physicist Robert Hooke made the first observation on structural colours when he described the tail feathers of the peacock. These feathers are pigmented brown but they also reflect blue, turquoise and green light and are iridescent. Forty years later, Isaac Newton described the mechanism whereby structural colour arises. Since then it has been recognized that the use of structural colouration is widespread in the animal kingdom. It occurs in the feathers of birds such as the bee-eater and the kingfisher, in the wings of many butterflies, the fur of some moles and the shells of oysters. Structural colouration is rare in the plant world but is responsible for the most intense blue known in nature: the berries of *Pollia condensata*. Another plant example is the gloss of buttercup petals.

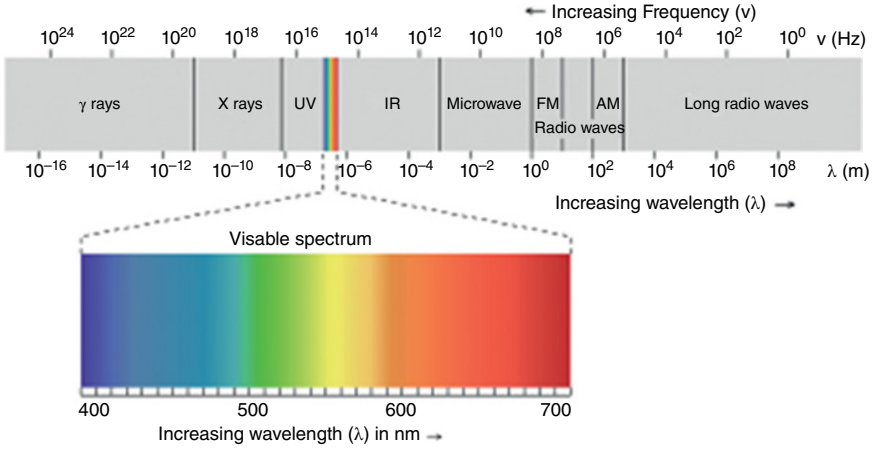
Structural colour is of particular interest for the development of artificial materials because it can be astonishingly vivid and produce a remarkable range of optical effects (iridescence, polarization, metallic sheen, antireflection) using physical structures constructed from a small number of biological (i.e. renewable) materials, such as keratin

Biomimetics: Nature-Inspired Design and Innovation, First Edition. Sandy B. Primrose.

and chitin. The structures that give the colour are often complex but arise from self-assembly, so their fabrication has minimum energy requirements. These structures combine colour with other desirable properties such as resistance to abrasion, water repellency, and photoprotection, which are desirable for artificial materials also.

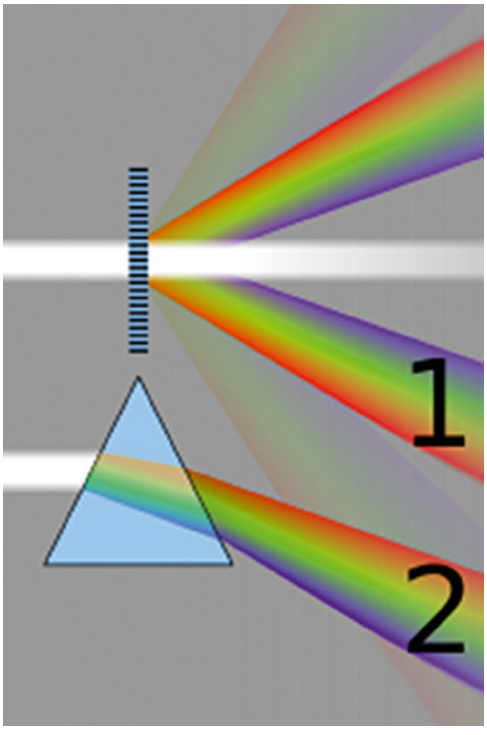
The Basic Properties of Light

Electromagnetic radiation (EMR) is classified by wavelength into radio waves, microwaves, infrared (IR), the visible spectrum that we perceive as light, ultraviolet, X-rays, and gamma rays. Visible light has wavelengths between 400 nm (ultraviolet, shorter wavelengths) and 700 nm (IR, longer wavelengths). Most light that we interact with is in the form of white light, which contains many or all of these wavelength ranges.



The *refractive index* of a material is a dimensionless number that describes how fast light propagates through the material. For example, the refractive index of water is 1.333, meaning that light travels 1.333 times as fast in a vacuum as in water. The refractive index of materials varies with the wavelength of light. This is called *dispersion* and explains why prisms divide white light into its constituent spectral colours. When light moves from one medium to another, it changes direction and this is known as *diffraction*. The greater the difference in refractive index between the two media, the greater is the angle of refraction.

Light can also be split across its spectrum using a diffraction grating – an optical component with a periodic structure that splits and diffracts light into several beams travelling in different directions. A diffraction grating can be manufactured by carving glass with a sharp tool into many precisely positioned parallel lines, with untouched regions acting like slits.



Comparison of the spectra obtained from a diffraction grating by diffraction (1), and a prism by refraction (2). Longer wavelengths (red) are diffracted more, but refracted less than shorter wavelengths (violet). Diffraction gratings work both for transmission of light and for reflection of light.

When we look at an object, the colour that we see depends on the physics of the object in its environment plus the characteristics of the perceiving eye and brain. Physically, objects have the colour of the light leaving their surfaces and this depends on the spectrum of the incident illumination, the reflectance properties of the surface and, in some cases, the angles of illumination and viewing. When white light falls on an opaque surface, there are several outcomes.

- Some or all of the wavelengths of light will be absorbed. If all of the wavelengths of light are absorbed, then the object will appear to be black. If only some of the wavelengths are absorbed then the object will appear to be coloured. A red pigment absorbs all wavelengths of light except those at the red end of the spectrum.
- The white light can be reflected as if it had fallen on a mirror, i.e. the object will appear to be white. A perfectly reflective object would have 100% reflectance and would absorb absolutely no light whatsoever. Such objects do not exist and even a mirror will absorb some light.

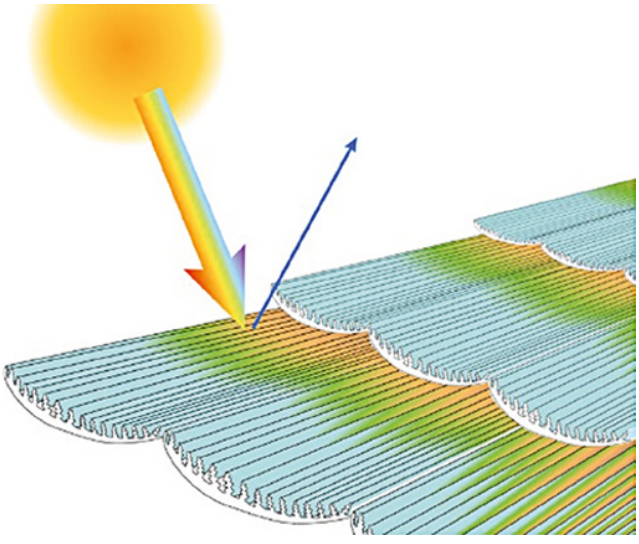


Figure 3.1 Light falling on a periodic microstructure is reflected at a given wavelength (blue in this case). *Source:* https://commons.wikimedia.org/wiki/File:Comparison_refraction_diffraction_spectra.svg.

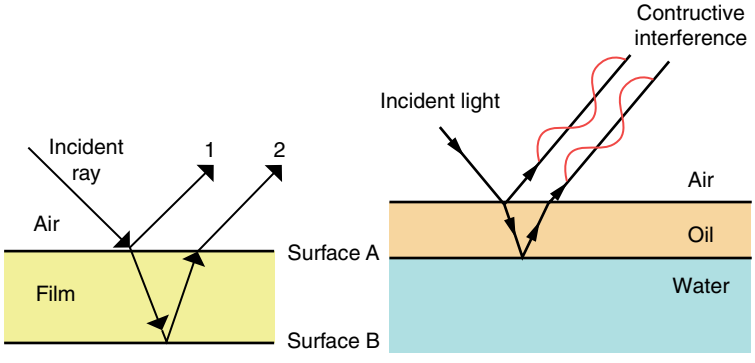
- It can be scattered (reflected with diffuse scattering), particularly if the surface is rough. The intensity of scattered light is inversely proportional to the fourth power of the wavelength, so blue light is scattered more than red light.

Structural colour arises when white light falls on a surface with periodic microstructures on the scale of the wavelengths of light (Figure 3.1). Physicists call such structures photonic crystals or photonic band-gap materials. A strongly scattered reflection maximum arises at a given wavelength and therefore with a distinctive colour. A similar effect is achieved if white light falls on very thin (<500 nm) structured layers of different materials. Layers at this scale have remarkable reflective properties due to light wave interference influenced greatly by the difference in refractive index between the layers (thin film interference).

Structural colours are common in nature, particularly in the animal world. The brightly coloured beetle *Chrysochroa raja* has a 1.5 µm layer on the wing casing containing alternating layers of two materials, each with a thickness of approximately 100 nm. The characteristic reflection from this structure is bright green when seen at normal incidence. The reflected colour shifts towards blue at higher angles of incidence, i.e. iridescence. The bright blue colour of *Morpho didius* butterfly wings is one of the best-known examples of structural colour. Each wing is covered in overlapping scales that feature prominent multilayered ridge structures. A series of lamellae protrude from each ridge giving it a profile resembling a Christmas tree. The periodicity of the multilayers and the many lamellae result in an intense blue reflection that can be seen from a distance of 400 yards (366 m). A key feature of the wings of *Morpho didius* butterflies is that they appear blue over a wide range of viewing angles, i.e. they are not iridescent. This is because the lamellae are arranged irregularly (positional disorder) such that they differ in height (see Figure 3.2 (a)–(e)).

Thin Film Interference

Thin film interference is a natural phenomenon in which light waves reflected by the upper and lower boundaries of a thin film interfere with one another, either enhancing or reducing the reflected light. If the crests of one of the waves coincide with the crests of the other, the amplitudes are additive. If the amplitudes of both waves are equal, the resultant amplitude would be doubled. Because light intensity varies directly as the square of the amplitude, if the amplitude is doubled then intensity is quadrupled. Such additive interference is called constructive interference. If the crests of one wave coincide with the troughs of the other wave, the resultant amplitude is decreased or may even be completely cancelled. This is called destructive interference. The result is a drop in intensity, or in the case of total cancellation, blackness.



Insects such as butterflies use colours and patterns for attraction and deception. Some butterflies look for certain colours or patterns when searching for a mate whereas others us their colour to hide from predators, i.e. colour is essential for survival. Periodic photonic structures are advantageous for many insects since a thickness of only a few micrometres is sufficient to obtain high optical reflectivities. This is important in flying insects where the

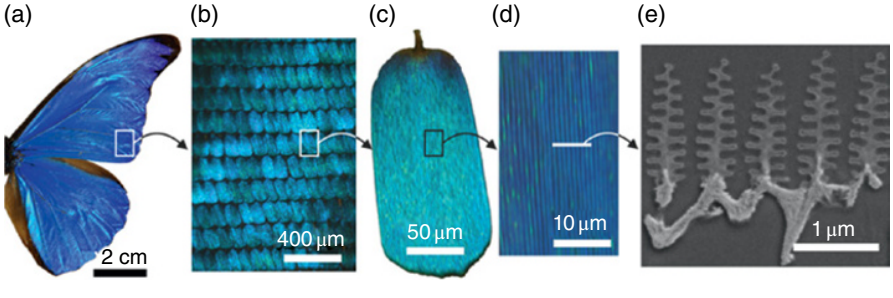


Figure 3.2 Detailed structure of the wings of the *Morpho* butterfly at increasing magnification. Note the periodic structure in (e) which is magnified two million times from (a). *Source:* Reproduced courtesy of the Biomimicry Institute.

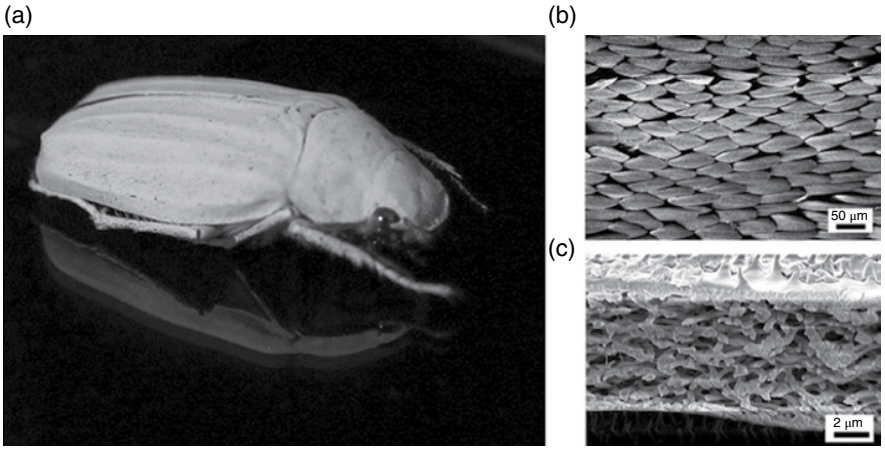


Figure 3.3 The origin of white structural colour. (a) The beetle *Lepidiota stigma*. (b) The beetle scales. (c) The internal structure of the scales showing the disordered fibres.

weight and function of optical materials must be balanced carefully. Periodic structures produce relatively saturated colours. By contrast, aperiodic structures have a white appearance since all wavelengths of light are scattered approximately equally. Such disordered systems have been found in butterflies (*Pieris rapae*) and beetles (*Cyphochilus* and *Lepidiota stigma*). The beetles have a coating of white scales that have an internal disordered tangle of 250 nm-diameter filaments (Figure 3.3 (a)–(c)). The fibres are sparsely packed with just the right number of voids, giving rise to a thorough scattering of light that causes the brilliant whiteness. The secret is not in the material itself, but the structure – the way the meshwork of fibres and voids scatters the light. The scales are among the most strongly scattering, low refractive index materials known. The whiteness of the scales (~70% reflection) compares favourably with those measured for many synthetic materials and yet the scales have a very low mass per unit area.

3.1 Photonic Biomimicry

In the manufactured world, most colour comes from the use of dyes and pigments. Dyes are soluble organic chemicals that impart colour by selective absorption of light. Their manufacture and use is not environmentally friendly because of the large amounts of energy and water involved. Pigments are particulate organic or inorganic solids that selectively absorb and/or scatter light. As with dyes, their manufacture requires energy and if they are mined, there is an environmental impact. For these reasons, there is great appeal in replacing dyes and pigments with structural colours.

The world's first structurally coloured fabric was Morphotex and it was modelled on the *Morpho* butterfly. It was developed and manufactured by Teijin Fiber Japan. This fibre consisted of 61 nylon and polyester fibres in alternating layers. By controlling the thickness of each layer, ranging from 70 to 100 nm, they were able to produce the four basic colours: red,

green, blue, and violet. Morphotex was used to great effect by designer Donna Sgro who created three garments with it, including the Morphotex Dress. This dress was recognized as an exemplary model of sustainable fashion when it was exhibited in the Science Museum in London in 2010. Unfortunately, Morphotex is no longer is available but *Morpho*-inspired colouring can be found in certain cosmetic products. L'Oreal has used synthetic materials to form periodic microstructures to creat eye shadow, lipsticks, and nail varnish that have no pigments – photonic cosmetics. A big advantage of photonic lipstick is that any transfer of the product onto another surface leaves only a white powder trace and not the colour. Also, the lipsticks can be formulated to avoid the oil that is used to give the product a shimmering appearance after application.

Analysis of *Morpho* butterflies has shown that the positional disorder among the identical, multilayered ridges on the wing scales means the blue structural colour can be seen from any viewing angle. Realizing that manufacturing such nanoscale structures in a laboratory would be close to impossible, one research group set out to develop alternative structures with the same effect. The group started with randomly sized silica microspheres with diameters ranging from 250 to 440 nm and coated them with a multilayer film of silicon dioxide and titanium dioxide. The size variation of the spheres created the necessary structural disorder. Then, using a combination of lithography and etching, they created a dense array of ridges with a periodicity of 700 nm. This 700 nm spacing matches that of the ridges on the scales of *Morpho* butterflies. The final product had the expected blue colour when viewed from most angles. What the group did next is even more interesting. They coated the layered structure with parylene, a protective polymer coating that is in wide commercial use. When the parylene coating was peeled off, it retained the nanoscale structure that had been created on the silica microspheres – and it was blue even though the film is transparent. Because the parylene film is flexible, it can be used to cover irregular surfaces without the loss of its blue structural colour.

Structural colouration is found not only in plants and animals but also in microbes. Bacteria of the genus *Flavobacterium* pack together in colonies that have striking metallic colours because their structure reflects light at certain wavelengths. One benefit of bacteria as experimental models is that mutants are easy to generate and analyse. For *Flavobacterium* this creates an opportunity to investigate the genetics of structural colouration, a task that would be much more difficult in plants or animals. With this in mind, Villads Egede Johansen at the University of Cambridge, UK, compared the optical properties and anatomy of wild-type (normal) and mutated bacterial colonies to understand how genes regulate the colour of the colony. When the dimensions of the cells were changed, there was a change in the geometry of the colonies, which resulted in a change of colour – the original metallic green colour of the colony could be changed to any colour in the visible spectrum from blue to red. It also was possible to create duller colouration or make the colour disappear entirely. This bacterial system can be applied to achieve tuneable living photonic structures that can be reproduced in abundance without using traditional nanofabrication methods.

White is a colour associated with purity, cleanliness, and freshness – the more brilliant the whiteness, the more these qualities are enhanced. Many technologies use coatings of calcium carbonate or kaolin to enhance the whiteness, brightness, and opacity of surfaces and materials. The paper industry is one of the largest users by volume of these white

coatings. When paper is coated, the particles of calcium carbonate or kaolin pack together to form a mineral matrix that surrounds a network of air-filled pores or voids. The refractive index contrast between mineral and air enables light scattering to occur. Optimization of paper appearance depends on the balance between the size, number, density, and separation of the air pores, but could the paper industry learn anything from the exceptional whiteness of *Cyphochilus* beetles?

It is the random network of interconnecting cuticular filaments within each scale that produces highly efficient optical whiteness and brightness in *Cyphochilus* beetles. The filament width and the packing density are the key variables in creating its optimally tuned appearance. For coatings, the optimization of whiteness depends on determining the optimal size of the light scattering unit. If the coating particles are small, the air voids also are small and this reduces the amount of light scattered even though the absolute number of voids is increased. The more optimally sized voids created by larger particles result in low scattering due to the low number of voids. Experimental results show that the best performance achievable with existing coatings do not replicate the effects seen with the random fibril system of *Cyphochilus* beetle scales, partly because existing coatings are manufactured with relatively uniform particle sizes. The introduction of randomness using coatings of mixed particle sizes or with mixed particle shapes is needed to achieve the whiteness of beetle scales.

Hendrick Hölscher and his colleagues at the Karlsruhe Institute of Technology, Germany, noted that *Cyphochilus* beetles produce their brilliant white appearance with porous chitin scales that are only 7 μm thick but effect a reflection of 65–70%. They reasoned that if nature can build thin yet efficient scattering layers from materials with a low refractive index, then a similar effect could be obtained with thin layers of other materials with low refractivity. Accordingly, they set out to produce a thin and flexible white film that could be manufactured on a large scale. There is an established process for making foams by saturating polymers such as polymethylmethacrylate (PMMA) with carbon dioxide. Instead of starting with bulk PMMA, as would happen in the industrial process for making foam, the Karlsruhe team made thin films of PMMA and then injected the carbon dioxide. By varying the process parameters – such as saturation temperature and pressure – they could control the size, shape, and thickness of the pores in the thin film. The best films had a reflectance of 90% at a wavelength of 600 nm and there was little change in reflectance over the range 400–800 nm. Given that the foaming process can be well controlled, it is possible to make the process reproducible – and it can be applied to other polymer materials.

3.2 Structure Can Influence Light Output

Bioluminescence is the widespread production and emission of light by a living organism and it occurs widely in marine vertebrates and invertebrates, as well as in some fungi, bacteria, and terrestrial invertebrates such as fireflies. In fireflies, the purpose of the light is to attract mates. The light is generated by a chemical reaction that takes place in specialized cells called photocytes that are located in a structure known as the lantern. When Jean-Pol Vigneron and colleagues examined the lantern structure using a scanning electron microscope they noticed some unusual features. There were nanoscale ribs and larger, misfit

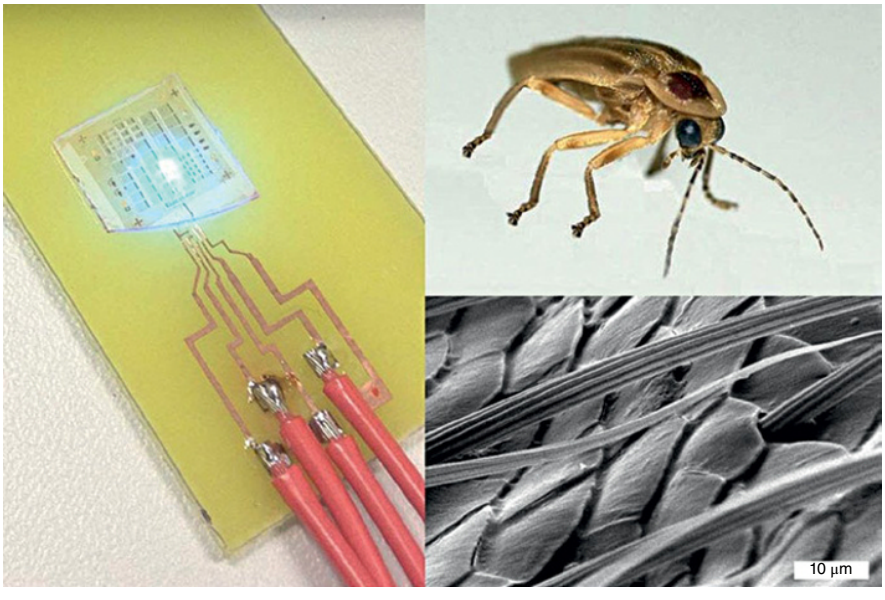


Figure 3.4 The misfit scales (bottom right) found on the lantern of the *Photuris* firefly (top right) are the inspiration for a GaN LED, coated with a 'factory-roof' pattern (left) that increased light extraction by more than 50%.

scales. Using computer simulations to model how these structures affected light transmission, they found that the sharp edges of the jagged misfit scales let out the most light by preventing internal reflection. Based on this discovery, a coating was developed (Figure 3.4) that increased the brightness of LEDs by 55%.

3.3 Cephalopods and Camouflage

Cephalopods are a class of invertebrates that includes octopus, cuttlefish, and squid. These animals are notable for their ability to change their body colouration. This ability has fascinated scientists since antiquity with some of the earliest observations of their behaviour recorded by the Greek philosopher Aristotle. Cephalopods use dynamic colouration in various ways, such as camouflage and intraspecies communication. This colouration uses pigments and structural colours and involves specialized photonic organs and cell types located at different depths within the skin. Close to the surface of the skin are chromatophores with red, yellow, and brown pigments that generate colour through selective light absorption. The chromatophores, which are arranged in an arrayed pattern, consist of a central pigment cell ringed by innervated muscle cells (Figure 3.5). This highly evolved natural architecture allows the pigment cells to be dynamically switched by the muscle cells between contracted point-like and expanded plate-like states, thereby modulating the local coloration and changing the transmission of light through the skin. Beneath the chromatophores are two classes of reflective cells – iridocytes and leucophores – that generate structural colour by light scattering. Iridocytes produce iridescence whereas leucophores

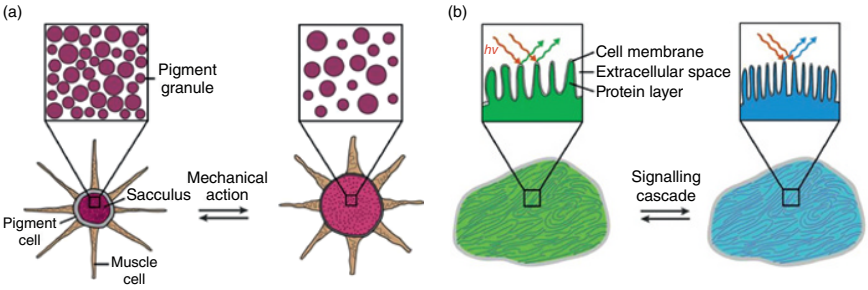


Figure 3.5 (a) Schematic of a cephalopod chromatophore organ in which a central chromatophore pigment cell is ringed by muscle cells. The adaptive chromatophore pigment cells contain internal saccule packed with pigment granules (inset), and they are expanded and contracted through the mechanical action of muscle cells. (b) A schematic of a squid iridocyte. The adaptive iridocytes contain alternating arrangements of membrane-enclosed protein layers and extracellular space (inset), for which the geometries and refractive index differences are altered via a biochemical signalling cascade. *Source:* Figure adapted from Xu et al. (2018).

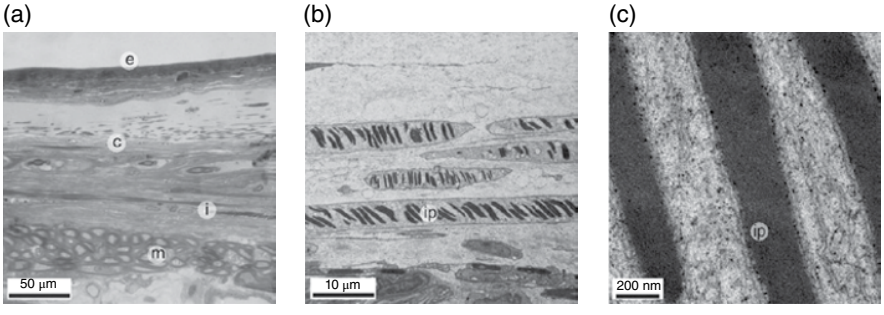


Figure 3.6 Section through the skin of a squid at increasing magnification (a)–(c) showing: e, epidermis; c, chromatophore; i, iridocyte; m, muscle; ip, iridocyte platelets. *Source:* Reproduced courtesy of DeMartini et al. (2013).

are broadband white reflectors. It is the interplay between chromatophores, leucophores, and iridocytes that enables cephalopods to dynamically change their colour.

The structural colour in butterflies and beetles described earlier results from the interaction of light with nanoscale structures made from hard materials such as keratin or chitin. By contrast, structural colour in cephalopods derives from a family of proteins known as reflectins that have a very high refractive index. Different reflectins occur in different cephalopods but all reflectins have the same general structure and composition. The reflectin is laid down as an array of platelets in the iridocytes (see Figure 3.6). Incident light passes through the reflectin layers (with a high refractive index) and the space between the layers (with a low refractive index) and is reflected at a particular wavelength (Figure 3.7). As the cephalopods are able to change the spacing between the arrays of platelets, they can change the wavelength of the reflected light so that they develop a particular colour.

Because the impressive ability of cephalopods to change colour is linked with reflectin, there has been much research on the potential of reflectins in photonic applications. Reflectins can be synthesized in bacteria using genetic engineering, and this simplifies

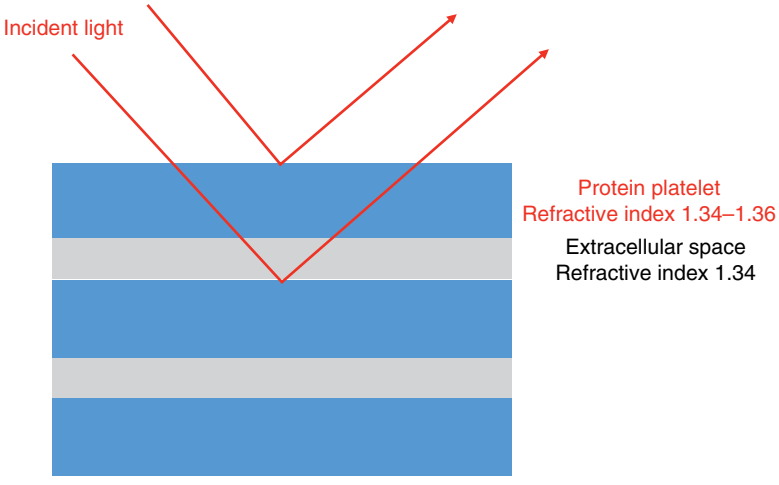


Figure 3.7 Refraction of light by iridocytes occurs from the platelets of reflectin and the extracellular space.

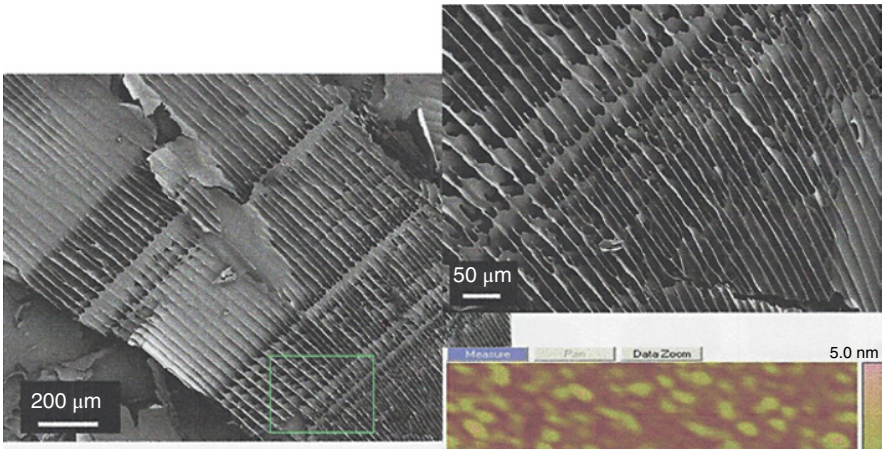


Figure 3.8 Lamellar structure of genetically engineered reflectin that has self-assembled. *Source:* Reproduce courtesy of Qin et al. (2012).

their synthesis and purification. Purified reflectin is an interesting material because it can self-assemble into structures such as spheres, ribbons, and diffraction gratings. These can further self-assemble into supramolecular structures like the ones shown in Figure 3.8. The protein is also unusual in consisting of a repeating structural motif separated by spacers. Again, using genetic engineering, it is possible to make a cut down protein consisting of a single motif and a stretch of linker and this mini-protein has the same self-assembly and light scattering properties as intact protein.

Thin films of reflectin exhibit structural colouration and the colour seen depends on the thickness of the film. An easy way to vary the thickness is to lay down multiple layers of the same thickness either in the same direction or at right angles to the previous layer. In this

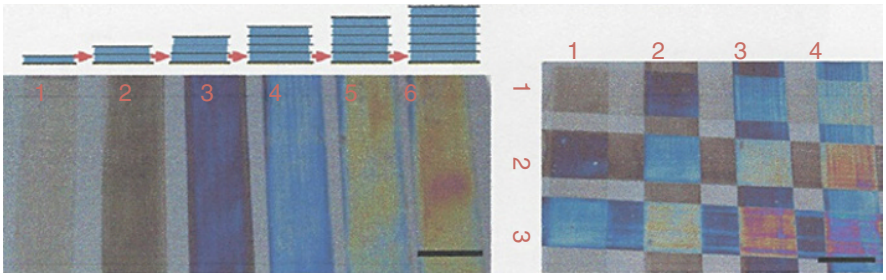


Figure 3.9 Thin film formation and structural colouration of reflectin-based materials. A solution casting of stacked thin films of reflectin (left) and cross-flow coating techniques (right). *Source:* Reproduced courtesy of Qin et al. (2012).

way the thickness of each film increases proportionately as the number of layers increases and the colour of the films changes from blue to red (Figure 3.9). The thickness and colour of these reflectin films are extremely sensitive to both hydration and pH. Exposure of the films to acid vapour causes a twofold increase in film thickness and drives the wavelength of the reflectance into the IR. An increase in relative humidity above 75% causes sufficient swelling to generate a visible colour change.

As mentioned earlier, reflectins and reflectin motifs can form an impressive array of thin films, fibres, and diffraction gratings with reflectance tunable by swelling or shrinking in response to changes in humidity or other factors. It must be stressed that the photonic effects observed are not attributable to the reflectins as such but to the complex structures that they can form by self-assembly. Alon Gorodetsky – who runs the Biomolecular Electronics Laboratory at the University of California, Irvine, USA – set out to exploit the opportunities offered by reflectin, including its potential application in military camouflage. With this in mind, Gorodetsky's team deposited reflectin as a thin film onto sticky tape. When they applied tension to the tape, the thickness of the film decreased and the reflectance shifted from the near IR to visible regions of the electromagnetic spectrum. That is, the optical properties of the tape could be controlled by mechanical stimuli. When the tape was applied to fabrics, it changed their appearance under IR imaging (Figure 3.10).

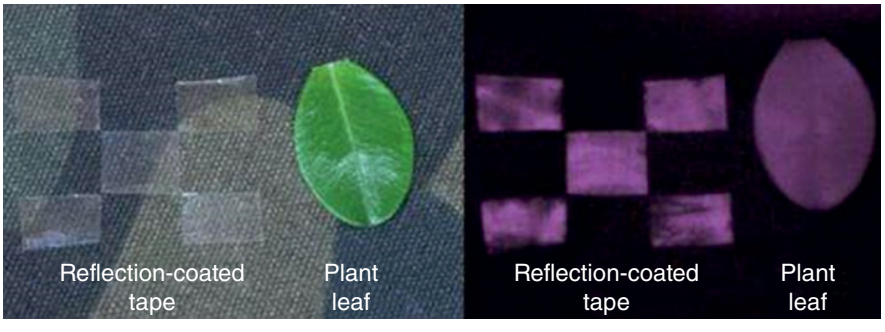


Figure 3.10 Reflectin coated tape and a plant leaf viewed under normal (left) and infrared (right) light. *Source:* From Phan et al. (2015).

3.4 Photonic Cooling

The silver ants of the Sahara desert, *Cataglyphis bombycina*, inhabit one of the hottest terrestrial environments on Earth. Their main food supply is the corpses of insects and spiders that have succumbed to the punishing heat. Surprisingly, their main foraging activity occurs during the day when the temperature of the desert surface can reach 70 °C. As the maximum body temperature that the ants can survive is only 53.6 °C, they must have some mechanism for reducing heat absorption and for shedding excess heat. Close examination of the ants shows that the dorsal (top) and lateral sides of their bodies are covered by dense and uniform arrays of hairs with a triangular cross-section. Measurements have shown that the hair-covered regions reflect 67% of the incoming solar radiation but only 41% if the hairs are removed. Individual hairs of given cross-sectional dimensions generate enhanced reflection due to scattering at specific wavelengths. Because there is considerable variation in cross-sectional dimensions between different hairs, the total hair cover acts as a coating with broadband reflection.

Radiative cooling is the natural process through which objects shed heat as IR radiation. All materials at room temperature emit IR (so-called black body radiation) at wavelengths of 5–15 μm; however, the process is not very efficient because it is counteracted by external influences that heat the object, such as sunlight in the case of the ant. Air, meanwhile, absorbs and emits very little radiation with wavelengths of 8–13 μm (mid-IR) and this allows the Earth to cool itself at night by emitting IR into space. The hair-covered parts of ants' bodies reflect very little mid-IR light but they can radiate it. The bottom surface of the ants is free of hairs, which minimizes the transfer of black body radiation from the desert sand to the ant.

In summary, Saharan silver ants are covered with a dense array of triangular hairs on the top and sides of their bodies. These hairs enable the ant to maintain a body temperature up to 20 °C lower than ambient in three ways. First, the hairs enhance reflectivity in the visible and near IR where solar radiation is maximal. Second, in the mid-IR where solar radiation becomes negligible, the hairs enable the ants to offload excess heat via blackbody radiation. Third, the ants bare bottom surface reflects mid-IR radiation from the desert floor. Understanding temperature control in Saharan silver ants has lead Professor Ronggui Yang at the University of Colorado Boulder, USA, to develop coatings that can cool down objects exposed to the full glare of the sun (Figure 3.11). Made out of glass microspheres, polymer, and silver, his coating material uses passive radiative cooling to dissipate heat from the object it covers. It emits the energy as IR radiation and also reflects solar light in the same way as the ant hairs. Most importantly, manufacture of the material can be scaled up at low cost using roll-to-roll manufacturing processes. It is produced and sold by a company called Radiative Cooling.

Outdoor enthusiasts will be familiar with space blankets that are used to reduce the heat loss from the body of a person suffering from shock (e.g. after an accident) or at risk from exposure. They often are given to marathon runners and other endurance athletes at the end of races, or while waiting for races to begin if the weather is chilly. Space blankets are popular with emergency workers because they are very low weight and low bulk items. In its standard configuration, a space blanket consists of a thin plastic sheet such as metallized polyethylene terephthalate (MPET) overlaid with a thin film of aluminium – an architecture that is highly effective at reflecting IR radiation (heat). One unexpected application of space blankets is their use by the military to hide their heat signatures.

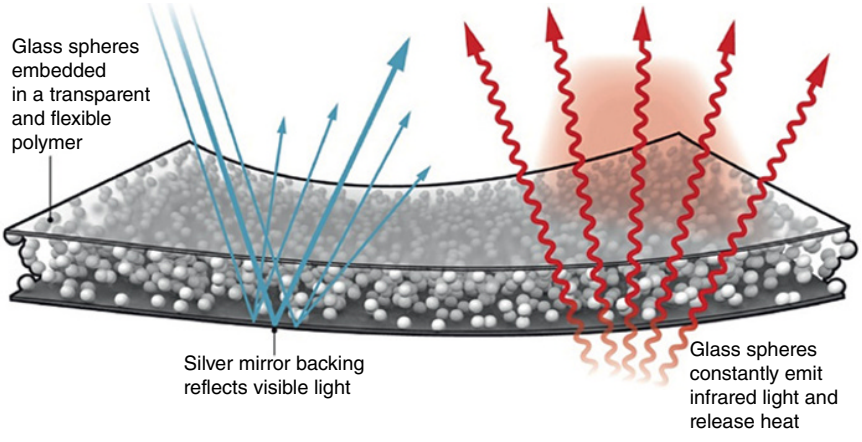


Figure 3.11 Novel material that can cool objects exposed to the full glare of the sun. *Source:* Reproduced courtesy of Professor Ronggui Yang.

Space blankets are very good at keeping people warm at cool temperatures but they are of little use for cooling at high temperatures. In a hot environment, they can be used to provide shade or provide protection against radiated heat, but using them to wrap a person would be counterproductive because body heat would get trapped by the airtight foil. This effect would exceed any benefit gained from heat reflection to the outside. A wearable fabric that can reduce body temperature would be extremely useful, especially if it could be 'tuned' to particular temperatures. Alon Gorodetsky has designed such a thermoregulatory material by taking inspiration from the observation that squids can change the colour of their skin by changing the shape of their chromatophores (Section 3.3).

The novel thermoregulatory material consists of a soft and stretchable IR-transparent polymer overlaid with an array of IR-reflecting metal domains stably anchored within the polymer via columnar nanostructures. In this design, the polymer matrix emulates the chromatophore-containing skin of the squid and the metal domains emulate the embedded chromatophores. In its base state, the new material reflects nearly all the incident IR radiation. If the material is stretched the metal domains become spread apart and uncover portions of the stretched polymer. In essence, stretching the material reversibly changes its ability to transmit and reflect IR radiation (heat).

Having made the thermoregulatory material, the next step was to determine the environmental setpoint temperatures, i.e. ones at which the body's skin temperature and outgoing heat flux remain constant and ensure individuals maintain their thermal comfort. Unstretched material had a setpoint temperature of 14.5 °C, similar to that of a space blanket. As the material was stretched, the setpoint temperature increased, reaching 22.7 °C at maximum stretch,which is similar to the value found for cotton. In practice, stretching would be achieved by movement and less heat would be lost by a sedentary person.

Gorodetsky has taken tuneable systems a step further by developing a device that can change its IR reflecting properties in response to external stimuli, with the design again being inspired by cephalopods. The starting point for the device was an electroactive polymer in the form of an elastomeric film coated on both sides with electrodes, a structure

often called a dielectric elastomer. When a voltage is applied, the film contracts in the thickness direction and expands in the film plane direction. The film returns to its original position when there is no voltage. In the Gorodetsky system, the elastomer is covered with an IR reflecting coating. Before electrical actuation, the film has a dense array of reflective microstructures. After actuation, the devices expend their active areas to modulate the amount of absorbed and reflected IR light.

Devices were prepared with aluminium-coated active areas in the shape of a swimming squid's silhouette (Figure 3.12) and these were imaged with a thermal IR camera

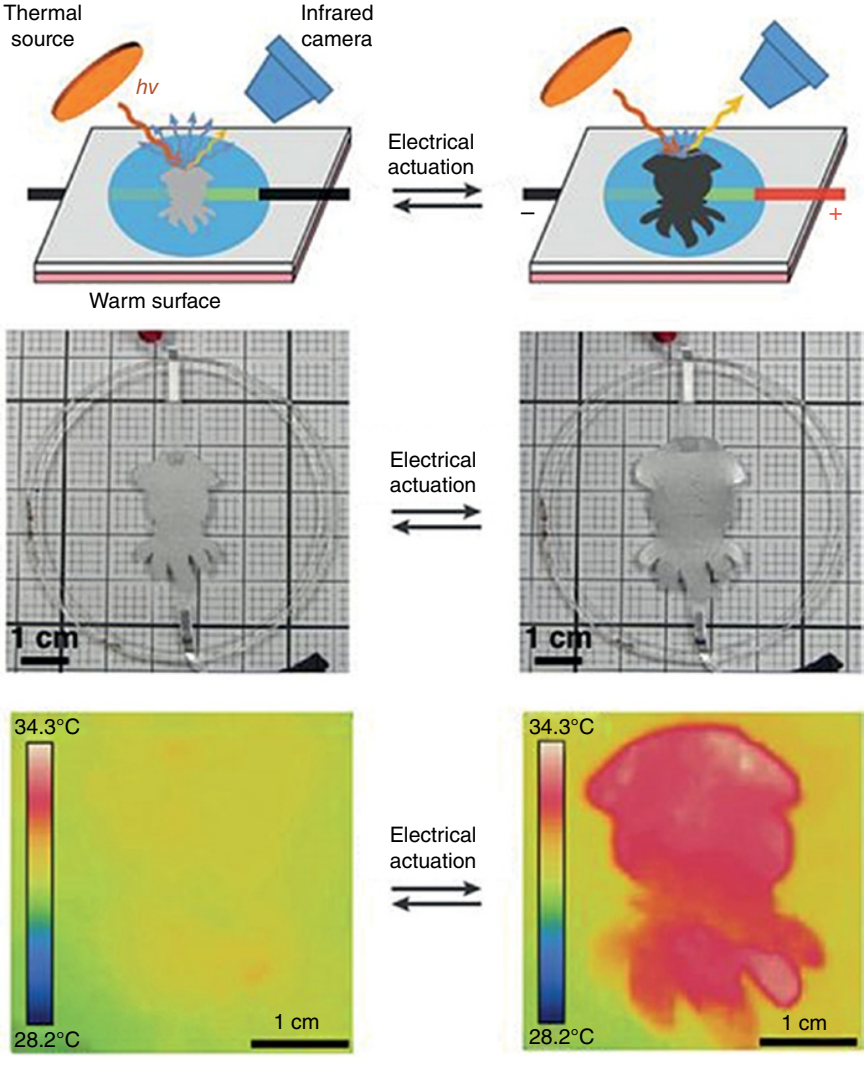


Figure 3.12 (Top) Schematic of a squid silhouette-shaped device maintained under a constant thermal flux and positioned above a warm surface before (left) and after (right) electrical actuation. (Middle) Digital camera images of the squid silhouette. (Bottom) Infrared camera images of the same sihouettes. *Source:* Figure from Xu et al. (2018).

under an incident heat flux above a surface with a locally elevated temperature. Before electrical actuation, a representative squid silhouette–shaped device featured a relatively small microstructured (wrinkled) active area and a negligible apparent temperature difference with the immediate surroundings. This effectively made it invisible above a warm surface with a temperature of ~35 °C, as revealed with IR camera imaging. By contrast, after electrical actuation, the squid silhouette–shaped device featured a larger flattened active area and an apparent temperature difference of ~2 °C with the immediate surroundings, which made it stand out as a specific shape, as revealed with IR camera imaging.

3.5 Biomimetic Antireflective Coatings

Whenever a ray of light moves from one medium to another (such as when light enters a sheet of glass after travelling through air), some portion of the light is reflected from the interface between the two media. An antireflective or antireflection (AR) coating is a type of optical coating applied to the surface of lenses and other optical elements to reduce this reflection. This improves the efficiency of imaging systems since more light is transmitted. In complex systems such as telescopes and microscopes, the reduction in reflections also improves the contrast of the image by elimination of stray light. In 1886, the great British physicist Lord Rayleigh discovered by chance the simplest form of AR coating. The optical glass available at the time tended to develop a tarnish on its surface with age, due to chemical reactions with the environment. Rayleigh tested some old, slightly tarnished pieces of glass, and found to his surprise that they transmitted more light than new, clean pieces. The tarnish replaces the air–glass interface with two interfaces: an air–tarnish interface and a tarnish–glass interface. Because the tarnish has a refractive index between those of glass and air, each of these interfaces exhibits less reflection than the air-glass interface did.

AR coatings are very effective in reducing surface reflections at specific wavelengths but are not very effective across a wide range of wavelengths. Their effectiveness also depends on the angle of view. One solution to this problem is to use multiple AR coatings laid down as a multilayer film. Such coatings can achieve a broadband response and larger acceptance angles but they are time consuming and expensive to manufacture. Also, differences in thermal expansion coefficients means that the different layers can delaminate. Making AR coatings that are effective at IR wavelengths is particularly challenging as the wavelength range is very broad and there are very few IR transparent materials. Given this problem it is pertinent to ask how animals minimize reflections especially as they do not appear to use AR coatings like those discussed here.

Hyperiids are small crustaceans that inhabit oceanic waters from the surface to over 4000 m deep. As hyperiids are transparent, it might be thought that they were invisible to predators. However, as noted earlier, light is reflected and refracted at interfaces between materials with different refractive indices. Seawater has a refractive index of 1.34 and the corresponding figure for hyperiids is 1.57. In water, the blue-green downward light is at least two orders of magnitude greater than horizontal radiance at all depths. A reflection of only 1% of this downward light into the horizontal plane could create a shadow visible

to predators. Laura Bagge at Duke University, USA, wondered if hyperiids had a mechanism for minimizing such shadows. When she and her colleagues examined the crustaceans using scanning electron microscopy they noted that the hyperiid legs were covered in a periodic array of nanoprotuberances about 200 nm high. These protuberances were similar in size and shape to structures seen on the wings of butterflies by Hendrick Hölscher in Karlsruhe and in the eyes of moths by Daniel Morse in Santa Barbara, USA. In each case their presence significantly reduces reflection by as much as 100-fold even at high view angles.

If animals use structural irregularities instead of AR coatings, could such an approach be used with manufactured objects? Daniel Morse and his colleagues decided to investigate this. They were able to fabricate light transparent films with nanostructures identical to those seen in the eye of moths. Testing showed these films had the desired AR effect when light was going from air (low refractive index) into a glass lens with a high refractive index. Reflection is also a problem when light is passing from glass or similar material into air as happens with, for example, a light-emitting diode. The good news is that the films work equally well in this application.

3.6 A Novel Glass Inspired by Spiders

Many of us at some time or another will have walked into a glass door simply because we did not see it: under certain light conditions, the reflective and transparent characteristics of glass make it nearly invisible. Birds have the same problem with glass as humans, but for them a collision is nearly always fatal. Over the past 40 years there has been a huge increase in the use of glass in buildings ranging from expansive windows to glass walls – central London is a good example of this trend. It is estimated that the number of avian fatalities is between 300 million and 1 billion birds per year worldwide. Migratory songbirds are disproportionately affected, which is concerning as many already are threatened by hunting and shrinking habitats.

Just as humans can inadvertently walk into glass, so they can also walk into spiders' webs – which can be an equally unpleasant experience. Birds are more fortunate than humans because they can see spiders' webs if they have been decorated with ultraviolet-reflective threads known as stabilimenta (Figure 3.13). Birds can see ultraviolet wavelengths of light whereas humans cannot (see Colour Vision Box). In the late 1990s, a German attorney with an interest in birds read a magazine article about orb weaver spiders and their use of stabilimenta. He was good friends with Hans-Joachim Arnold, the owner of Arnold Glas, and encouraged him to investigate how the concept of stabilimenta might be applied to glass to prevent birds from striking windows. Arnold rose to the challenge and the company developed ORNILUX. This is a ultraviolet-reflective glass coating that is visible to birds but is transparent to humans who cannot see ultraviolet light. Research showed that a patterned coating, instead of a solid coating, made the contrast of the glazing more intense. The preferred criss-cross pattern (Figure 3.14) is nearly invisible to the human eye and has been branded 'Mikado' after the German name for the game of pick-up sticks.

Figure 3.13 Ultraviolet-reflective stabilimenta in the web of a spider.

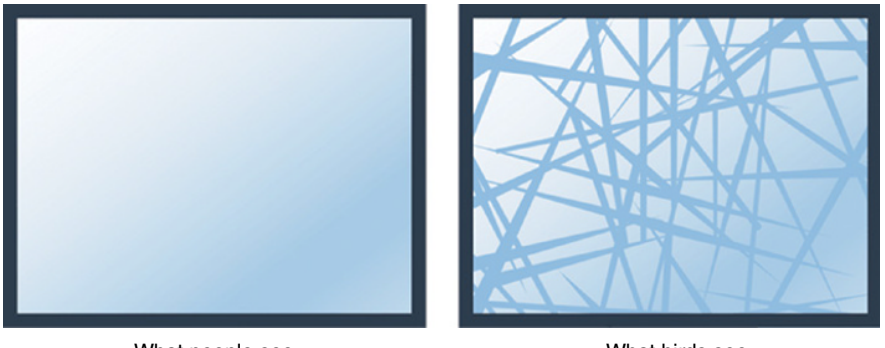
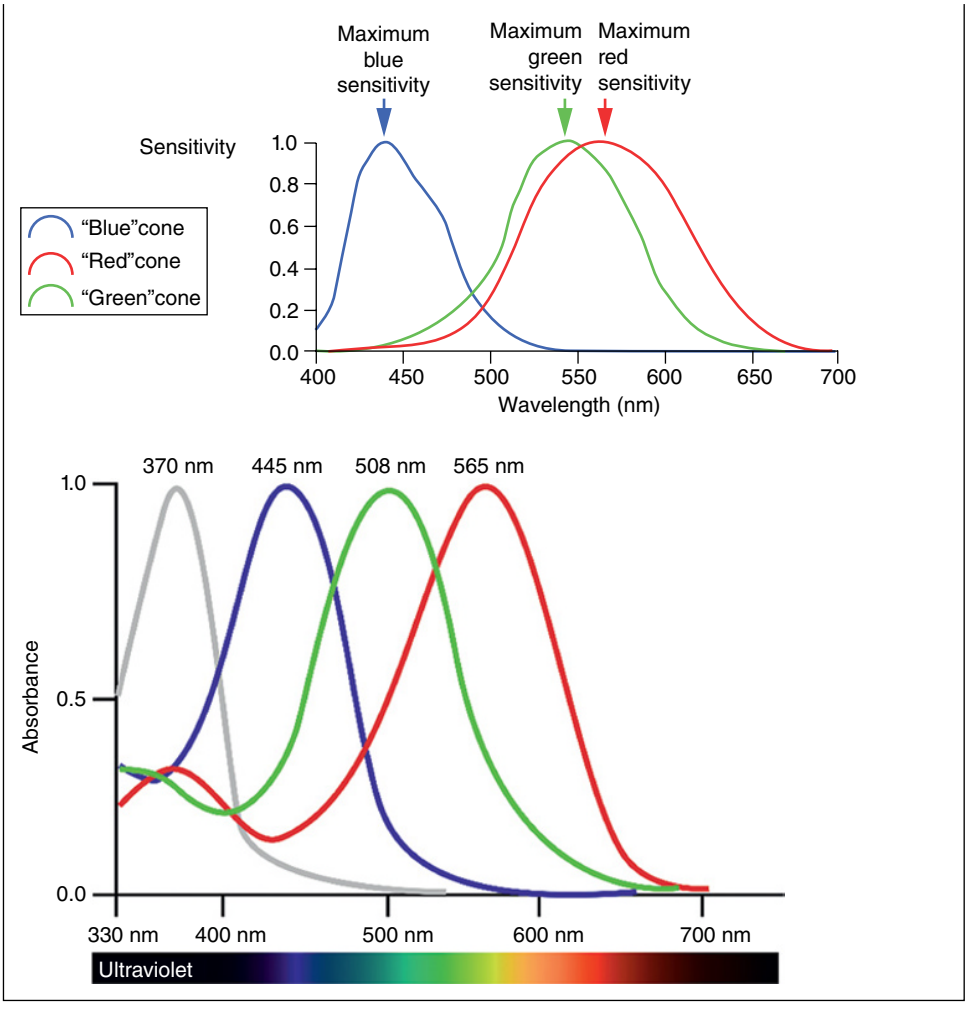


Figure 3.14 The Mikado 'bird proof' glass produced by Arnold Glas. *Source:* Arnold Glas.

Colour Vision

Colour vision is the ability of animals to perceive differences between light composed of different wavelengths independently of light intensity. It is possible due to photoreceptors in the retina of the eye known as cones. Cones have light-sensitive pigments that enable animals to recognize colour. In humans, there are three types of cones containing pigments that absorb either red, green, or blue light. Using these cones, humans can see wavelengths of light between 400 and 700 nm ('visible light'). When the pigments inside the cones absorbs light of particular wavelengths, the information is sent through the optic nerve to the brain. The brain processes this information such that we can distinguish countless shades of colour. Many birds and bees have four sets of cones rather than the three found in humans. The fourth set absorbs light in the ultraviolet range. Consequently, they not only see things unaided that humans cannot but they also see objects in a different colour to humans.



Relevant Innovations Described in Other Chapters

Novel textiles (Chapter 5, Section 5.4).

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4

The Built Environment

> *To make the world work for a hundred percent of humanity, in the shortest possible time, through spontaneous cooperation, without ecological offense or the disadvantage of anyone.*
>
> Mission statement of the late Buckminster Fuller

In the late nineteenth century, Antoni Gaudí was so influenced by the atmosphere of forests that he decided to recreate it in the interior of his masterpiece, the Sagrada Familia cathedral in Barcelona. Tree-like columns branch off near the roof and, in-between, the skylights contain green and gold glass to reflect light. Enhancing the feeling of standing on a forest floor are large coloured glass windows letting in dappled sunlight. Since Gaudí, many architects have drawn inspiration from nature for the design of awe-inspiring buildings. For example, the Lotus Temple in Delhi is built in the shape of a floating half open lotus set amidst pools and gardens. The Helix is a landmark bridge at Singapore's Marina Bay inspired by the geometric arrangement of DNA, with a walkway encircled by opposing double helix structures of stainless steel. These structures are not examples of biomimicry, however, because they only copy their biological counterparts in appearance. True biomimicry goes beyond structural and aesthetic similarities and makes use of the functional aspects of natural systems. Nature-inspired designs may not even resemble their natural counterparts. Fortunately, there are plenty of examples of true biomimicry in the built environment.

4.1 Cooling Buildings the Termite Way

The architect Mick Pearce was born in Zimbabwe where he has worked for much of his career. Committed to appropriate and responsive architecture, he has specialized in the development of buildings that have low maintenance, low capital and running costs and renewable architecture. Pearce firmly believes that effective design should draw inspiration from local nature. He famously put this into practice with his design for the Eastgate Centre in Harare, which is modelled on the architecture of local termite mounds.

Termites belonging to the genus *Macrotermes* occur throughout tropical Africa and Asia. There are over 300 species, most of which build elaborate mounds (Figure 4.1) that can

Biomimetics: Nature-Inspired Design and Innovation, First Edition. Sandy B. Primrose.

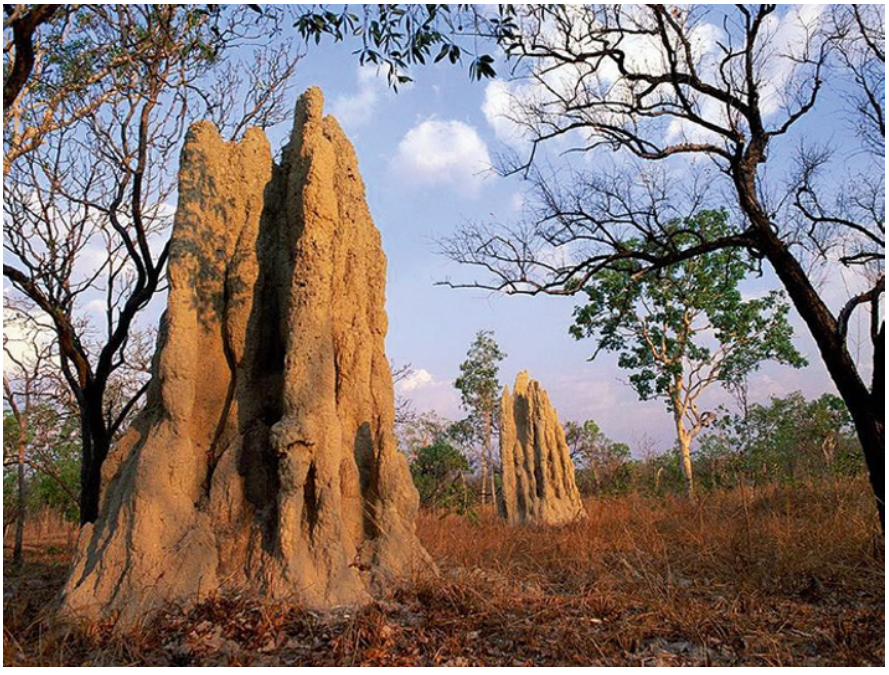


Figure 4.1 Termite mounds. Note the size of the mounds relative to the trees.

reach 3 m high. Some termites, such as *Macrotermes michaelensii*, cultivate fungi to use as food and it has long been believed that to optimize fungus growth the temperature of the mound needs to be kept between 29 and 32 °C. Since the external temperature can vary from 2 to 42 °C, depending on the time of day, there must a mechanism for maintaining an almost constant temperature within the mound.

In 1960, Swiss entomologist Martin Lüscher developed the concept of the air-conditioned termite nest. The driving force was not a need to keep a fungus at a constant temperature but as a means of dissipating the enormous amounts of heat, estimated to be 50–200 W, generated by termite activity. In Lüscher's conception, hot air produced by termite metabolism rises to the top of the mound where oxygen, carbon dioxide, heat, and water vapour are exchanged with outside air via the porous walls (Figure 4.2). The density of the air at the top of the mound increases as a result of this exchange and sinks to the cellar below the mound where the termites are active. Once there, the air is ready to be powered on another circuit of 'thermosiphon flow' through the mound. Some termite mounds have a chimney that opens to the outside (Figure 4.2), which enables cooling by a mechanism called 'induced flow' by biologists and 'the stack effect' by architects. The hot air escapes from the chimney and pulls in cooler air from vents close to the ground.

Mick Pearce made use of both thermosiphon and induced flow cooling when designing the Eastgate Centre (Figure 4.3). The Centre comprises two buildings side by side linked together by an atrium covered by a glass roof. Along the ridge of the red tiled roof are 48 brick funnels topping internal stacks that can pull the air out of the seven floors of offices below. Heat gain is reduced by limited glazing, especially on the sides facing the sun,

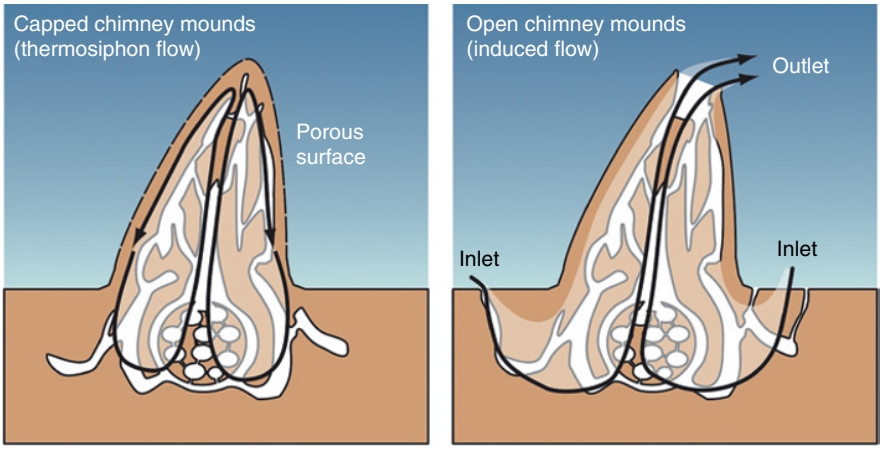


Figure 4.2 The two types of cooling in termite mounds. *Source:* Reproduced courtesy of Scott Turner.

Figure 4.3 The Eastgate Centre in Harare. Note how the design minimizes opportunities for the sun to heat the air inside the building.

and by large overhangs on the windows that keep the direct sun off the glass. During the day, the heavy building mass and a rock storage in the basement absorb the heat of the environment and human activity aided by fans that give two air changes per hour. This is effectively thermosiphon flow. At night, cool air is allowed into the bottom of the building and starts the induced flow, with the hot daytime air venting through the roof into the

much colder night air. Fans that provide 10 air changes per hour facilitate transfer of heat from the building mass to the internal air. As the building cools down, cold air is stored in the basement and then distributed next day into offices via hollow floors and ceiling vents.

The Eastgate Centre opened in 1996 and since then its temperature control has been equal to or slightly better than originally predicted by Ove Arup, the engineers responsible for construction. The Centre uses 35% less total energy than the average consumption of six other 'conventional' buildings in Harare with standard HVAC systems. The saving on capital cost compared with full HVAC was 10% of total building cost. During the frequent shut downs of mains power, or of HVAC systems due to poor maintenance in other buildings, the Eastgate Centre continues to operate within acceptable comfort levels. Not surprisingly, the design of the Eastgate Centre is seen as one of the greatest examples of biomimicry. There is just one problem: contrary to popular opinion, termites do not regulate the temperature of their nests.

In a classic paper in 2008, Scott Turner and Rupert Soar showed that the temperature within termite nests varies by 17 °C between summer and winter and closely approximates the temperature of the ground at a depth of 1 m. They also found that in mounds with open chimneys, capping the chimney to stop induced flow had no effect on nest temperature. The termite nests are embedded in the capacious thermal sink of the deep soil and their temperature is driven by this large thermal capacity. That is, the mound infrastructure and nest ventilation play little role in controlling nest temperature. Scott Turner and Rupert Soar discovered that termite nests are functionally much like the lungs of animals. This led them to suggest that instead of being barriers, walls could be adaptive interfaces, i.e. they could be functional.

The design of the Eastgate Centre may have been based on erroneous ideas about how termite mounds function but it is still an outstanding example of biomimicry because architect Mick Pearce got his design inspiration from these mounds. Ten years later, he used the same design principles for the Council House 2 (CH2) building in Melbourne, Australia. An additional biomimetic feature is the facade of the building, which is composed of an epidermis (outer skin) and a dermis (inner skin). The dermis consists of the outside zone and houses the stairs, lifts, ducts, balconies, sunscreens, and foliage, with the inner line defining the extent of the 'fire compartment'. The sun and glare control for the building is located in the epidermis. The north facing facade is composed of steel trellises and balconies supporting vertical gardens nine stories high. The foliage protects the building from the sun and filters sunlight for a reduction of indoor glare. Covering the west facing facade is a series of timber louvres that open and close automatically depending on the strength of the sun.

To date, termite mounds have been the inspiration for air cooling in modern buildings but perhaps we have missed a bigger opportunity. Tom McKeag, co-founder of *Zygote Quarterly*, has pointed out that termites take ordinary soil constituents and build structures up to 25 ft (~8 m) tall that require a stick of dynamite to remove. They maintain precise living conditions for millions of inhabitants and do this with brains the size of a pinhead!

If you have ever travelled to different parts of the world, you will have realized that a particular temperature in a desert region feels much more comfortable than the same temperature in a tropical region. The difference between the two is their relative humidity: the higher the humidity, the more uncomfortable we feel because the amount of water vapour

in the air slows the evaporation of perspiration and keeps the body from cooling. People often think that the role of air conditioning systems is simply to reduce temperature. In reality, much of their cooling effect comes from dehumidification. In traditional air cooling systems the air is passed over a cooling coil such that it reaches its dew point temperature. The dew point is the temperature to which air must be cooled to become saturated with water vapour. When further cooled, the airborne water vapour will condense to form liquid water (dew).

High energy demands is a major problem associated with the use of conventional air conditioning systems. In many parts of the world, as in Harare (see earlier), electric utilities regularly have trouble servicing peak air conditioning loads. A more energy-efficient process for reducing humidity is to pass the air through liquid or solid desiccants. Most readers will be familiar with the packets of silica gel that can be found in packaging to prevent moisture damage to new products. For air conditioning in buildings the best desiccants are lithium chloride, lithium bromide, or calcium chloride, but these salts are very corrosive to the metals used in air handling systems. The brown dog tick from the insect world rather than termites might provide one solution to this problem.

Ticks are able to remain hydrated and viable despite waiting for months between blood meals because they are able to absorb water from the atmosphere by secreting a hydrophilic solution from their mouths. Once the solution is saturated, the tick draws the now hydrated secretion back into its mouth. This adaptation allows ticks to absorb water vapour from close to saturation down to 43% relative humidity. The secretion does not damage tick tissues so identifying the hygroscopic salts it contains could provide inspiration for new desiccants for dehumidifiers.

4.2 Functional Structures Inspired by Nature

There are many situations, such as airport terminals and shopping malls, where large open buildings are needed to create a feeling of space and to facilitate orientation. A challenge for architects is how to stabilize the large roof structures that accompany such buildings while minimizing the amount of usable floor space taken up by roof supports. Architects Gerkan, Marg and Partners came up with one solution in the 1990s when they designed the new airport buildings at Stuttgart Airport. They used tree-like support structures for the roof, which is divided into 12 sections partitioned by skylights. One single support consists of four attached tubular poles that form the ‘trunk’ of the tree. Each pole spreads into multiple branches that are distributed to carry the roof loads in compression with minimal bending moments (Figure 4.4). All the loads from the roof pass down through the branches into the trunk and then down into the foundation.

What makes the structure of the tree-like support branches holding up the roof so unique is how large a span the column holds up in comparison to its footprint at ground level. However, even though trees inspired the design of the Stuttgart Airport terminal, the inspiration ends at its appearance. Unlike real trees, the outermost branches of the roof supports carry relatively heavy loads. The column structure more closely resembles umbels, the flower clusters that are characteristic of the parsley family (Figure 4.5). They have stalks of nearly equal length that spring from a common centre much in the same way as the spokes of an umbrella.

Figure 4.4 The roof of Stuttgart Airport terminal showing the tree-like supports for the roof.

Figure 4.5 Flower umbels in a member of the parsley family (Apiaceae).

In contrast to the tree-like structures used at Stuttgart Airport to minimize the number of roof supports, the biomes at the Eden Project in Cornwall have no ground supports at all. Grimshaw Architects designed the biomes and their initial inspiration came from geodesic domes. Walther Bauersfeld, the chief engineer of the Carl Zeiss optical company, built the first geodesic dome just after World War I; however, starting in the 1950s, the American architect Buckminster Fuller popularized the use of geodesic domes. The geodesic dome appealed to Fuller because it was extremely strong for its weight, its 'omnitriangulated'

surface provided an inherently stable structure, and because a sphere encloses the greatest volume for the least surface area.

The two biome buildings at the Eden Project each consist of several domes joined together (Figure 4.6). The biomes are located in a disused china clay pit that is over 200 ft (61 m) deep but at the time the biomes were being designed, the clay pits were still being mined. In the face of this constantly shifting landscape, Grimshaw took inspiration from soap bubbles. These adapt to any surface they settle on and when two or more bubbles join, the line of the join is always perpendicular. Basing the 'lean to' biome structures on soap bubbles was a perfect way to build on the uneven and shifting sands of the pit.

In what might be thought of as 'reverse biomimicry', Buckminster Fuller's geodesic domes provided the solution to the structure of spherical viruses. A virus particle consists of nucleic acid (the genetic material) surrounded by a protective coat of protein called a capsid, which is formed from identical protein subunits called capsomeres. Electron microscopy has revealed that many viruses are spherical (Figure 4.7), but how the capsomeres, which have an irregular shape, could be packed into a regular shape was not known. After studying the structure of geodesic domes, Donald Caspar and Aaron Klug in Cambridge (UK) realized that a regular icosahedron is the optimum way of forming a closed shell from identical subunits. A regular icosahedron has 20 identical triangular faces and on each face 3 identical but irregular capsomeres can be arranged symmetrically.

The Landesgartenschau Exhibition Hall at the University of Stuttgart (Figure 4.8) is another building with no internal supports and the inspiration for the construction of this building

Figure 4.6 The biomes at the Eden Project. The top three domes make up the tropical biome and the two domes that partly can be seen on the right make up the Mediterranean biome.

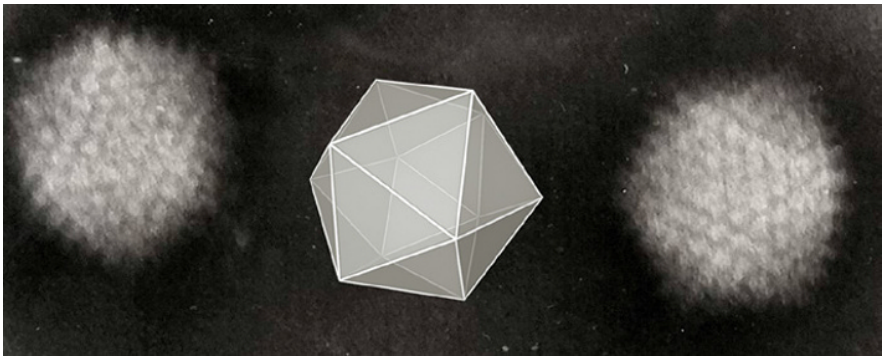


Figure 4.7 Electron micrographs (left and right) of a spherical virus and a model of a regular icosahedron (centre).

Figure 4.8 The Landesgartenschau Exhibition Hall at the University of Stuttgart. *Source:* Reproduced courtesy of ICD Institute for Computational Design and Construction, Faculty of Architecture and Urban Planning.

came from sea urchins. The skeleton of sea urchins is a modular system made of calcium carbonate plates that are joined by microscopic interlocking projections along the plate edges. Although each plate is very thin, the assembled structure is very strong. The main structure of the exhibition hall was assembled from 243 different plywood plates that were manufactured off-site by a robotic fabrication method. The building is arranged in two spaces, an entrance of area and an exhibition area, with a large glass opening at the end framing views of the surrounding landscape. Each area has its own domed ceiling made of convex polygonal beech plates and the two are connected by a narrower passage made of concave plates. With an external surface area of 245 m^2, a floor space of 125 m^2 and a maximum height of 17 m, the entire structure required just 12 m^3 of beech wood. Just as nothing ever is wasted in nature, the same was true with this building: off-cuts from the fabrication process were used to create the parquet flooring inside. One of the most notable features of the building is that, just like the sea urchin skeleton, the wooden panels comprising the entire structure are only 50 mm thick.

The University of Stuttgart has taken biomimicry a stage further than the exhibition hall. Its Institute for Computational Design (ICD) has collaborated with the Institute of Building Structures and Structural Design (ITKE) to design a new research pavilion every year. Each yearly iteration replicates a particular biological process. For the 2016–2017 pavilion (Figure 4.8), the team examined two species of leaf miner moths whose larvae spin silk 'hammocks' that stretch between connection points on a bent leaf. With yet more bioinspiration, the final structure was constructed by spinning fibres in much the same way as the leaf miners except that drones were used.

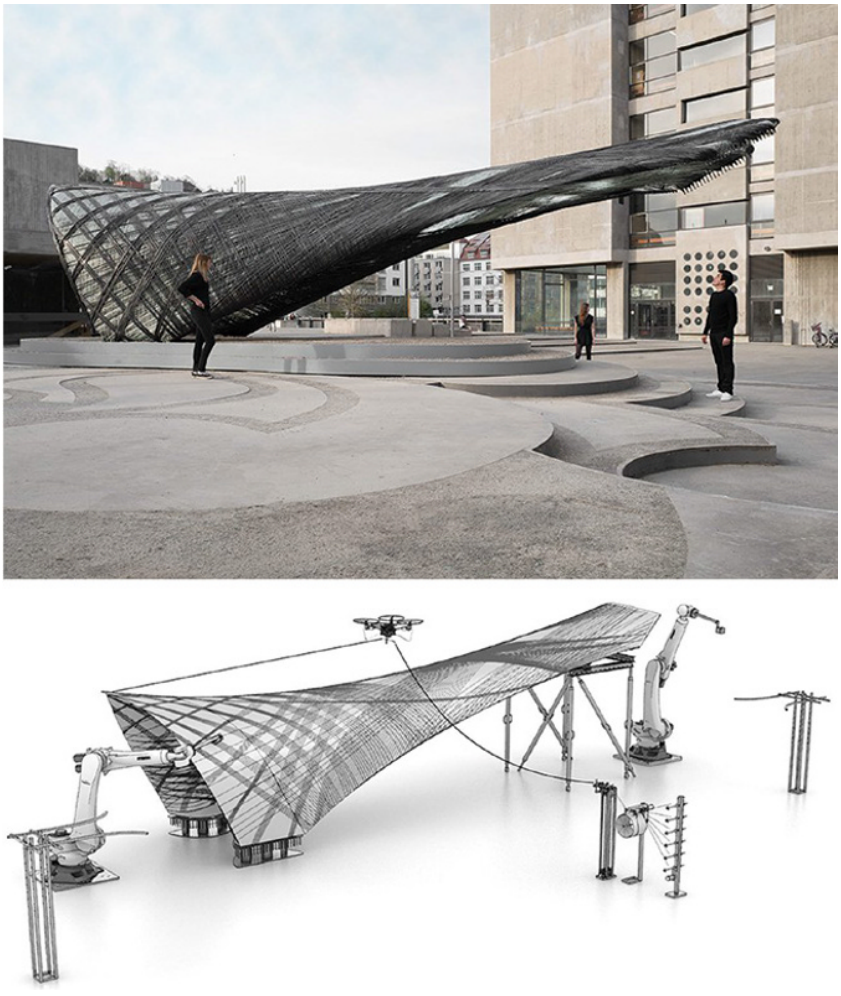


Figure 4.9 The 2016–2017 Research Pavilion at the University of Stuttgart. The final pavilion after construction (top) and the method of construction by spinning fibres (bottom). *Source:* Reproduced courtesy of ICD Institute for Computational Design and Construction, Faculty of Architecture and Urban Planning.

4.3 Self-Cleaning Surfaces

In the 1970s, Wilhelm Barthlott was the first botanist to study biological surfaces using scanning electron microscopy. His main interest was plant systematics and he was interested to know if the fascinating nano- and micro-structures that he saw could be used for classifying different plant taxa. To study these surface structures the leaves had to be prepared and cleaned. Barthlott soon realized that the leaves of some species were always clean whereas the surfaces of other species were always dirty. Surprisingly, there was a correlation between cleanliness and wettability. The smooth hydrophilic leaf surfaces were markedly dirty whereas the water-repellent, hydrophobic leaf surfaces with microscale roughness were always clean. A publication detailing these observations went unnoticed outside of a small group of plant taxonomists.

In the 1990s, Barthlott[1] and his student Christoph Neinhuis began a detailed investigation on the structural and functional basis of the self-cleaning ability of certain plant leaves. They

chose the lotus plant (*Nelumbo nucifera*) as their model because its leaves are always clean even though it grows in very muddy water. The cleanliness of the leaves in such an environment is so noticeable that the lotus has become a symbol of purity in many Eastern cultures. Examination of the surface of lotus leaves under a microscope revealed that the surface of the outer layer of cells (epidermis) is not smooth but is bumpy. This bumpy epidermis is covered by a thin layer of wax crystals that are water-repellent (Figure 4.10). These two properties make the leaf super-hydrophobic (contact angle >140°) and self-cleaning. Water falling onto

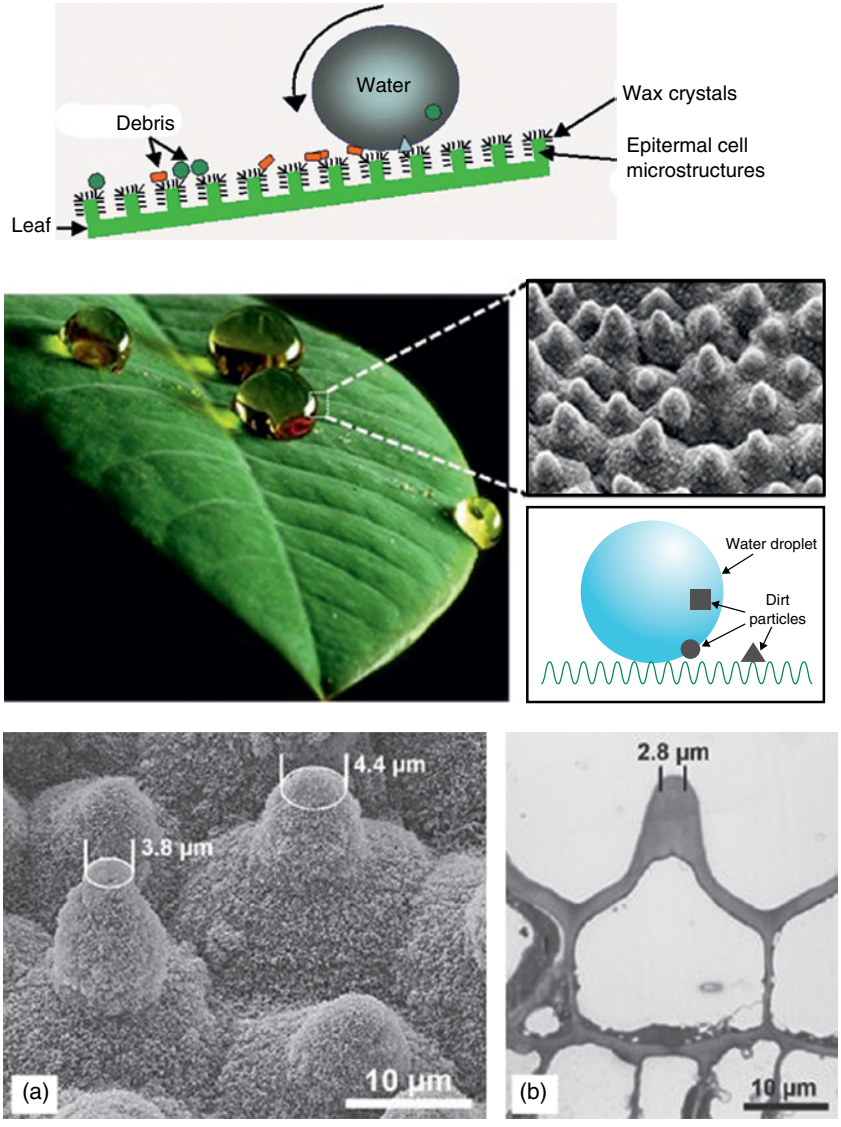
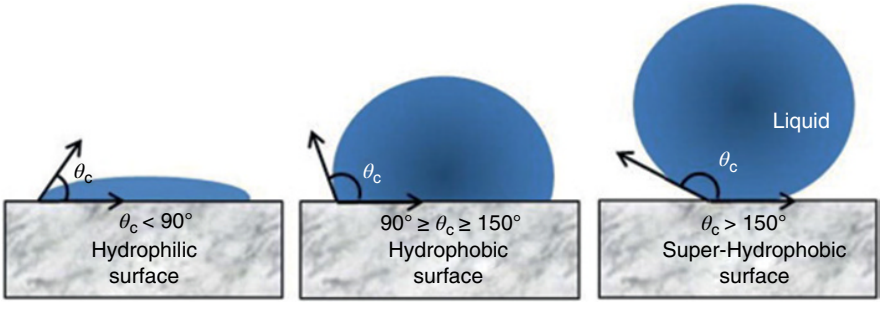


Figure 4.10 How the lotus leaf is self-cleaning. (Top) diagrammatic representation of a water drop rolling down the surface of a lotus leaf where it will pick up any dirt in its path. (Centre) Water on a lotus leaf and a large-scale magnification of part of the leaf surface showing the bumpy surface. (Bottom) Electron micrograph of the bumpy surface (left) and a thin section through a bump (right).

the surface of the leaf forms nearly spherical beads that easily roll off; any dirt clings to the water droplet rather than to the waxy, bumpy surface of the leaf, and so is carried away. It is this complex surface coating that enables the leaf to be self-cleaning, a phenomenon dubbed the 'lotus effect' (now trademarked as Lotus-Effect®).

Wetting and Contact Angle

Wetting is the ability of a liquid to maintain contact with a solid surface that results from intermolecular interactions when the two are brought together. The degree of wetting (wettability) is determined by a balance between adhesive and cohesive forces. Adhesive forces between a liquid and solid cause a liquid drop to spread across the surface. Cohesive forces (surface tension) within the liquid cause the drop to ball up and avoid contact with the surface. The balance between these opposing forces is quantified by measuring the contact angle. As the tendency of a drop to spread out over a flat, solid surface increases, the contact angle decreases. Thus, the contact angle provides an inverse measure of wettability. A contact angle less than 90° (low contact angle) usually indicates that wetting of the surface is very favourable, and the fluid will spread over a large area of the surface. If the liquid forms a thin film on the surface there is near-perfect wettability and contact angle will be close to zero. Contact angles greater than 90° (high contact angle) generally means that wetting of the surface is unfavourable, so the fluid will minimize contact with the surface and form a compact liquid droplet. For water, a wettable surface may also be termed hydrophilic and a nonwettable surface hydrophobic. Superhydrophobic surfaces have contact angles greater than 150°, showing almost no contact between the liquid drop and the surface.



At the time when the Lotus-Effect was discovered nobody had ever considered that objects might clean themselves when their surface was modified. Accordingly, there was little interest from industry – but there was a change of opinion following the granting of a patent. Soon there were collaborations with manufacturers of paints, roof tiles, and producers of lacquer additives, plastics, and textiles. The best-known product to arise from these collaborations is Lotusan® facade paint (Sto SE & Co. KGaA), which has been on the market since the late 1990s. The Lotus-Effect with this paint comes from the inclusion of materials that form a microtextured surface that mimics the lotus leaf (Figure 4.11).

Olga Speck and her colleagues at the University of Freiburg carried out a detailed product sustainability assessment on Lotusan and compared its performance with a conventional facade paint. Although Lotusan was the more expensive product, the extra cost was more than offset by its longer lifetime, resulting in reduced material demand and lower labour costs.

Detailed analysis of treated surfaces has shown that Lotusan does more than keep the surface clean and bright: painted surfaces stay free of fungi and algae for many years even when they are directly under trees. Algae and fungi produce acids that can degrade surfaces and the traditional way of preventing their growth is to add biocides to facade paints; however, these biocides slowly leach into the environment where their toxicity is a concern. Self-cleaning paints are thus an eco-friendly alternative to biocides. The Lotus-Effect has been applied to several other materials including: Erlus Lotus (Erlus AG), self-cleaning clay roof tiles that stay free of moss, algae, soot, and other dirt; Mincor TX TT (BASF), a fabric coating used to manufacture self-cleaning awnings, tents, and patio umbrellas; and as the basis for the Nanosphere fabric finish (Schoeller Technologies) for conventional clothing and for the next generation of non-stick cookware (Lotus Rock, Biolux Kerama). The original non-stick cookware made use of coatings such as Teflon where the fluorine atoms provided the surface hydrophobicity; however, these surfaces leach fluorinated chemicals into food. In the new generation of non-stick cookware, a coating of silicon oxide crystals mimics the lotus leaf by producing surface roughness and hydrophobicity.

It is worth noting that there are non-biomimetic self-cleaning materials. Luigi Cassar working at Italcementi developed self-cleaning concrete that works by photocatalysis. This concrete contains titanium dioxide and, in the presence of sunlight, reactive oxygen species are created that decompose organic pollutants. There are two downsides with this approach. First, inorganic pollutants are not destroyed, whereas they would wash off a surface treated

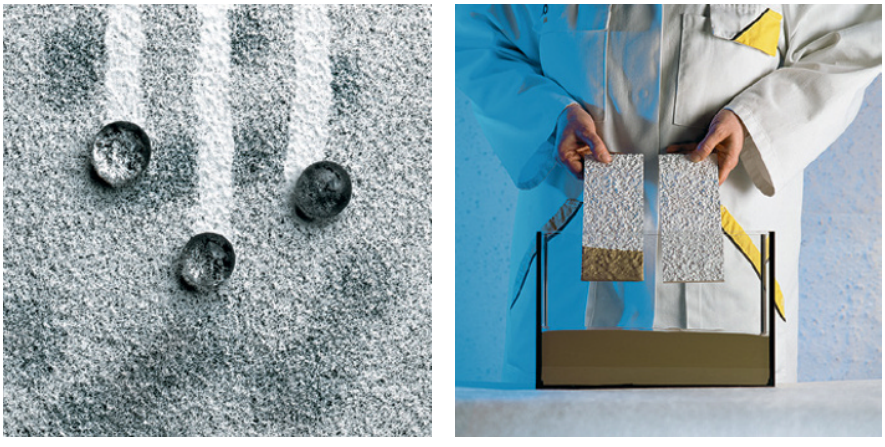


Figure 4.11 Lotus effect on a painted surface. (Left) rain washing dirt off a surface painted with Lotusan. (Right) comparison of self-cleaning by two surfaces, one painted with Lotusan and one painted with ordinary paint. *Source:* Reproduced courtesy of Sto Ltd.

with Lotusan. Second, self-cleaning concrete interacts with nitrous oxide in the air to generate nitrates that ultimately will pollute waterways. Titanium dioxide is also the key ingredient in most self-cleaning glass but there are some varieties, such as that manufactured by Ferro AG, which are based on the Lotus-Effect.

4.4 Self-Healing Concrete

Concrete is the single most widely used construction material in the world because it is cheap and widely adaptable. However, it has a relatively low tensile strength and so is susceptible to cracking. This cracking in conventional reinforced concrete is virtually unavoidable because of thermal effects, early-age shrinkage, mechanical loading, freeze–thaw effects, or a combination of these factors. Cracks allow the ingress of water, carbon dioxide, and chloride ions into the structure, which eventually reach the steel reinforcement. When the steel erodes, it swells causing more cracks and eventual deterioration. Repairing damaged concrete is painstaking, labour-intensive, and costly. Because concrete manufacture is responsible for 8% of the world's carbon dioxide emissions, any conventional repairs or replacement of concrete structures will have a significant carbon footprint.

Construction materials such as concrete are static and unresponsive. By contrast, living organisms can repair damage to the biological materials that comprise their structure, as exemplified by the healing of bone fractures. The bone healing process has three overlapping stages: inflammation, bone production, and bone remodelling. When the bone is fractured, there is bleeding into the area, leading to inflammation and blood clotting at the fracture site. This provides the initial structural stability and framework for producing new bone. Bone production begins when the clotted blood formed by inflammation is replaced with fibrous tissue and cartilage (known as soft callus). As healing progresses, the soft callus is replaced with hard bone (known as hard callus), which is visible on X-rays several weeks after the fracture. Bone remodelling, the final phase of bone healing, goes on for several months. The bone continues to form and becomes compact, returning to its original shape. Could the bone healing process be mimicked for the repair of concrete?

Hendrik Jonkers of Delft Technical University in the Netherlands is a microbiologist who studies the interplay of bacterial ecology and metabolism. He knew that under the right environmental conditions some microorganisms can produce calcium carbonate, the building block of animal shells and pearls. Jonkers wondered if these microorganisms could be used to create self-healing concrete. One potential problem was the alkalinity of concrete: it has a pH value >10 and thus toxic to most organisms. He isolated a bacterium (*Bacillus sphaericus*) that had the ability to produce calcium carbonate from carbon dioxide from the alkaline soda lakes that occur in various parts of the world. An important characteristic of *B. sphaericus* is that it can form spores that are highly resistant, dormant structures. The spores remain inactive when they are encapsulated with nutrients and incorporated into concrete. When there is water ingress, the spores germinate and produce calcium carbonate that seals the cracks (Figure 4.12).

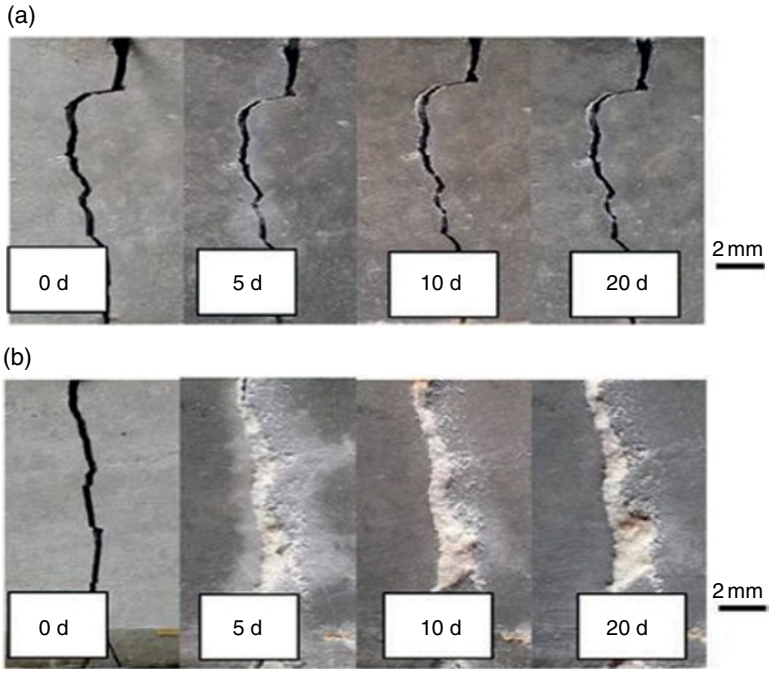


Figure 4.12 Changes in cracks in concrete over 20 days: ordinary concrete (top) and self-healing concrete (bottom). *Source:* Reproduced courtesy of Qian et al. (2015).

Different formulations of Jonkers' bacterium have been produced and a company (Basilisk Concrete) has been established to commercialize them. However, the key question is whether self-healing concrete can be used on a live construction site and not just in a laboratory environment. The first real test came during a major road upgrade near Abergavenny in South Wales, UK. Mock retaining walls, or panels, were built on a site compound using the same construction processes as the concrete structures being built for the permanent works. The panels then were damaged by controlled loading and this generated cracks in them. Subsequent monitoring of the panels showed that self-healing occurred but different formulations were best suited to different types of cracks. Therefore, it will be necessary to identify the damage mechanism involved to select the best formulation.

There is much more work to be done before microbially induced self-healing of concrete becomes commonplace. In the meantime, a group at Binghamton University in the USA is pioneering the use of a fungus instead of bacteria and Jonkers has extended his method to the repair of concrete in low temperature marine environments.

4.5 New Building Materials

The built environment is constructed using a limited palette of traditional materials: concrete, bricks, glass, steel, and wood. Nearly three billion tons of cement are produced each year releasing vast amounts of carbon dioxide. Traditional brick-making is not any better as

Figure 4.13 A bioMASON brick manufactured at ambient temperature. *Source:* Reproduced courtesy of bioMASON, Inc.

it involves baking clay in kilns at 2000 °C for several days. The 1.23 trillion bricks produced each year result in 800 million tons of carbon emissions. Ginger Krieg Dosier was working for an architectural firm in 2005 when she was tasked with looking into green alternatives for building materials. When it came to brick and masonry, her searches came up with nothing. When she moved to North Carolina State University to teach architecture she started to investigate potential ways to make masonry more eco-friendly.

Dosier was fascinated by how coral was able to make incredible structural formations that could withstand water and erosion. Coral essentially is colonies of polyps embedded in a calcium carbonate shell. Dosier wondered if the process of coral formation could be replicated to create bricks. Eventually she found out how to do it and founded BioMason to exploit the technology. To make each brick, the company starts with sand packed into rectangular moulds. The moulds are inoculated with a bacterium called *Sporosarcina pasteurii*. Over the course of several days, an irrigation system feeds the sand with nutrient-rich water containing calcium ions. Each bacteria-covered grain of sand acts as a nucleus and calcium carbonate crystals begin to form around it. The crystals grow larger and larger, filling in the gaps between the grains of sand. After three to five days, the bricks (Figure 4.13) are ready for use – the same time as it takes to kiln-fire a conventional brick but with a fraction of the energy input. The bricks have proved to be as durable as sandstone and can be shaped into multiple shapes and sizes. To ensure that the manufacturing process is as green as the product itself, the water is reused to produce the next batch of bricks.

4.6 A Sunshade Modelled on Trees

Most people savour the pleasurable warmth of the sun as winter turns to spring, but as temperatures rise with the approach of summer, many of us seek shade from the sun. If we want to sit outside then we usually do so under a sunshade to keep off the direct rays of the sun but, because of lack of ventilation, the air may still feel stiflingly hot. Professor Satoshi Sakai of Kyoto University (Japan) noted that the surfaces of leaves are cooler than the ambient air, even under direct sunlight, and this led him to develop a product called the COMOLEVI Forest Canopy. 'Comolevi' is a Japanese word meaning 'sunlight filtering through leaves'.

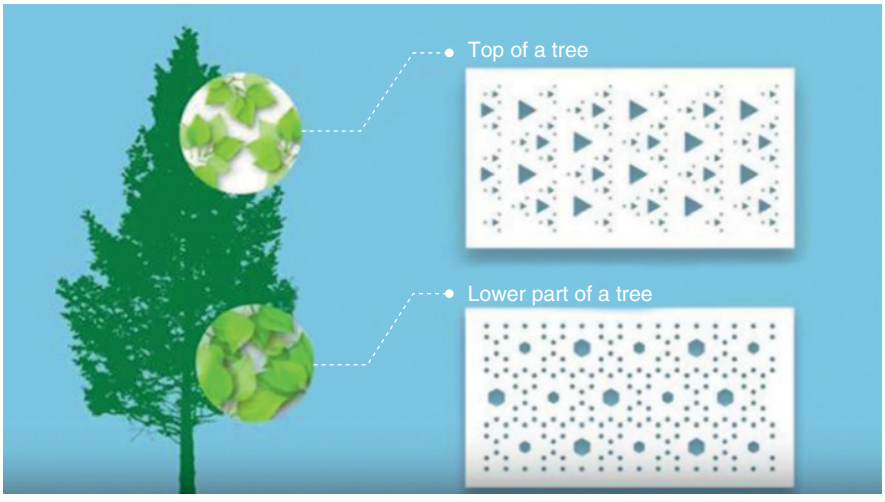


Figure 4.14 The two patterns of canopy in the COMOLEVI Forest Canopy.

The COMOLEVI Forest Canopy works by mimicking nature's fractal shading and was designed using a mathematical concept known as Sierpinski Tetrahedrons (see Sierpinski Tetrahedron Box). Rather than one solid sheet hung above to provide shade, the canopy is made of two sheets with two different fractal patterns cut into them (Figure 4.14). The top pattern is made with a pattern of triangular cutouts that model the leaves at the top of the tree. These leaves move faster in the wind but in smaller amplitude. The bottom canopy is cut with hexagonal cutouts that mimic the lower leaves on a tree. These leaves move slower but with larger amplitude.

The combination of these two canopies helps provide shade to the user while also simulating the comforting feel of sitting under a tree. Furthermore, the holes in the canvas allow air to pass through which helps cool the canvas itself. A typical solid canvas does not allow air to pass through it: it heats up and in turn heats the air below it. The COMOLEVI Forest Canopy allows air to pass which thus cools the canvas and the air underneath. In comparison to a typical solid canvas, the COMOLEVI Forest Canopy stays up to 12 °C cooler and this leads to much cooler air temperatures underneath.

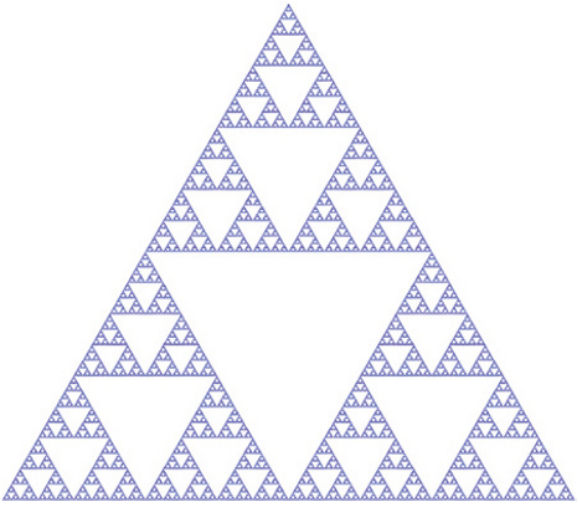
The COMOLEVI Forest Canopy was designed to provide better and more natural shade to humans. However, its impact could be much greater. Since there is more airflow and less trapped heat, this design could provide better temperature regulation on a larger scale and this in turn could potentially help with the climate and global warming.

4.7 Solar Ivy

Many households are installing solar panels in order to reduce electricity bills. These panels, also known as photovoltaics, capture the sun's energy using photovoltaic cells and convert it into electricity. The cells don't need direct sunlight to work – they can still

Sierpinski Tetrahedron

A Sierpinski triangle is a fractal based on an equilateral triangle, made by dividing the triangle into four smaller triangles, removing the central triangle and then repeating for each of the three remaining triangle. If you repeat this process forever you get a fractal. A Sierpinski tetrahedron is a three-dimensional version of the Sierpinski triangle and is made up of four smaller tetrahedra with a space in the middle.



generate some electricity on a cloudy day, which is particularly useful in countries like the UK that have very variable weather. For space reasons, most household solar panels are installed on roofs but they adversely affect the visual appearance of buildings. A Brooklyn-based company, SMIT (Sustainably Minded Interactive Technology) has developed a more aesthetically pleasing alternative called Solar Ivy.

Ivy receives direct sunlight without having to compete with other plants by growing vertically using walls for support. SMIT has developed solar panels that look like leaves and the solar leaves come in different colours, spacing, and orientation. These panels are hung on the walls of buildings and are arranged to look like a normal ivy covering.

4.8 The Future: Fully Responsive Buildings

Buildings are usually static structures. At best, they have a limited ability to monitor surrounding environmental conditions, e.g. temperature, using sensors and to respond to them. However, B+U Architecture has shown what the future might hold by turning a structure into an artificial organism. Their 'Apertures' installation looks like something out of a science fiction film but it is capable of determining how many people are present. It features heat sensors that detect the presence of visitors when they are near porthole

apertures. The sensors feed these heat readings into an algorithm and translate them into sound. When a few people are in the installation, a low hum is emitted and this attracts more visitors. As the number of visitors increases, the sound gets louder until at close to maximum capacity it becomes a shriek. This shrieking repels visitors and the sound subsides again. Jenny Sabin of Cornell University has taken a different approach. She has developed electronic materials that can sense the presence of people by detecting changes in ambient light and that respond by changing colour. For the moment, these are demonstrator projects but they give an indication of what the future might hold. The reader with a particular interest in this topic should read the paper by Heinrich and colleagues (2019) cited below.

Relevant Innovations Described in Other Chapters

Omnilux glass to prevent bird strikes (Chapter 3, Section 3.6).
Self-cleaning materials (Chapter 5, Section 5.1).
Self-healing materials (Chapter 5, Section 5.3).

Note

1 Professor Barthlott also recognized the benefits of the *Salvinia* effect (see Chapter 2, Section 2.10) as a potential means of preventing biofouling.

Suggested Reading

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Xu, Q., Zhang, W., Dong, C. et al. (2016). Biomimetic self-cleaning surfaces: synthesis, mechanism and applications. *Journal of the Royal Society Interface* https://doi.org/10.1098/rsif.2016.0300.

5

Smart Materials

Let Nature be your teacher

William Wordsworth

Peter Fratzl is head of the Biomaterials Department at the Max Planck Institute of Colloids and Interfaces (Germany) and has been a pioneer in the field of biomimetic materials. In a classic paper in 2007, he asked 'What can we really learn from nature's structural materials?' In this paper, he compared the approach of nature to that of the material scientist and noted some key differences. First, nature uses a very limited range of elements and never uses metals for their mechanical properties, unlike the engineer. Second, natural materials often combine stiff and soft components in hierarchical structures, as is the case for bone, silk, and mother of pearl. Hierarchical materials are ones that contain various structural elements, each of which contains its own structural elements. Such complex materials would not be the first choice of an engineer or a material scientist but their use is the way that nature makes strong materials at ambient temperatures. Third, natural materials often have the capability to self-repair, e.g. bone, and this distinguishes them from most manufactured materials. Fratzl cited other differences (see Figure 5.1), but it is choice of material, hierarchy, and self-healing that we will focus on in this chapter.

5.1 Self-Cleaning Materials

5.1.1 Reducing Bacterial Growth Without Disinfectants

The contamination of surfaces with microbes, particularly bacteria, is a major issue for healthcare professionals. Pathogens such as methicillin-resistant *Staphylococcus aureus* (MRSA), vancomycin-resistant *Enterococcus* (VRE), and *Escherichia coli* and its relatives are able to survive on surfaces for months and can be a major source of hospital-acquired infections. The problem is particularly acute with in-dwelling biomedical devices such as catheters, blood access systems, and surgical drains. The initial colonization of a surface leads to the formation of a thicker biofilm that is resistant to antimicrobial agents and that

Biomimetics: Nature-Inspired Design and Innovation, First Edition. Sandy B. Primrose.

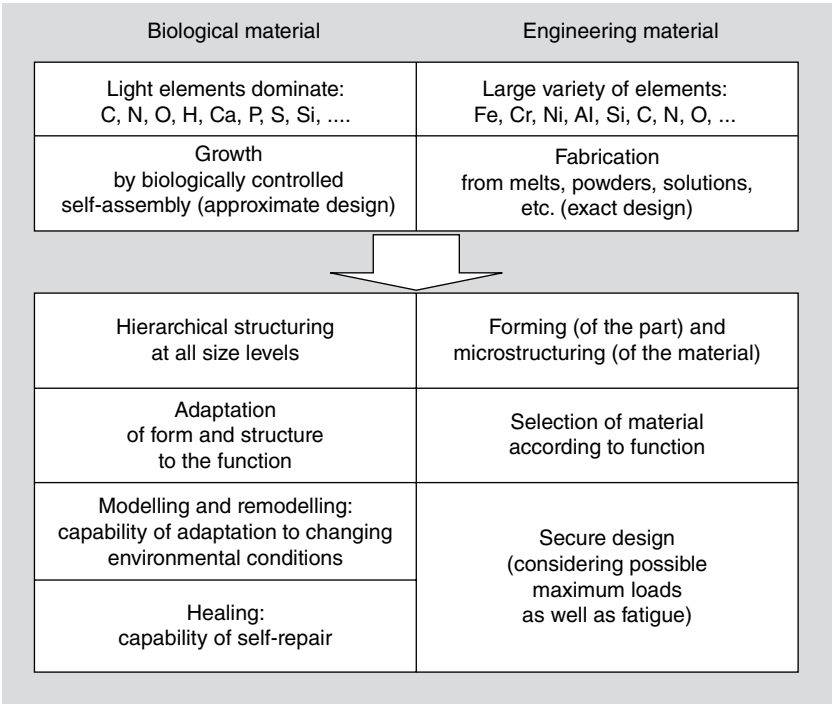

Figure 5.1 Differences between natural and synthetic materials. *Source:* from Fratzl (2007).

acts as a focus for infection. According to a study carried out by the Centers for Disease Control and Prevention, about 26% of healthcare-related infections in the USA in 2011 were caused by device-associated infections in acute care hospitals.

There are three strategies for eliminating or reducing surface contamination: use of biocides to prevent biofilm formation, surfaces that repel microorganisms, and surfaces that self-clean. Nature seems to use a combination of these three approaches. Biocides fall into two categories: disinfectants and antibiotics. The advantage of disinfectants is that microbes seldom develop resistance to them, but the disadvantage is that at effective concentrations they are toxic to human cells. So, disinfectants are good for killing microorganisms but all residues of them need to be removed. Most antibiotics are not toxic to human cells but many microorganisms either are naturally resistant to them or can develop resistance. Inappropriate use of antibiotics means that many pathogens that were previously sensitive to them are now resistant. This is a major problem worldwide. The message is clear – biocides should not be used to prevent biofouling of in-dwelling devices.

As noted in Chapter 2 (Section 2.9), the investigation of micropatterned surfaces that mimic sharkskin to prevent biofouling of ship's hulls, led Tony Brennan at the University of Florida (USA) to invent Sharklet® (Figure 5.2). He reasoned that micropatterned surfaces should be equally effective at preventing biofilm formation on medical materials, and this was indeed true. When tested with *S. aureus,* a smooth surface showed colonies of biofilm

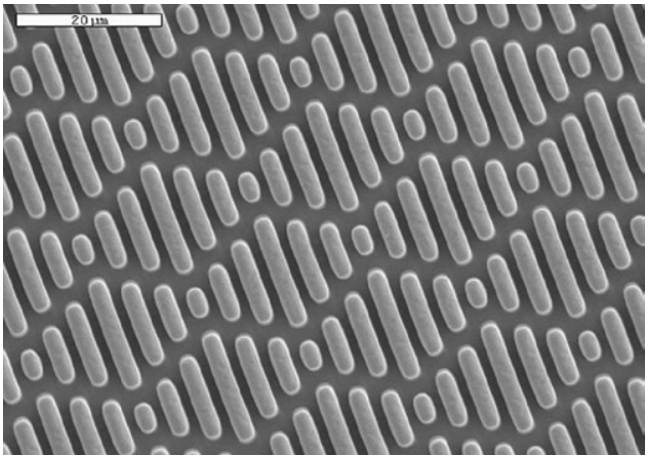

Figure 5.2 An example of biofilm-resistant Sharklet material showing the diamond-shaped repeating pattern.

after 7 days and mature biofilm after 14 days. The same material with a Sharklet surface did not show evidence of early biofilm colonization until day 21.

There are several different Sharklet micropatterns and most of those tested reduce surface colonization by bacteria of clinical relevance. One of the most effective is a diamond-shaped repeating pattern of seven features. The width of the features is 2 µm, the spacing between them is 2 µm, and the lengths of the features range from 4 to 16 µm in increments of 4 µm. To put these sizes in context, the common urinary tract pathogen *E. coli* is 2 µm long. When flat and cylindrical surfaces were tested in animal models of infection, the pattern just described reduced adherence and transference of several key pathogens by 90–99% compared with smooth surfaces. In this context, adherence is the ability of the bacteria to colonize a surface and transference is the ability of bacteria to move between tissue (e.g. the urethra) and the device (e.g. catheter). Sharklet micropatterning also significantly reduced the accumulation of mucus and the development of biofilm on endotracheal tubes, a major problem for patients undergoing mechanical ventilation.

The exact mechanism whereby microstructured surfaces remain free of biofouling is not understood. It has been suggested that it is a combination of anisotropic (directional) flow of water and superhydrophobicity (lotus self-cleaning effect, Chapter 4, Section 4.3), but this remains to be proven. What is known is that species that remain free of fouling (e.g. crabs, bivalves such as mussels, and egg cases of certain fish), all have outer surfaces that are micropatterned. More important, provided these surfaces remain intact, they remain free of colonization for the life of the organism, which can be several years. By contrast, Sharklet and similar materials only remain free of organisms for a matter of weeks. This implies that more than micropatterning is at work and there is evidence that the organisms also secrete compounds that prevent colonization. To mimic this effect, titanium dioxide particles have been attached to sharkskin surfaces where they both repel and kill bacteria when activated by light.

5.1.2 Pitcher Plants and Non-stick Surfaces

Carnivorous plants have developed the ability to trap animals, usually insects, and to digest them as a source of nitrogen. There are various different trapping mechanisms including flypaper traps (e.g. sundews), snap traps (e.g. Venus flytrap), and pitfall traps (e.g. pitcher plants). *Nepenthes* species are a type of pitcher plant that attracts insects by secreting a nectar with a floral fragrance. The visiting insects fall into the pitcher and are trapped there by various mechanisms before being digested. There were numerous theories on how the insects fell into the pitchers until Holger Bohn and Walter Federle (2004) showed that the rim of the pitcher (peristome) is very wettable (see Chapter 4, Section 4.3). The thin film of water that forms on the peristome in damp conditions acts as a lubricant and any insects landing on it aquaplane into the pitchers.

Joanna Aizenberg at Harvard University (USA) has developed an omnirepellent material modelled on the *Nepenthes* peristome. This involves a stable, immobilized, and smooth liquid surface locked in place by a specially designed porous solid. This novel slippery liquid-infused porous surface (SLIPS®) exploits the extreme stability of the fully wetted liquid film to maintain repellency in a broad range of environments (Figure 5.3). The design of stable SLIPS is based on three important criteria. First, the chemical affinity between the lubricating fluid and the solid should be higher than that between the ambient fluid and the solid. Second, the solid surface should be roughened to increase the surface area for the adhesion of the lubricating fluid and its immobilization. Third, the lubricating fluid and the ambient fluid should be immiscible.

SLIPS-based materials have been tested with a range of bacteria and remain free of biofilms over a seven-day test period. In this respect, they resemble Sharklet, but Sharklet is superhydrophobic whereas SLIPS materials are superhydrophilic. Expanded polytetrafluoroethylene (ePTFE) is used widely in implanted medical devices because it is very tough, non-adhesive, and superhydrophobic, but it is susceptible to biofouling. Aizenberg and her colleagues have infused ePTFE with perfluorocarbon liquids to generate SLIPS surfaces that exhibit a 99% reduction in *S. aureus* adhesion. Equally important is the observation that SLIPS-modified surfaces do not inhibit any of the body's natural defence mechanisms such as phagocytosis, macrophage viability, etc.

SLIPS materials often outperform their hydrophobic counterparts in terms of liquid-shedding abilities. However, the lack of drop–solid interactions on SLIPS surfaces means that controlling the motion of the liquid droplets can be difficult. Chris Thorogood and colleagues at Oxford University (UK) revisited the 'pitfall' trapping mechanism of *Nepenthes* and focused on the role of the macroscopic grooves on the peristome. When they introduced microscopic grooves on SLIPS surfaces, droplets would follow the contour of the grooves even when they ran across a surface that was tilted downwards. This observation has implications for the use of SLIPS materials in microfluidics.

The SLIPS technology is being commercialized by a company spun-out of Harvard University called Adaptive Surface Technologies. Several products featuring SLIPS are already on the market; including SLIPS Foul Protect™, a marine paint that prevents biofouling of ships' hulls (see also Chapter 2, Section 2.9); and a range of coatings that allow sticky fluids such as paints and adhesives to flow through pipes or out of containers without leaving a residue.

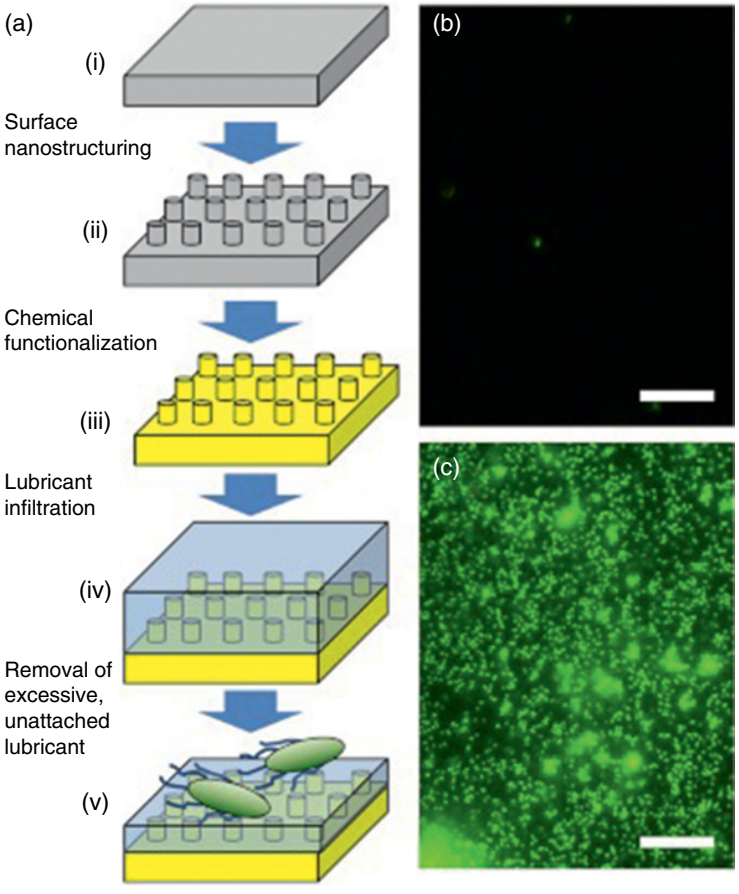

Figure 5.3 SLIPS preparation and biofilm attachment to surfaces. (a) Schematic of slippery liquid-infused porous surface (SLIPS) material concept. A flat substrate (i) is nano-patterned or roughened (ii), chemically functionalized (iii), and infused with a compatible lubricating liquid (iv), of which the excess is removed (v). (b) and (c) Fluorescence micrographs of attached bacteria following 48 hours incubation of *Pseudomonas aeruginosa* biofilm on SLIPS (b) and superhydrophobic polytetrafluoroethylene (PTFE) (c). *Source:* Reproduced courtesy of the National Academy of Sciences.

Hydrocarbon-based polymers such as polyethylene and polypropylene are the most common plastics in the world in terms of production volume. They are widely used for packaging applications because of their chemical resistance and low cost. Despite the obvious attractions of converting extruded film packaging directly into SLIPS to maximize product drainage, this had not been done because films of polyethylene were considered resistant to impregnation by oils. Polyethylene has been used as a backing material for SLIPS because of its chemical and moisture resistance. However, Jonathan Boreyko at Virginia Tech (USA) found a way to directly and stably impregnate polyethylene with lubricating oil to convert it into SLIPS. These new SLIPS repel water and viscous fluids such as ketchup and yoghurt, making them ideal for packaging applications.

5.2 Novel Adhesives

5.2.1 Novel Glues Inspired by Marine Animals

Anyone who has spent any time at the seaside can hardly have failed to notice that the rocks are covered in organisms such as mussels. But, how many people have given any thought to how a mussel can stick to a rock despite being battered by storm waves in excess of 25 m s^{-1}? One person who has is Herbert Waite, distinguished professor at the University of California, Santa Barbara (USA). His interest started when he was a student in the 1970s, continues to the present day, and has led to the development of novel adhesives.

The key to mussel adhesion is a structure known as the byssus, which consists of a bundle of threads (Figure 5.4) produced one thread at a time by a process not unlike that of injection moulding for plastics. When the foot of the mussel touches a surface, it transports precursors of the byssus down a groove in the foot and these take seconds to set into a solid strand. A sticky pad (the byssal plaque) at the end of each thread sticks firmly to the rock, boat hull, or any other surface with which it comes into contact. Waite analysed the proteins in the byssal threads and plaque, and in the glands that produce them. In each case he found substantial amounts of 3,4-dihydroxyphenylalanine (L-DOPA), a rare catechol-containing amino acid.

Waite's findings inspired numerous research groups to try to develop new adhesives using catechol-based chemistry. A key driver was the need to develop adhesives that can function successfully in aqueous environments, where other glues often fail. One such novel adhesive is poly(catechol) styrene, which was developed by Jonathan Wilker at Purdue University (USA) and is about 17 times stronger than the natural adhesive produced by mussels. This is unusual for a biomimetic product because normally synthetic versions of natural materials and compounds almost never achieve performances as good as the natural systems from which they were developed.

Adhesion to wet and dynamic from which surfaces is important in many different fields and is especially so in health care. Wound closure is usually carried out with sutures or staples but these cause additional tissue damage. This becomes critical when they are used

Figure 5.4 A mussel attached to a rock showing byssal threads. Note that the threads end in plaques.

where friable tissue is present, e.g. after myocardial infarction or in young infants. The alternative way to close wounds is to use tissue adhesives but these are far from ideal. Cyanoacrylate (Superglue) is the strongest class of tissue adhesive but is cytotoxic, incompatible with wet surfaces, and forms rigid plastics that cannot accommodate dynamic movement of tissues. Other tissue glues are based on fibrin but these are easily washed out as they have weak adhesive properties. One mussel-inspired solution to this problem is to link dopamine to a gelatine backbone. This material is capable of immediate wet adhesion on tissue surfaces but its real strength comes from the addition of ferric ions and genipin. The addition of ferric ions results in instantaneous cross-linking, while genipin – a non-toxic compound from gardenia fruit – provides additional covalent cross-linking. A mussel-inspired glue called Cell-Tak is sold by Corning Inc.

Herbert Waite has been disappointed by the emphasis on L-DOPA – to the exclusion of anything else – by scientists developing new adhesives. Mussel adhesion is a much more complex process than interaction of L-DOPA-containing proteins with a solid surface. Also, mussel adhesion in nature is not permanent: the bonds attaching the byssal threads to the substratum can be broken and reformed, unlike manufactured glues. Although L-DOPA occurs in other marine adhesives (e.g. the 'cement' used by sandcastle worms and similar creatures), other organisms such as barnacles and sea stars attach to surfaces using DOPA-free proteins. There is plenty of scope to develop more novel adhesives.

Terminology Associated with Adhesives (and Other Materials)

Adhesion is the tendency of dissimilar particles or surfaces to cling to one another (cohesion refers to the tendency of similar or identical particles/surfaces to cling to one another).

In the context of adhesives, **surface energy** is the energy released in the bonding of two surfaces. Another way to view the surface energy is to relate it to the work required to cleave a material to create two surfaces. The units of work of adhesion are joules per metre squared ($J\,m^{-2}$).

Stress is the force applied to an object that can lead to deformation. It usually is measured in kiloPascals (kPa) or pounds per square inch.

Strain is the response of a system to an applied stress. It is defined as the amount of deformation in the direction of the applied force divided by the initial length of the material.

Stiffness is the extent to which an object resists deformation in response to an applied force.

Hysteresis refers to the restructuring of the adhesive interface over some period of time, with the result being that the work needed to separate two surfaces is greater than the work that was gained by bringing them together.

Hardness is the relative resistance of a material's surface to penetration by a harder body.

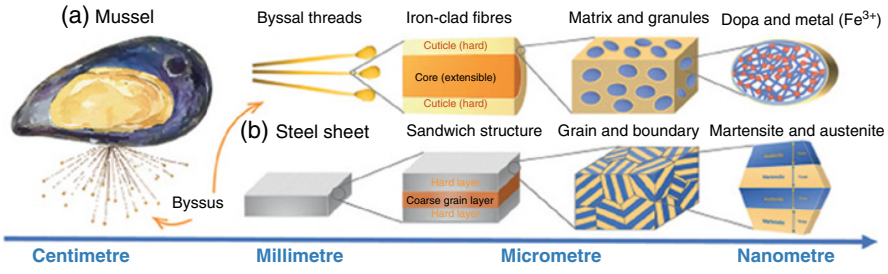

Figure 5.5 Comparison of the structure of byssal threads and the biomimetic hierarchical steel developed by Cao and Lu. *Source:* Reproduced courtesy of Cao (2018).

5.2.2 Hierarchical Steels Modelled on Byssal Threads

Steel is an alloy of iron that contains up to 2.1% carbon. Within the limited range of varying proportions of carbon and iron that make a steel, several types of metallurgical structures with very different properties can form. For example, steels with high strength often have low ductility and toughness. As many engineering applications require all of these mutually exclusive properties, the final alloy selected is often a compromise. Shan Cao and Jian Lu from the City University of Hong Kong had noted that nature is adept at developing damage-tolerant materials that are both strong and ductile through the use of hierarchical structures. A good example is byssal threads: these have tensile strengths of ~120 MPa (17 000 psi), yet are ductile and extensible.

Byssal threads contain two kinds of protein complexes. Granules are heavily cross-linked via DOPA and ferric ions and provide strength, whereas the less cross-linked matrix protein provides extensibility. Cao and Lu hypothesized that a similar mechanical response could be generated in steel if it was manufactured with a hierarchical structure. Accordingly, they developed a hierarchical steel (Figure 5.5) that was a sandwich of different allotropes (austenite and martensite). The 'bread' in the sandwich was a mixture of the two allotropes (to give strength) while the 'filling' was simply austenite (to give ductability). When tested mechanically, the hierarchical steel had much greater strength and ductility than currently available high-performance steels.

Some Definitions Used in Materials Science

Allotrope: each of two or more different physical forms in which a material can exist. Graphite, charcoal, and diamond are all allotropes of carbon.

Ductile: the ability to be deformed without losing toughness; pliable, not brittle.

Hierarchical: a solid that contains structural elements that themselves have structure.

Strength: a measure of how well a material can resist being deformed from its original shape.

Toughness: the ability of a material to absorb energy and plastically deform without fracturing.

5.2.3 Glues from Terrestrial Slugs

Terrestrial slugs are tasty morsels for many hungry animals as they lack any protective shells. One slug, *Arion subfuscus* (Figure 5.6), has a novel defensive strategy: it produces a mucus that sticks it firmly to any surface so that it cannot be prised off even if the surface is wet. In many ways the slug mucus is like chewing gum stuck to the sole of a shoe. Andrew Smith at Ithaca College in New York State (USA) has been studying this mucus for many years and has discovered that it is a very unusual glue: it is a strong adhesive despite being a dilute gel. It contains more than 95% water but can produce shear strengths over 100 kPa (15 psi). Notably, the glue seems to have an unusually high toughness for a gel. Most other gels are either weak and highly deformable, like nasal mucus or stiff and easily fractured like gelatine. *A. subfuscus* glue has a stiffness similar to 20% gelatine yet it can be stretched to 10 times its initial length. This combination of stiffness and deformability make it an ideal glue.

Andrew Smith has analysed the structure of the glue and found that it consists of two separate, intertwining networks of polymers with different properties: negatively charged proteins and proteoglycans (proteins heavily substituted with sugars). The two polymers combine to give a toughness that is several orders of magnitude greater than either network individually. The proteoglycans form a viscous and highly deformable material with virtually no stiffness but which contribute to toughness. The proteins, on the other hand, can cross-link and provide stiffness while also contributing to toughness. More than 10 different proteins are present in the glue and these proteins seem to have different functions. Many are equally abundant in the glue and in the much weaker mucus used for locomotion, but several are characteristic of the glue.

Characteristic glue proteins can stiffen gels and their presence correlates with a dramatic rise in toughness and adhesiveness. They are metal-binding proteins and the mechanics of the glue depends on metals such as iron, calcium, and zinc. Interactions involving metal ions directly link polymers, while metal catalysed oxidation leads to other cross-links.

Figure 5.6 The dusky arion slug (*Arion subfuscus*).

Jianyu Li, a material scientist at Harvard University, had been searching the scientific literature for clues on how to make a better surgical adhesive. He wanted something that could repair a delicate organ without causing the damage of stitches or staples or the risk of air or fluid leaks. Mussel-inspired adhesives, like those described earlier, rely on relatively weak physical interactions and have low adhesion energies (1–10 J m^{-2}). Commercially available medical adhesives can form covalent bonds with tissues and have higher adhesion energies, of the order of 10 J m^{-2}; however, they are brittle and susceptible to debonding. By comparison, cartilage has a high toughness (1000 J m^{-2}) and bonds to bones with an adhesion energy of 800 J m^{-2}. Li came across the work of Andrew Smith on the glue of *A. subfuscus* and got the inspiration he needed.

Like the defensive glue of slugs, the adhesive developed by Li and his colleagues consists of two layers: an adhesive surface and a dissipative matrix. The adhesive surface bonds to the substrate (tissue) through electrostatic interactions, covalent bonds, and physical penetration, even when the substrate is wet. The matrix dissipates energy through hysteresis under deformation. Several different polymers were tested for the adhesive surface and the best were chitosan and polyallylamine with adhesion energies in excess of 1000 J m^{-2}. The dissipative matrix was provided by an alginate–polyacrylamide hydrogel. When stress is applied to it, the bonds between the alginate and the calcium ions break and dissipate energy (Figure 5.7).

The new surgical adhesive was found to have a surface energy of 1116 J m^{-2} when tested on porcine skin, even when the skin was covered with blood. When tested on a beating heart, a strong adhesion was formed on the curved surface with a peak strength of ~80 kPa, eight times higher than commercial tissue adhesives. The adhesive patched holes in rat livers and remained attached for the duration of the two-week experiment, while an injectable version sealed a hole in a pig heart. A key feature of this new adhesive is that the maximum adhesion energy is not achieved immediately but develops over a period of 90–100 minutes. This property confers greater utility for surgeons, giving them time to ensure that it is applied correctly. An even more useful adhesive can be made by replacing the polyacrylamide with poly(*N*-isopropyl acrylamide). This shrinks at temperatures of 32 °C and above and so facilitates wound closure as normal body temperature is 37 °C.

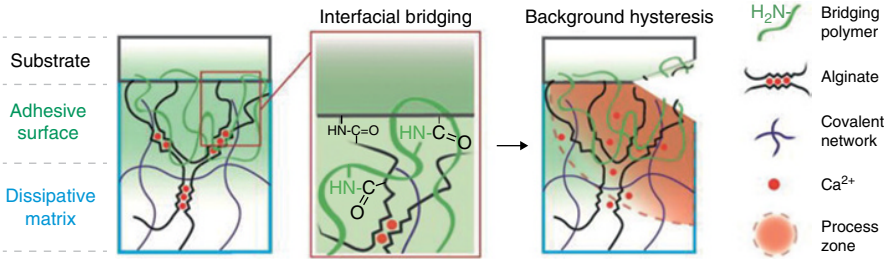

Figure 5.7 The adhesive consists of a dissipative matrix (light blue square) made of a hydrogel containing both ionically (calcium) crosslinked and covalently crosslinked polymers (black and blue lines), and an adhesive surface that contains a bridging polymer with primary amines (green lines). The bridging polymer penetrates into the adhesive and the substrate (light green region). When a crack approaches, a process zone (orange area) dissipates significant energy as ionic bonds between alginate chains and calcium ions break. *Source:* Reproduced courtesy of the American Association for the Advancement of Science.

5.2.4 Gecko-Inspired Dry Adhesives

The ability of lizards to climb smooth vertical walls and cross ceilings has amused and fascinated people since Aristotle in the third century BCE wrote about them in his book *History of Animals*. However, it was not until 2000 that the unique mechanism of lizard adhesion was determined following studies on the tokay gecko by Keller Autumn and Robert Full at the University of California, Berkeley (USA). There are over 1000 species of gecko and at least half of them have adhesive toe pads. Microscopy has shown that each toe pad has nearly 500 000 hairs known as setae (Figure 5.8). These setae are only one-tenth the diameter of a human hair and they further split into hundreds of smaller structures called spatulas. When an individual spatula lands on a surface, a van der Waals force is generated. These forces are intermolecular forces created by induced polarization of molecules. Although these forces are very weak and of negligible importance in most circumstances, they become very significant at the nanoscale. In gecko feet, each spatula generates an attractive force of just 0.4 μN[1] but the combined force of millions of spatulas generates an adhesive force of 10 N. This is more than enough to support an animal that weighs just 70 g.

Since the original work of Autumn and Full, it has been shown that capillary forces and contact electrification may also contribute to adhesion on wet surfaces. Regardless, an adhesive force of 10 N is generated from a foot area of just 100 mm^2 and this has attracted the interest of scientists wanting to develop dry adhesives. Two other aspects of gecko adhesion are of particular interest. The first of these relates to the ability of geckos to run across surfaces because this involves rapid attachment to and detachment from a surface. The gecko attaches to a surface by sliding the toe pads backwards to maximize setal contact. It detaches the toe pads by peeling them off the surface, like removing a sticking plaster from skin, since this involves breaking only a small number of setae–surface contacts at any given instant. The second feature of interest is the ability of setae to remain free of contaminants as a build-up of particles would inhibit contact with a surface. Though not fully understood, it seems that the material and nanostructure of the setae are optimized to ensure that particles will adhere more strongly to the surfaces on which the gecko walks rather than to the setal surface. This need to self-clean is probably the reason that the seta are made from very low surface energy materials when high surface energy setae would provide enhanced performance in the absence of cleanliness considerations.

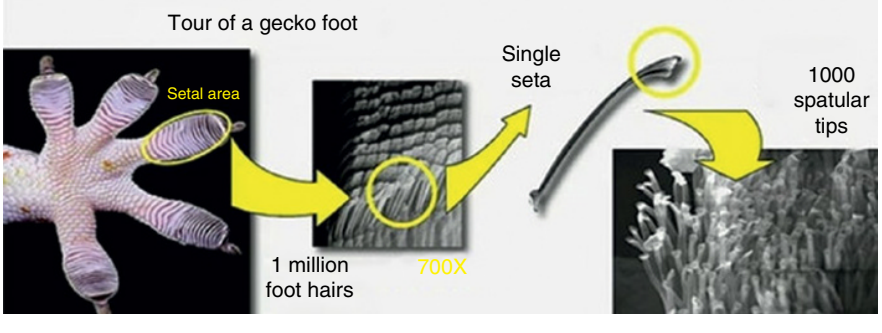

Figure 5.8 The structure of the gecko foot shown at different magnifications.

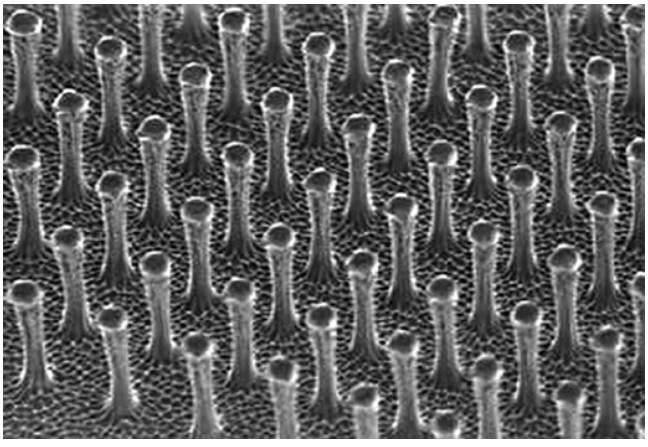

Figure 5.9 Gecko tape shown at high magnification.

Liquid adhesives, like those described earlier, cure or flow in such a way that they permanently bond two surfaces together. By contrast, a dry adhesive will create a non-destructive temporary bond that can be undone and re-made without degradation of either of the materials that are being bonded. In this respect, the gecko's foot acts like a dry adhesive. Andre Geim, who was later awarded the Nobel Prize for his work on graphene, and his collaborators at the University of Manchester (UK) were the first to develop a gecko-inspired adhesive in 2003. They called it 'gecko tape'. It was made by microfabrication of dense arrays of flexible plastic pillars whose geometry was optimized to ensure their collective adhesion (Figure 5.9). As had been predicted, each pillar had approximately the same adhesive force as a single gecko seta.

As Geim and colleagues freely admitted, their gecko tape suffered from poor durability and high fabrication costs. Since then, researchers have created new versions using silicones, urethanes, plastics, carbon nanotubes, and other materials with impressive properties such as reusability, self-cleaning, controllability, and adhesion to rough surfaces. These adhesives are gradually being evaluated for their ability to solve outstanding problems. For example, small robots have been developed that climb walls with the aid of gecko-style adhesives, although they cannot support as large a load as predicted. The Stickybot robot, for example, should be able to support 5 kg but can only support 500 g. This problem arises because of scaling issues and is best illustrated by reference to animals. As the length (L) of an animal increases, its volume – and hence mass – will increase as L^3, but the area of its adhesive organs increases as L^2. The result is that either the adhesive organs must become disproportionately larger or their intrinsic performance per unit area must increase to provide the same secure grip.

Spider-Man is a fictional superhero who has been appearing in American comic books for over 50 years and more recently in some blockbuster films. According to the original story, he acquired his ability to cling to and climb up walls after a bite from a radioactive spider! Since his first appearance, many people have wanted to emulate his fictional climbing ability, an attribute that appeals to military chiefs. Indeed, the US Department of Defense has reported getting a human to climb a wall using gecko-inspired adhesives but no details have been released. Getting a human to climb a wall using the gecko technology is a real test of

Figure 5.10 A man climbing a wall using the adhesive hand attachment developed by Cutkosky et al. *Source:* Reproduced courtesy of Mark Cutkosky.

the ability to scale the technology. With many of the dry adhesives developed to date, over 1 ft^2 (929 cm^2) of adhesive per hand would be required to support a 70 kg human climber.

Mark Cutkosky, a professor of mechanical engineering at Stanford University (USA), and his colleagues took up the challenge of generating a system for mimicking Spider-Man. They began by measuring the stress distribution on gecko toes and found that only a fraction of the adhesive area contacted the surface. Also, the load was not evenly distributed even in the areas that did make contact. Similar results were observed with a different species of gecko suggesting that load-sharing in gecko adhesion systems may not be ideal. This motivated Cutkosky's team to develop a load-sharing hand attachment composed of large numbers of small adhesive tiles. Using this attachment, a 70 kg human was able to climb a vertical glass wall (Figure 5.10) – albeit slower than a gecko but a significant achievement nevertheless.

One of the limitations of most of the work on dry adhesives to date is that they have focussed on imitating the microstructure of the gecko foot. Limited attention has been given to the macromolecules (lipids, proteins, etc.) that are found there, even though some of these components probably give additional functionality to gecko locomotion. What is clear is that the potential of gecko-inspired adhesives is far from exhausted.

5.3 Self-Healing Materials

Self-healing materials are substances that have the built-in ability to automatically repair damage to themselves without any external diagnosis of the problem or human intervention. Generally, materials will degrade over time due to fatigue, environmental conditions, or damage incurred during operation. Cracks and other types of damage on a microscopic level have been shown to change the thermal, electrical, and acoustical properties of materials, and the

propagation of cracks can lead to eventual failure of the material. In general, cracks are hard to detect at an early stage, and manual intervention is required for periodic inspections and repairs. In contrast, self-healing materials counter degradation through the initiation of a repair mechanism that responds to the micro-damage. Plants and animals have the capacity to both seal and heal wounds, which has inspired the development of a number of self-healing materials.

Nacre, also known as mother of pearl, is an organic–inorganic composite material produced by some molluscs as an inner shell layer and also makes up the outer coating of pearls. It has attracted much attention from materials scientists because of its extraordinary combination of stiffness, toughness, and strength. It also has the capacity to repair minor defects abiologically. Nacre is composed of hexagonal platelets of aragonite (a form of calcium carbonate) bound together with elastic biopolymers (such as chitin, lustrin, and silk-like proteins) that provide sacrificial bonds for self-repair (Figure 5.11). Inspired by this healing mechanism, Eduardo Saiz and colleagues at Imperial College in London created a nacre biomimetic (Figure 5.12) . This consists of inorganic glass bricks (made from microscope slides) bonded with poly(borosiloxane). When a stress is applied

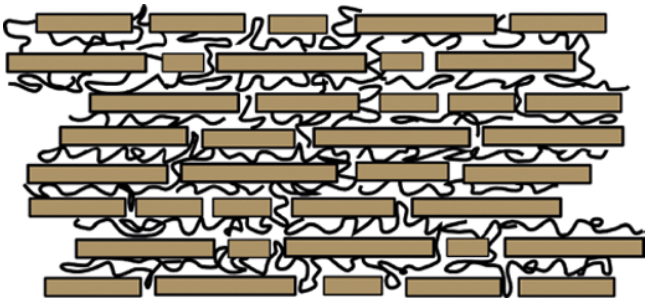

Figure 5.11 Schematic structure of nacre.

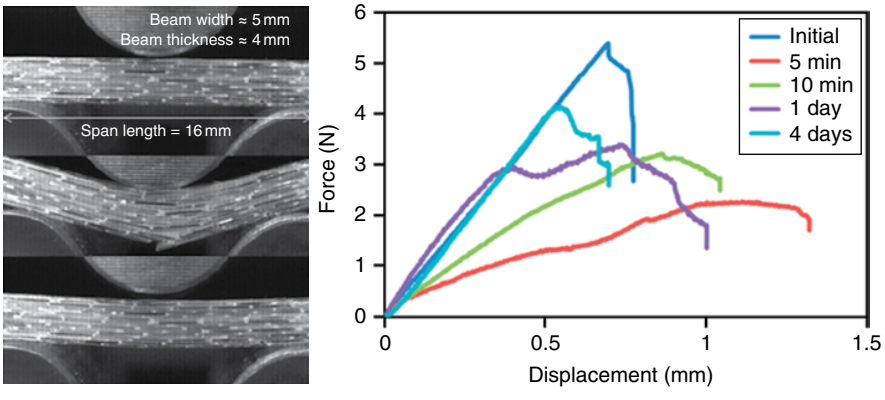

Figure 5.12 On the left, optical images of bending before (top) during (middle) and after (bottom) fracture. The bottom picture shows how the composite autonomously reaches the initial configuration and undergoes self-healing at the interfaces. The capillary bridges are able to bring the bricks together and reform the structure upon releasing the force and without applying external pressure. On the right, force vs. displacement healing curves of brick/mortar composite samples after set amount of times. *Source:* Reproduced courtesy of D'Elia et al. (2016).

to the biomimetic material, it bends and eventually starts to fracture. It resumes its original shape when the stress is removed and over time the cracks self-heal, such that after four days the material has regained its original stiffness.

In Section 5.2.1, the reader was introduced to novel glues inspired by the adhesive plaques at the ends of the byssal threads of mussels. The threads have remarkable shock-absorbing and self-healing capacities. The core of the threads is comprised of collagenous modular proteins organized as folded nanofibrils held together by histidine–zinc bonds. If the byssal threads are stretched by wave action, the histidine–metal bonds break and the length of the threads increases by up to 50%. After the wave-induced stress is removed, the threads contract as the core proteins re-fold but their mechanical strength is not regained immediately. This requires the sacrificial histidine–zinc bonds to re-form and this takes some time.

A mimic of the byssal core fibrils has been created by substituting the linear polysaccharide chitosan with nitrocatechol. This molecule, called CNC, forms a hydrogel when dipped in ferric chloride. On drying, the hydrogel forms a stiff polymer as a consequence of the formation of catechol–iron bonds similar to the DOPA–iron bonds seen in the sticky byssal plaque. The polymer has a mechanical strength similar to common engineering plastics such as polycarbonate but can be elongated over 50% before breaking. During breakage, the catechol–iron bonds rupture but the break can be repaired seamlessly if the polymer is incubated under the right conditions to allow the bonds to re-form. Although the healing process is similar to that occurring with the byssal threads, it is not self-healing as occurs with the nacre biomimetic described earlier.

5.4 Novel Textiles

5.4.1 Smart Textiles that Respond to their Surroundings

The current trend in textile science is the development of smart fabrics that can sense, adapt, and respond to their surroundings. Nature is a source of inspiration because it has an abundance of examples of responsive fibrous structures. For example, many plants are able to achieve passive actuation of organs by controlling anisotropic deformation of cells upon exposure to moisture. Plant cell walls are made of stiff cellulosic fibrils embedded in a moisture-sensitive softer matrix consisting of hemicelluloses, pectin, and hydrophobic lignin. The absorption and desorption of moisture by the plant cell wall matrix causes anisotropic deformation of the cell wall. The orientation of the cellulosic fibrils in the cell walls, as well as their stiffness, is crucial in determining the degree and the direction of the bending actuation. This hygromorphic behaviour is seen in pinecones, which only release their seeds when it is dry. The cones have bilayered scales and only one of the layers responds to humidity. The scales gape open when it is dry, releasing the cone's seed, but close when it is damp. The scales of seed-bearing pinecones move in response to changes in relative humidity.

The pinecone principle is mimicked in textiles developed by two companies. The Swiss company Schoeller Textil AG has a fabric consisting of a polymer membrane sandwiched between two textile layers. The molecular structure of the polymer opens when the body

is warm and this allows excess heat and moisture to escape. As the body cools, the polymer contracts, increasing the insulating properties of the fabric and trapping heat against the skin. British company MMT Textiles has developed Inotek™ fibres. These curl and become shorter as humidity increases. When the fibres are incorporated into yarn, the yarn becomes thinner as humidity increases and becomes more permeable to air. As the humidity decreases the fibres return to their original state, the yarn becomes thicker, and insulation increases.

5.4.2 A Polar Bear-Inspired Material for Heat Insulation

Polar bears live above the Arctic Circle in one of the harshest climates in the world. They maintain their internal body temperature at 37 °C even though winter temperatures fall below −40 °C. The main body feature allowing them to do this is the hair that comprises their fur. Unlike the hair of humans and other mammals, the hair of polar bears is hollow. These hollow hairs have several interesting properties. First, they are transparent but appear white because they scatter light (see Chapter 3, Section 3.1). Second, they are very effective at absorbing infrared radiation, that portion of the electromagnetic spectrum that humans and most other mammals cannot see but can feel as heat. An interesting consequence of this property is that a polar bear is invisible in the infrared if the temperature at the surface of its coat matches the temperature of the ice and snow around it. Third, the hollow hairs limit the movement of heat from the bear's body to the external environment even when the bear is swimming in ice-cold water.

Aerogels are synthetic porous ultralight materials derived from a gel in which the liquid component for the gel has been replaced with a gas. The result is a solid with extremely low density and low thermal conductivity. In an effort to create an aerogel that mimicked the structure of polar bear fur, scientists from the University of Science and Technology of China manufactured millions of hollowed-out carbon tubes, each the size of a single strand of hair. The carbon tubes were then wound into a spaghetti-like aerogel block. Their faux-polar bear fur was lighter in weight and more resistant to heat flow compared to other aerogels, was barely affected by water, and was very stretchy – all properties that should give it wide applicability.

5.4.3 Safety Helmets Inspired by Woodpeckers

Nirhuda Surabhi was riding his bike through Notting Hill in London when he had an accident. He ended up in hospital with concussion even though he had been wearing a helmet. At the time, he was doing a master's degree in design and his accident inspired him to design a better bicycle helmet. Surabhi knew that the heads of woodpeckers experience forces of 1200 *g* and yet experience no brain damage. Researching the anatomy of woodpeckers, he discovered that the beak and the skull are not joined together as they are in other birds. Rather, the base of the beak and the skull are separated by a piece of spongy cartilage. This acts as a shock absorber and helps cushion repeated blows. Could such a spongy layer be recreated and used to line the inside of a bicycle helmet?

Surahbi tested over 150 materials before he found what he was looking for – cardboard. Not just any cardboard, but cardboard with an internal honeycomb structure. Hexagonal structures like honeycomb are a common way that nature gets exceptional strength from lightweight materials. To construct the liner, individual ribs were cut from the cardboard and assembled into an interlocking, helmet-shaped lattice. The lattice, called Kranium, then was inserted into the shell of a helmet as a replacement for the usual polystyrene insert. Laboratory tests showed that the Kranium liner absorbed three times as much force as a conventional liner and was 15% lighter.

The Kranium helmet was launched at the London cycle show in 2011 but it has not been a commercial success. One reason may be that the Kranium insert is very resistant to top blows but such blows seldom happen in cycle accidents. When hit from the side the Kranium performs no better than polystyrene. Nevertheless, Surabhi deserves credit for his unusual approach to the problem. The key question is whether the Kranium can be redesigned to meet the needs of cyclists. As noted elsewhere in this book, nature seldom solves a problem in a simple way. In the case of the woodpecker, protection from the force of pecking involves not just shock absorbent material but special cranial structures and neck muscles.

Crash helmets for cyclists are a form of body armour. So, would animals with a hardened exterior provide a better inspiration for body armour than a woodpecker? Zachary White and Franck Vernerey at the University of Colorado (USA) have reviewed the ways that animals protect themselves from external threats and have concluded that natural body armour lacks the appropriate balance of weight, flexibility, and protection required by military personnel. The carapace of a turtle is constructed in such a way that a heavy blow by a thick piece of wood would do no damage and might not even be felt by the occupant. Unfortunately, the carapace is heavy and greatly restricts turtle mobility. Another problem with natural systems is that they have never needed to evolve to resist high velocity penetration by bullets.

A number of animals, e.g. armadillos, are protected by overlapping hard plates. The hardness of the individual plates comes from their hierarchical structure (see introductory paragraphs) and so are lightweight and collectively the plates give great flexibility. The US company Pinnacle Armor, now defunct, created a form of body armour called Dragon Skin that mimicked armadillo body protection. This armour was made with high tensile strength ceramic discs and performed well in ballistics tests but the US Department of Defense refused to approve it for use by military personnel in conflict zones.

Relevant Material in Other Chapters

Photonic biomimicry (Chapter 3, Section 3.1).
Self-healing concrete (Chapter 4, Section 4.4).

Note

1 One newton (N) is the force required to accelerate an object of mass 1 kg at 1 m s^{-2}.

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6

Smart Devices

Nature is always wise in every part.

Edward, Second Baron Thurlow

6.1 Burrowing Robots Based on Razor Clams

Amos Winter is a professor of mechanical engineering at Massachusetts Institute of Technology (USA) and he has been studying how the Atlantic razor clam (*Ensis directus*) burrows into soil. This might seem an esoteric field of study but it could have economic benefit. Winter explains the relevance of his research by considering what happens when you stick a finger into either a bucket of water or a bucket of sand. The water will exhibit relatively no resistance and you will be able to push your finger to the bottom. By contrast, when you push your finger into the sand, the resistance will increase quickly until you can push no further. With granular materials like sand, but not liquids, the insertion force increases with depth and the insertion energy scales with the square of the depth.

The razor clam inhabits estuarine environments where it burrows in the soil and mud. Based on measurements of the force that the clam can produce (10 N) it should only be able to burrow to a depth of 1–2 cm; in reality, clams can dig to nearly 1 m deep at a speed of $1\,\mathrm{cm\,s^{-1}}$. The clam must have a method for manipulating the surrounding soil to reduce the burrowing drag and the energy required for penetration. Winter found that when the razor clam begins to dig, it first retracts its shell, releasing the stress in its body and the soil around it. This causes the soil to begin collapsing, creating a localized landslide around the animal. As the clam continues to contract, reducing its own volume, it sucks water into the region of falling soil creating a fluidized mix like quicksand. Moving through fluidized soil, rather than static soil, reduces the drag forces on the animal to within its strength capabilities. Also, burrowing with local fluidization requires energy that scales linearly with depth rather than depth squared as would be the case for moving through static soil.

Winter's interest in the razor clam began with his PhD research. This was concerned with finding ways to anchor autonomous underwater vehicles (AUVs) to a seabed or riverbed without consuming a great deal of energy. Robotic vehicles have little battery power so any energy consumed by the anchoring system reduces the AUV's operating

Biomimetics: Nature-Inspired Design and Innovation, First Edition. Sandy B. Primrose.

Figure 6.1 A razor clam, left, which inspired the RoboClam, right. *Source:* Reproduced courtesy of Amos Winter.

time. The clam is of particular interest because it can burrow for half a kilometre using the energy of an AA battery. The clam's method of movement also offers engineers a way of reducing the energy costs associated with digging. With this in mind, Winter and his colleagues developed a clam mimic that they call RoboClam. The robot has two pieces of metal that mimic the clam shells (Figure 6.1) and these are actuated by compressed air. The RoboClam fluidizes soils as expected and a version compatible with underwater vehicles is being developed in collaboration with Bluefin Robotics (Massachusetts, USA).

6.2 Novel Sensors

6.2.1 Bioinspired Underwater Pressure Sensors

Backswimmers (*Notonecta* sp.) are predatory aquatic insects that can retain air layers on the surface of their forewings, just like the floating fern (*Salvinia*) discussed earlier (Chapter 2, Section 2.10). The stable air layers of *Salvinia* have been studied for their potential to reduce ships' drag, whereas those of *Notonecta* are of interest because of their role in detecting sound and movement. Wilhelm Barthlott and his colleagues at the University of Bonn (Germany) noted that the forewings of *Notonecta* are carpeted with tiny densely packed hairs known as microtrichia that stabilize the air layers. Sticking through the microtrichia are much larger hairs known as setae and these are connected to nerves, i.e. they act as sensors that detect pressure changes in the air layer, which allows the backswimmers to detect prey.

Instruments for measuring pressure changes usually use piezoelectric materials or membranes. After studying *Notonecta*, the University of Bonn team wondered if thin air layers could be used to measure underwater pressure changes. To test this idea, they made an air-retaining surface by placing a 3×3 array of 3 mm needles on a 5 mm square plate. This array retains a layer of air when placed in a tank of water. A laser beam was shone on the air–water interface above the array and the reflected beam detected by a photosensitive diode (Figure 6.2). Any pressure changes in the liquid cause a displacement of the air–liquid

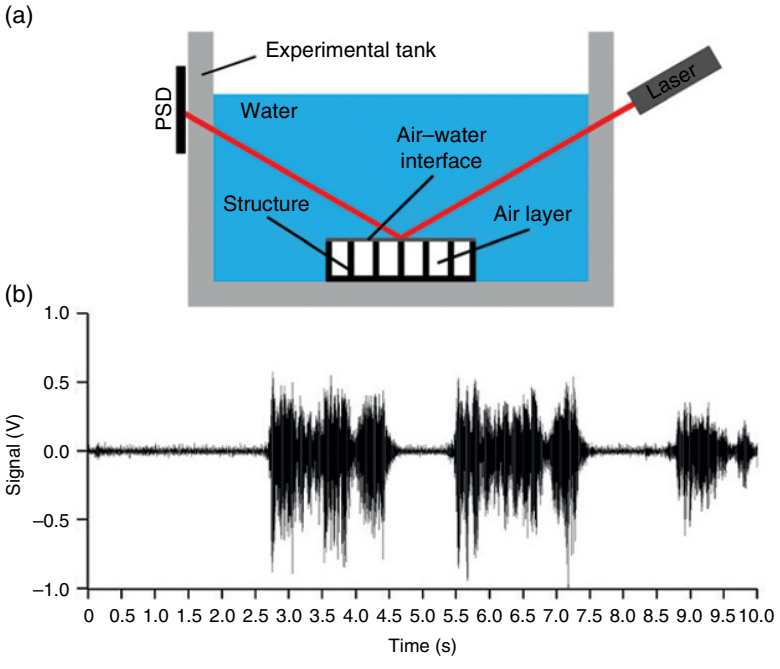

Figure 6.2 (a) Setup used for the proof of concept for the biomimetic *Notonecta* sensor. *Source:* Reproduced courtesy of Mail et al. (2018). (b) Diode signal showing the output voltage which corresponds to the operators talking in front of the tank.

interface and result in changes in the diode signal. In practice, the system is so sensitive that it can detect the operators talking in front of the tank. This novel sensory system has potential for the development of highly precise underwater sensors.

6.2.2 Crack-Based Strain Sensors

The joints of many spiders have slit sense organs, more commonly called lyriform slit organs because they resemble a lyre (Figure 6.3). Vibrations cause the slits to open and close and the organ is so sensitive to minor perturbation that it can detect another spider, or an insect, scratching leaves several metres away. On learning of the exquisite sensitivity of the lyriform slit organ, Professor Mansoo Choi of the Seoul National University set out to create a manufactured version. Initially, he and his colleagues placed a very thin layer of platinum on top of a flexible polymer and bent it to generate cracks in the metal. After several months of effort, they hit on the right thickness of platinum and the correct bending movement to generate minute, parallel cracks. By measuring the electrical resistance of the platinum layer they were able to measure the frequency and magnitude of vibrations delivered to their sensor.

Despite being relatively primitive, the first sensor built could detect vibrations as gentle as the movement of a ladybird's wings and when placed on a violin could distinguish between the different notes being played. Even more impressive, the sensor had a gauge factor of over 2000 in the 0–2% strain range. The gauge factor is the ratio of the relative

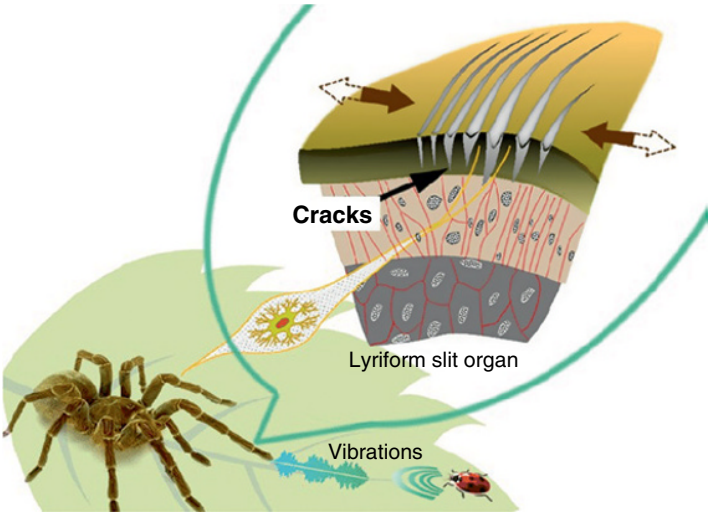

Figure 6.3 Schematic of the spiders' sensing minute vibrations with the lyriform organ near their leg joints. Micronscale cracks embedded into the exoskeleton of spiders, cutting the lyriform organ into discrete islands. The lyriform organ responds to mechanical disturbance by converting vibration stimulus into deformation of the lyriform organ (represented by the brown arrows).

change in electrical resistance to mechanical strain and is one of the most important measures of strain gauge performance. Most strain gauges have gauge factors of 100 or less, while for thin film metals the values are as low as 2. Equally impressive was the sensitivity of the system – it could detect vibrations with amplitudes as low as 10 nm (0.01 mm).

The crack-based sensor described here had a number of disadvantages. These included susceptibility to fouling by extraneous liquids and a limitation on the number of times the device could be stimulated before mechanical failure. New versions of the sensor have been developed that use metal films other than platinum and these have gauge factors of 10 000 or more. The sensors are encased in polyimide, a material widely used in flexible electronics, and this protects the sensor from the environment.

6.2.3 Ice Plants and Actuators

In Chapter 5 (Section 5.4.1), we saw how the reversible opening/closing of pinecone scales upon wetting/drying led to the development of moisture-sensitive clothing. Ice plants, such as *Delosperma* species, have pentagonal seed capsules whose opening is also actuated by water. In the presence of sufficient water, the capsules undergo a reversible origami-like unfolding. The cells that drive this are organized in a structure that can be described as a flattened honeycomb. When the cell contents absorb water, the cells swell and the whole structure adopts a recognizable honeycomb structure. Although the capsule cells are living entities, the actuation mechanism is a physical phenomenon rather than a biological one, i.e. it is passive.

At the Max Planck Institute of Colloids and Interfaces (Germany), Peter Fratzl and his colleagues set out to develop actuators that mimicked the ice plant seed capsules. Their first structures were made up of a mesh of material that was inert to water with the pores

of the mesh filled with a highly water-responsive material. As expected, the mesh contracted when the humidity was low and opened out when the humidity was high. The team then realized that there was an even simpler solution: the mesh can be constructed from a bilayer of a wood veneer glued to a thick layer of paper (Figure 6.4). This bilayer responds to water in the same way that a bimetallic strip responds to temperature because the wood expands more than the paper. Actuation of this system is slow but it could be used to automatically open and close canopies and movable roofs.

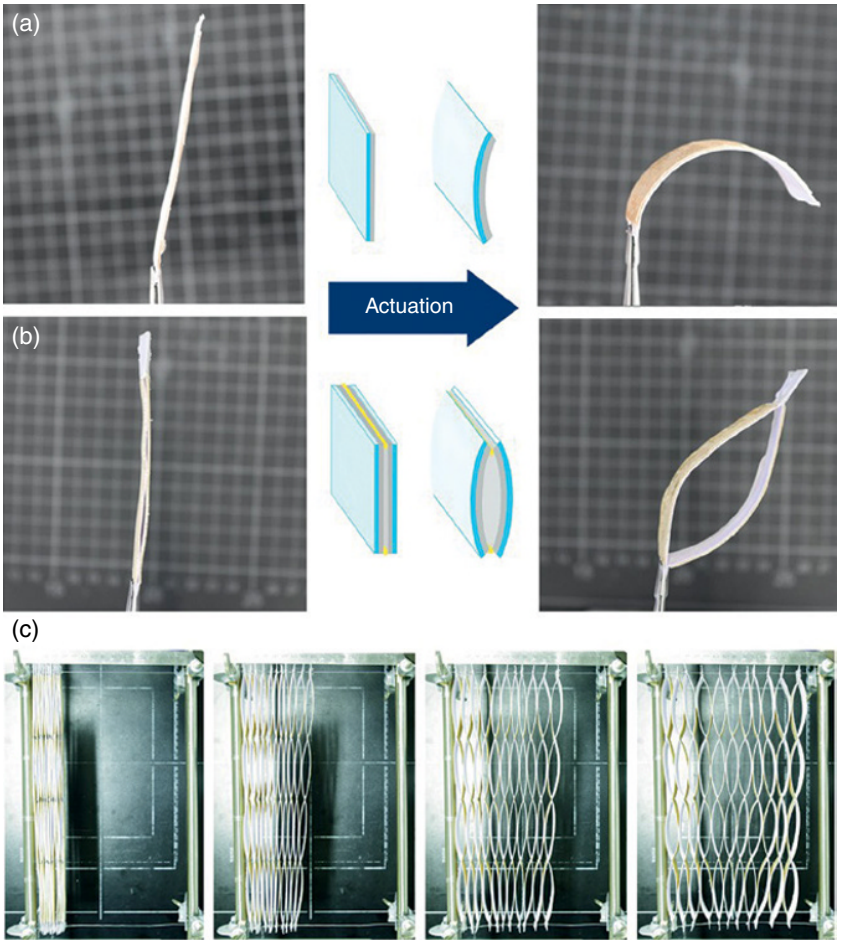

Figure 6.4 Passive hydro-actuation of bioinspired bilayer–honeycomb device. Initial (left) and final actuated state (right) of the passive hydro-actuation upon changing the relative humidity from 50 to 95% are depicted at different levels of the design. (a) A bilayer made up of spruce veneer (active layer) glued to a thick paper (passive layer), bends upon anisotropic swelling of the spruce veneer in the direction perpendicular to the cellulose fibrils orientation. (b) Two such bilayers attached together constructs a cell-like structure that can open/close upon changes in the relative humidity. (c) Scaling up the bilayer–cell concept into a hydro-actuated honeycomb prototype that expands up to fivefold upon actuation (sequential images after 0, 2, 4, and 16 hours of exposure to 95% RH). *Source:* Reproduced courtesy of Giuducci et al. (2018).

6.3 Passive Water Collection

Water scarcity is the lack of sufficient available water resources to meet the demands of water usage within a region. It is an issue on every continent and affects around 2.8 billion people around the world. There are two causes of water scarcity: economic water scarcity and physical or absolute water scarcity. Economic water scarcity is a result of poor management of the sufficient available water resources and can be resolved using readily available technology. Physical water scarcity is a result of inadequate natural water resources to supply a region's demand, as exemplified by much of Australia and Africa. In areas where physical scarcity is a problem, it is essential to trap and utilize what little water there is. Everywhere on Earth, even in deserts, the surrounding atmosphere contains some water and this can be trapped as dew or fog. Dew is a form of precipitation that occurs naturally when atmospheric water vapour condenses onto a substrate. Fog is distinct from dew in that fog is made of droplets of water that condense around particles in the air. Ideas for collecting water from dew and fog have come from studies on three different organisms: desert beetles, spiders, and cacti. Each of these organisms demonstrates four key steps: condensation, coalescence, transportation, and absorption.

6.3.1 Inspiration from the Namib Desert Beetle

The Namib Desert of southern Africa is one of the most arid areas of the world, receiving only 1.4 cm (0.55 in.) of rain per year, and yet it is home to a number of animals. One of these is the fogstand beetle (*Stenocara gracilipes*) that can collect water from fog on its bumpy back surface (Figure 6.5). The beetle's back consists of alternating wax-coated hydrophobic troughs and non-waxy hydrophilic bumps that serve the purpose of coalescence and transportation. In the evening, the beetle stands on ridges of sand facing into the fog-laden wind blowing in from the Atlantic Ocean. Minute water droplets collect on the hydrophilic bumps and grow in size. Accumulation continues until the combined droplet

Figure 6.5 A Namib Desert beetle (*Stenocara gracilipes*).

weight overcomes the water's electrostatic attraction to the bumps as well as any opposing force of the wind. Once the drop reaches the critical size it rolls down the beetle's back and into its mouth. The beetle has a second method of water collection. At night, it will lose heat to the atmosphere by radiation and water in fog will condense on its back and be collected in the same way as dew.

The design of the Dew Bank Bottle (Figure 6.6) was inspired by the fog-harvesting technique of the Namib Desert beetle. The black dome-shaped invention, which resembles the beetle's body, is placed outside in the evening. The steel body cools during the night and in the morning, when the surrounding air begins to warm, water droplets condense on the cool surface of the bottle. The dewdrops collected are channelled down ridges in the surface to an enclosed circular chamber that holds the water. The Dew Bank Bottle is an example of an energy-independent method of sourcing safe drinking water. There is no reason why buildings in arid areas could not be built on the same principle.

A true mimic of the Namib beetle would have a superhydrophobic surface with a pattern of hydrophilic spots. However, making such a structure typically involves expensive, multistep lithographic mask-based strategies because of the challenge of combining hydrophobic species with hydrophilic ones. Peng Wang and co-workers at the King Abdullah University Of Science and Technology (Saudi Arabia) have now designed an elegant inkjet printing strategy that can continuously produce the required surfaces on a large scale. The team were inspired by the dopamine adhesives of marine mussels (see Chapter 5, Section 5.2.1) that can stick to almost any kind of surface. They introduced superhydrophilic polydopamine spots onto superhydrophobic surfaces but this in itself was a challenge as it involves the addition of an aqueous dopamine precursor onto a hydrophobic surface. The solution was to use two solvents: ethanol and ethylene glycol. Ethanol reduces the surface tension of the dopamine solution while ethylene glycol lowers its vapour pressure. This enabled the dopamine solution to be stable on the surface, thus allowing it to polymerize to polydopamine. Surfaces made in this way can collect over 60 ml of water per square centimetre in one hour. The next step is to find the optimum size of hydrophilic bumps to maximize water collection.

Figure 6.6 The Dew Bank Bottle.

6.3.2 Collecting Water with Spiders' Webs

Fog typically contains 0.05–0.5 g of water per cubic metre and the water droplets range in diameter from 1 to 40 μm. In countries where there is no established infrastructure for water supply, people living on coasts harvest water from fog. Fog harvesters are mesh nets (Figure 6.7), usually 1 m^2, erected perpendicular to the path of the wind. An ideal location is a high altitude arid area near cold offshore currents, where fog is common. The wind blows fog through the device, the mesh catches the droplets, and gravity pulls the water down into containers underneath. The efficiency of a fog collector depends on the material of the net, the size of the holes and filament, and any chemical coating. In particular, the mesh holes have to be just the right size. If they are too large, the droplets will pass through the mesh. If the holes are too small, the water will be held in the net by surface tension and will not slide down into the collector. Efficient fog collectors can harvest up to 10% of the moisture in the air but often the efficiency is much less.

Anyone who has visited a park or garden on a foggy day, particularly in autumn, will have noticed that spiders' webs are visible because of the water condensed on them

Figure 6.7 Fog harvesting nets (top) and water condensed on spider's webs (bottom).

(Figure 6.7). This property of webs has been of particular interest to several groups of Chinese scientists and they have shown that silk fibres change their structure in response to water. Once in contact with humidity, tiny sections of the thread aggregate into spindle-knots, whose randomly arranged nanofibres provide a roughly, knobbly texture. In between these knots are smooth areas, known as joints (Figure 6.8), where the fibres are neatly aligned. The joints allow water to slide along the fibre until it hits a knot, where dewdrops accumulate. The movement of the liquid drops is driven by two factors: surface energy gradients and differences in Laplace pressure (see Laplace Pressure Definition Box). The surface energy gradients arise from differences in roughness such that water moves from the joints (less hydrophilic, low surface energy) to the spindle-knots (more hydrophilic, high surface energy). The spindle-shaped geometry of the knots generates differences in Laplace pressure.

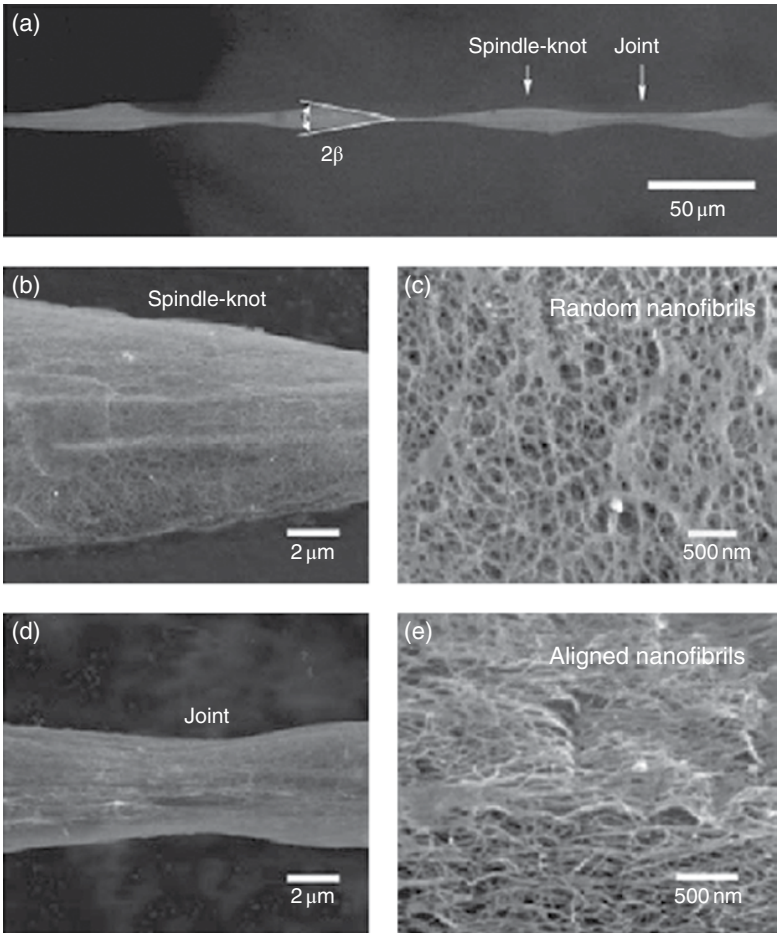

Figure 6.8 Structure of the silk fibres that spiders use to construct their nests. (a) Low magnification image with the apex angle having a value of 2β. (b) and (d) Medium magnification images of spindle-knots and joints respectively. (c) and (e) High magnification images of spindle-knots and joints respectively. *Source:* Reproduced courtesy of Springer.

Laplace Pressure Definition
The **Laplace pressure** is the pressure difference between the inside and the outside of a curved surface that forms the boundary between a gas region and a liquid region. The pressure difference is caused by the surface tension of the interface between liquid and gas.

Numerous research groups have fabricated artificial spider silks using polymers such as polyvinyl acetate, poly(methylmethyacrylate), and polystyrene. As expected, the water collection ability of each artificial silk was influenced by the fabrication conditions and the geometry of the spindle-knots. The bigger the spindle-knots the greater the rate of water collection. At the time of writing, the most efficient water collecting system was an easily fabricated cavity microfibre with unique surface roughness, mechanical strength, and long-term durability. A piece of mesh made from this material and less than 77 cm^2 (12 $in.^2$) was able to collect 1 litre of water in three hours – enough to meet the needs of a person for one day.

6.3.3 Cactus-Inspired Water Collection

With most plants, only a small proportion of the water absorbed by the roots is used for growth and metabolism: most of the water is lost through leaf transpiration. Plants that grow in arid areas have to minimize the loss of water by transpiration and have evolved several mechanisms for doing this. In cacti, minimization of water loss is achieved by replacing the large surface area of leaves with spines and locating photosynthesis in the swollen stems. Cactus spines are very sharp and it is perceived wisdom that their role is to protect the plant from being eaten by animals; however, spines have another more important role – they facilitate the collection of water from fog.

The bunny ears cactus, *Opuntia microdasys*, has been the model organism for studying water collection by cacti. Its spines have a complex structure consisting of three parts with different structural features: the tip with barbs, the middle region with graduated grooves, and the base with belted trichomes (see Figure 6.9). Researchers led by Lei Jiang of China's Beijing National Laboratory for Molecular Sciences wondered whether smaller structures might also play a role in the water-harvesting phenomenon. When they took a closer look, they found that within the clusters of spines on the cactus stem, there are also tiny cones, roughly 100 μm tall, that contribute to the cactus's ability to collect water (Figure 6.10). Jiang's team then made mimics of these arrays of cones out of polydimethylsiloxane and studied how various arrangements influenced the structures' water-harvesting abilities. Arrays with a hexagonal arrangement proved to be the most efficient because air flowed through these staggered cones rapidly, quickly moving water droplets along each cone. By making the cones of an oleophilic material, it was possible to separate oil from water.

6.4 Insects and Origami

Of all the insects in the world, one of the most appealing must be the ladybird with its red 'body' decorated with black spots. In reality, this spotted 'body' is two forewings known as elytra, which serve as protective cases for the hindwings. These hindwings are folded away

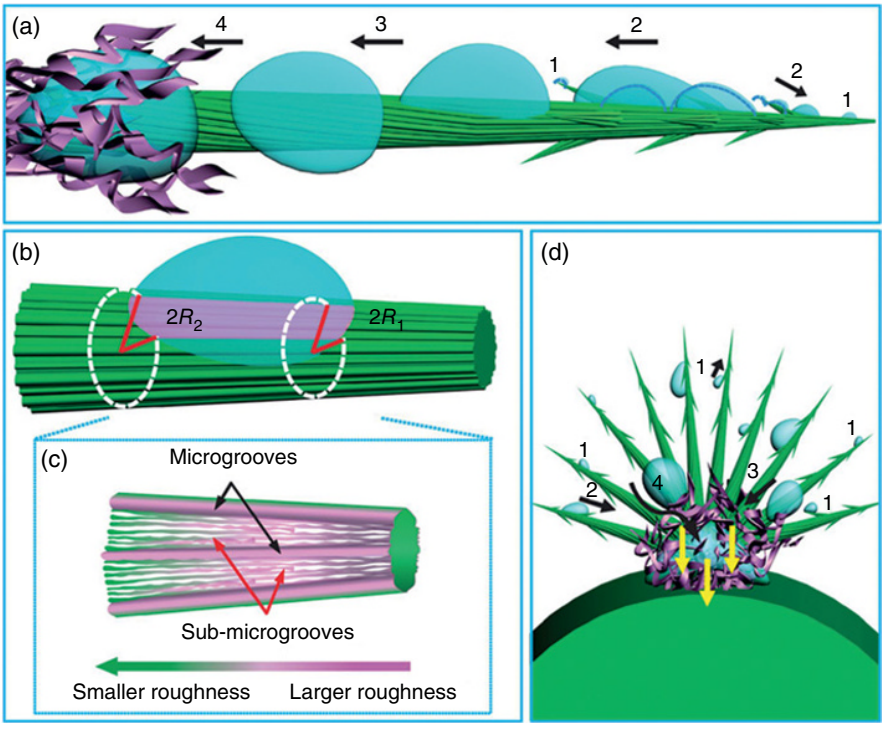

Figure 6.9 The mechanism of the fog collection by the cactus *Opuntia macrodasys*. (a) An overview of the efficient fog collection system which progresses from deposition on the barbs and the spine (1), collection on the tip of the spine (2), transportation on the gradient grooves (3), and absorption upon contact with the trichomes (4). (b) and (c) Analysis of the driving forces arising from the gradient of the Laplace pressure and the gradient of the surface-free energy. A water drop on a conical spine moves towards the base side with the larger radius (R_2) due to the relatively smaller Laplace pressure (b). In addition to the conical shape, the surface of the spine is covered with multilevel grooves. The gradient of the microgrooves is sparser near the base than near the tip of the spine (as indicated by the black arrows). The aligned submicrogrooves are similar in size along the spine as indicated by the red arrows (c). This gradient of the microgrooves produces a gradient of roughness, contributing to a gradient of the surface-free energy along the spine, driving the water drops towards the base side. (d) Cooperation among the multiple spines, the multiple trichomes, and the spines–trichomes. *Source:* Reproduced courtesy of Ju et al. (2014).

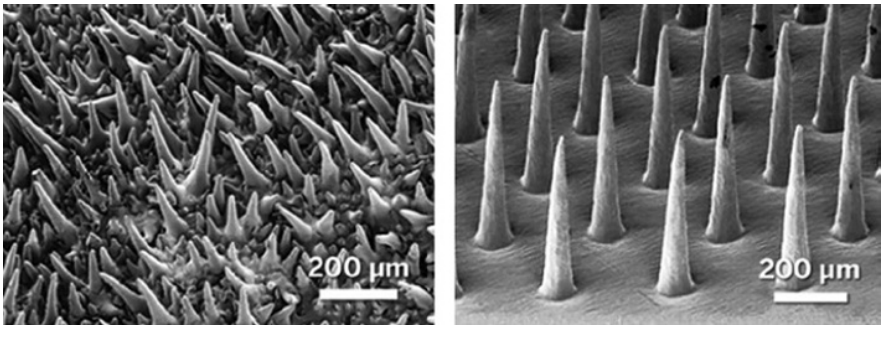

Figure 6.10 These scanning electron micrographs show microscale cones from a cactus stem (left) and mimics made from polydimethylsiloxane (right). *Source:* Reproduced courtesy of John Wiley & Sons, Ltd.

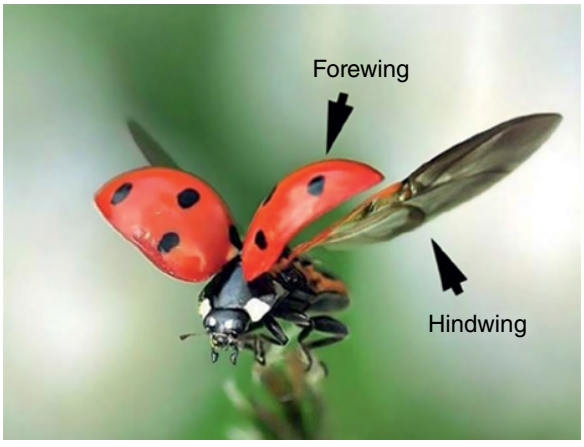

Figure 6.11 The forewings (elytra) and hindwings of a ladybird.

beneath the elytra when the ladybird is walking about. When the ladybird wishes to fly, it deploys its wings (Figure 6.11) in only a 10th of a second and the unfolded wings are sturdy enough to allow it to move at up to 37 mph (60kph). When it lands, it folds away its hindwings in just two seconds. During a single day the ladybird will fold and unfold its wings hundreds of times – and never get it wrong. From a biomechanical point of view, the hindwings in ladybirds successfully address two conflicting requirements: the deformability (instability) required for wing folding and the strength (stability) required for flying.

Scientists studying the folding and unfolding of ladybird wings had a major problem: they could not see what was happening underneath the red and black elytra (forewings). To solve this problem, Professor Kazuya Saito and colleagues at the University of Tokyo used microsurgery to replace the natural elytra with artificial transparent ones. Using high-speed cameras, they were able to film the folding and unfolding process. The process by which the wings collapse is akin to origami and the scientists used computed tomography (CT) scans to figure out the precise pattern of folds. They were even able to recreate the folding pattern using origami paper. The mechanism whereby the wings unfold quickly and adopt a rigid shape involves veins. These veins are very much like a carpenter's tape measure that can be retracted into its case when not needed but is rigid when pulled out of its case. When the elytra are closed, the veins are compressed but they immediately spring out when the elytra are opened. Now that we know how the ladybird integrates structural stability and deformability, the same principles could be applied to space-deployable structures (solar panels, antenna reflectors), wings of carrier-based aircraft, and even common items such as umbrellas.

Not all flying insects fold their wings in the same way as ladybirds. Wasps, for example, have origami wings composed of rigid tiles of cuticle connected through soft resilin joints. Resilin is one of the most efficient elastic proteins known and is capable of storing and releasing mechanical energy for rapid wing folding and unfolding. It works as a spring in much the same way as the wing veins of ladybirds. A team at the École Polytechnique Fédérale de Lausanne (Switzerland) designed a structure that mimics the wings of the dragonfly *Brachythemis contaminata*. It was composed of elastomeric membranes, akin to

resilin joints, sandwiched between rigid tiles, akin to the insect cuticles. The particular elastomeric membrane and rigid tiles selected were chosen because they had the same Young's modulus (see Young's Modulus Definition Box) as resilin and the cuticle. The functionality of their system was tested in two robotic systems. In the first, it was used to make a foldable frame that would support a hovering drone but which would buckle in collision and prevent damage. In the second application, the material was used to fabricate a gripper that can manipulate objects but can buckle to avoid overloading them. This fits with the current trend in robotics which is to create 'softer' robots that can adapt to a given function and operate safely alongside humans.

Definition
Young's modulus is a mechanical property that measures the stiffness of a solid material and is equal to the longitudinal stress divided by the strain (see section 5.2.1).

6.5 Mosquito Bites and Injection Needles

The response of people to injections ranges from slightly painful to outright trauma but, regardless, they are something we all have to endure at some time or another. Children, in particular, associate needles with pain but it does not have to be like this. Most of us will have been bitten by mosquitos, possibly multiple times, and the chances are that we never felt anything at the time. Mosquitos bite humans to suck blood and to do this they inject us with an anticoagulant. We only know that we have been bitten much later when we develop a sensitivity reaction to the anticoagulant. How does the mosquito bite us painlessly? Bharat Bhushan and his colleagues at Ohio State University (USA) have found the answer.

The fascicle (Figure 6.12) is the tube used by the mosquito to suck blood. It is very soft at the tip but hardens as it gets closer to the head of the mosquito. The softness of the tip reduces the pain that will be felt by the host and secretion of a local anaesthetic reduces the pain even more. The softness of the tip should increase the force required to penetrate the skin. To compensate, the tip has a serrated edge and the mosquito vibrates this with a frequency of 15 Hz and a movement of less than a 10th of a millimetre: it literally saws its way through the skin. The force needed by the mosquito to penetrate the skin is three times lower than with a hypodermic needle. A lower insertion force means less tissue deformation that in turn reduces nerve sensations.

Bhushan and his colleagues have designed a mosquito-inspired microneedle and now need to show that it is possible to make it. Meanwhile, Jeff Capadona and colleagues at Case Western Reserve University have studied another aspect of mosquito biting to facilitate implanting microprobes into the brain. For insertion into the brain, the microelectrodes must be stiff enough not to buckle but soft enough not to cause tissue damage which will initiate inflammatory reactions. The mosquito faces a similar problem with its fascicle and solves the problem by using the labium as an insertion guide. To mimic the mosquito's approach, microelectrode guides were fabricated from polytetrafluoroethylene (PTFE) and poly(methyl methacrylate) (Figure 6.12). Using these guides, the force required to cause buckling was nearly four times greater and surgical success went from 0 to 100%.

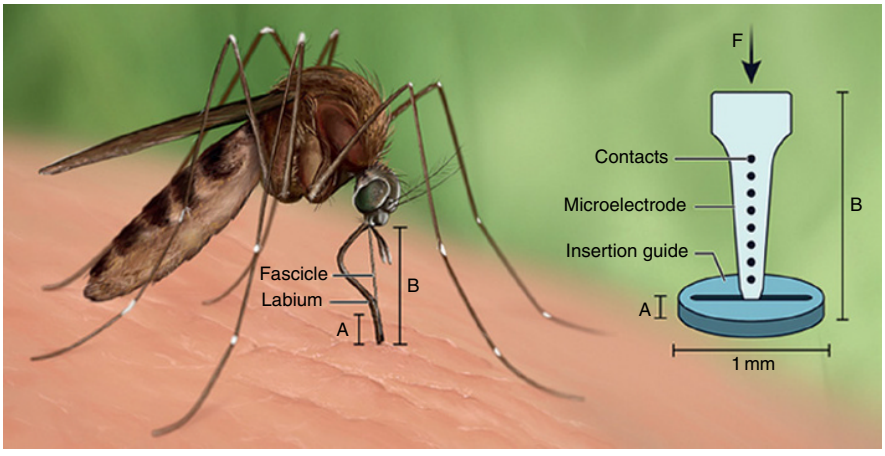

Figure 6.12 Mosquitos use their labium to brace the fascicle during insertion through the tough skin. Mechanically, this changes the end-condition of the fascicle from a free- to a fixed-end condition and reduces the effective length (B reduces to A). To facilitate microelectrode insertion into the skull, a manufactured guide of the type shown is placed on the skull above the site of device implantation. A narrow slit, slightly wider than the microelectrode provides lateral support and the additional bracing prevents buckling. *Source:* Reproduced courtesy of Shoffstall et al. (2018).

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7

The Influence of Biology on Computer Science

Living organisms are consummate problem solvers. They exhibit a versatility that puts the best computer programs to shame.

John H. Holland

Previous chapters have focussed on biomimetics and mostly contain descriptions of ongoing attempts by scientists to emulate the materials and control mechanisms that exist in nature. This chapter is quite different in two respects. First, computer scientists have sought inspiration from nature rather than trying to copy it. Second, they have been doing it for a long time and have made significant progress, notwithstanding the quote at the top of the page. Some of the bioinspired developments are presented below but only at a superficial level. There are two reasons for this. First, a proper understanding requires a detailed knowledge of computer science. Second, books longer than this one have been devoted to each of the topics covered here.

Some Terminology Used in Computer Science

Most people will know that an *algorithm* is a sequence of instructions, typically to solve a class of problems or to perform a computation. Algorithms are unambiguous specifications for performing calculation, data processing, automated reasoning, and other tasks. Many readers will be less familiar with *heuristics*. A heuristic is a technique designed for solving a problem more quickly when classic methods are too slow, or for finding an approximate solution when classic methods fail to find any exact solution. A heuristic is a function that ranks alternatives in search algorithms at each branching step based on available information to decide which branch to follow. The objective of a heuristic is to produce a solution in a reasonable time frame that is good enough for solving the problem at hand. This solution may not be the best of all the solutions to this problem, or it may simply approximate the exact solution. It is still valuable because finding this solution does not require a prohibitively long time.

In an optimization problem, the *search space*, or *solution space*, is the set of all possible points (sets of values of the choice variables) that satisfy the problem's constraints. This is the initial set of candidate solutions to the problem, before the set of candidates has been narrowed down.

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7.1 Genetic Algorithms

John Henry Holland was a mathematician and physicist who in 1959 received one of the first doctorates in a new field called computer science. Inspired by R.A. Fisher's classical book *The Genetical Theory of Natural Selection*, Holland developed computer algorithms that essentially evolved and learned from experience, much as living organisms do. Those algorithms, now known as genetic algorithms, have enabled scientists to explore complex systems that cannot be broken down into simpler parts to be examined. In 1975, he published a ground-breaking book on genetic algorithms entitled *Adaptation in Natural and Artificial Systems*. Not long after publication of this book, Holland supervised a PhD student who used genetic algorithms to optimize gas pipeline operations. That student was David Goldberg and he went on to write one of the most cited books in computer science: *Genetic Algorithms in Search, Optimization and Machine Learning*.

The first attempts to apply evolutionary principles to computer science were made in the late 1950s and early 1960s. There was little success because the programs developed reflected contemporary biological thinking: mutation was the key driver of evolution rather than mating. Holland recognized this weakness and developed new algorithms that were suited to evolution by both mutation and mating. Over the next decade, he extended the scope of his genetic algorithms by creating a genetic code that could represent the structure of any computer program.

Holland's system consisted of a set of rules, each of which performed particular actions every time its conditions were satisfied by some piece of information. The conditions and actions are represented by strings ('chromosomes') of bits ('genes') corresponding to the presence or absence of specific characteristics in the rules' input and output. For each characteristic that was present, the string would contain a 1 in the appropriate position, and for each that was absent, it would contain a 0 (Figure 7.1). For example, a classifier rule that recognized sheep might be encoded by a string of 1's for the bits corresponding to 'woolly', 'has four legs', 'eats grass', 'produces milk' and 0's for 'inanimate', 'has hands', and 'talks'. In reality, the programmer chooses the simplest and most primitive characteristics that can be combined to classify a wide range of objects and situations.

To solve a particular problem, one simply starts with a population of random strings of 1's and 0's and rates each string ('chromosome') according to the quality of the result. Depending on the particular problem, the measure of fitness could be the optimal way from A to B (quickest or fastest or fewest obstacles), design of a complex building that minimizes materials usage, etc. Once a fitness score has been determined for each string, the fittest are selected for 'recombination' and 'mutation' (Figure 7.2). This process continues (Figure 7.3) until it does not produce offspring that are significantly different from previous generations (the population of strings in each iteration). It is possible to make the algorithm more robust by including a 'speciation' heuristic. This penalizes crossover between candidate solutions that are too similar

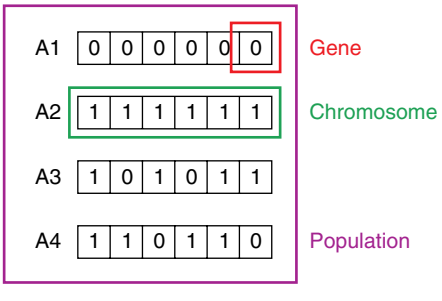

Figure 7.1 Structure of a simple population of alternatives in a genetic algorithm. *Source:* Reproduced courtesy of Vijini Mallawaarachchi.

and encourages population diversity. Another variation, known as adaptive genetic algorithms, involves changing the probability of recombination and mutation in each generation to maintain the population diversity. Finally, mutations need not be the single base changes shown in Figure 7.2: they can include insertions, deletions, and transpositions of the type seen in real genomes.

Like any algorithm, genetic algorithms have their limitations. With some problems, it is very difficult to define the fitness expression. In such cases a simulation may be used, e.g. computational fluid dynamics may be used to determine the air resistance of a vehicle. A problem with this approach is that repeated fitness evaluation can be prohibitively costly in terms of computer power and time to get an answer. Practically, it may be necessary to forgo an exact evaluation and use an approximated fitness. Another problem with genetic algorithms is that they do not scale well with complexity. There is often an exponential increase in search space size when the number of elements that are exposed to mutation is large. This makes it difficult to use the technique on problems such as designing an engine or an aeroplane. In this case, the best that can be done is to optimize the fan blades or the aerofoils.

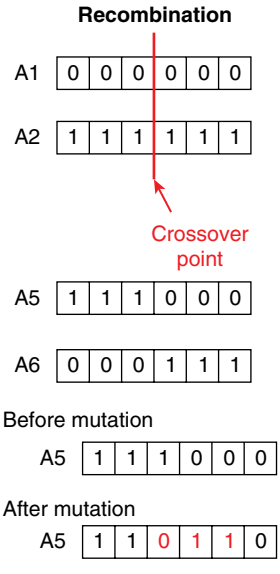

Figure 7.2 Recombination and mutation in a genetic algorithm. *Source:* Reproduced courtesy of Vijini Mallawaarachchi.

In an analogy with the living world, genetic algorithms have evolved significantly from the primitive form first described over 50 years ago. One significant variant is 'genetic programming' that was invented in 1988 by John Koza, a PhD student of John Holland. This is a technique where computer programs rather than function parameters are optimized. In genetic programming, the individuals are non-linear entities of different sizes and shapes analogous to taxonomic dendrograms. Another significant variation is gene expression

```
START
Generate the initial population
Compute fitness
REPEAT
    Selection
    Crossover
    Mutation
    Compute fitness
UNTIL population has converged
STOP
```

Figure 7.3 Pseudocode for a genetic algorithm. *Source:* Reproduced courtesy of Vijini Mallawaarachchi.

programming introduced by Cândida Ferreira in 2001. This also uses populations of computer programs (genotypes) encoded as linear strings of fixed length (chromosomes) but these are expressed as computer programs of different sizes and shapes (the phenotype).

7.2 Swarm Intelligence

Swarming is a collective behaviour of animals of similar size that aggregate, either milling about the same spot or moving en masse in a particular direction. Examples are the swarming of bees, the flocking of birds and the shoaling of fish. During swarming, the animals follow very simple rules. There is no centralized control structure dictating how individuals should behave. Rather, local random interactions between them leads to the emergence of 'intelligent' global behaviour unknown to the individual animals. Scientists have modelled swarming and this has led to the development of swarm intelligence as a component of artificial intelligence.

In 1986, Craig Reynolds developed the first model of swarming which simulated the flocking behaviour of birds. The computer program was called Boids, where the name 'boids' corresponds to 'bird-oid object' or bird-like object. In the program, the boids follow three rules:

- Move in the same direction as their neighbours,
- Remain close to their neighbours,
- Avoid collision with their neighbours.

More complex rules can be added such as obstacle avoidance and goal seeking. Regardless, there are two basic models. In the metric distance model, a particular boid pays attention to all the boids within an inner zone of repulsion, a middle zone of alignment and an outer zone of attraction (Figure 7.4). In the topological distance model, a particular boid pays attention only to the six or seven closest boids irrespective of their distance from it.

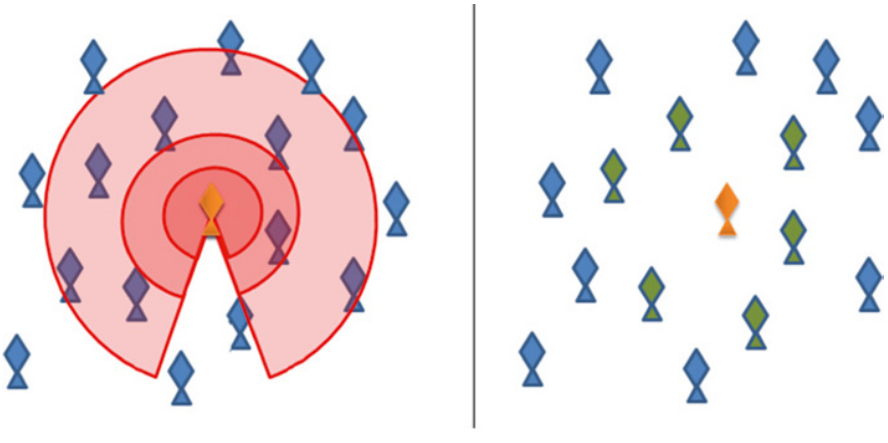

Figure 7.4 Diagram showing the difference between the metric distance model (left) and the topological distance model (right). In the metric distance model, the orange boid pays attention to all the other boids (shown in blue) within a certain distance. In the topological distance model, the orange boid only pays attention to the six boids (shown in green) nearest to it, regardless of their distance.

The metric distance model is representative of fish shoals where the fish rely on visual signals and hydrodynamic signals from the water. The topological model is representative of flocks of starlings.

The boids framework often is used in computer graphics to provide realistic-looking representations of flocks of birds and other creatures, such as schools of fish or herds of animals. The 1992 film *Batman Returns* was one of the first movies to use Boids and featured computer-generated bat swarms and armies of penguins marching through the streets of Gotham City. *The Lord of the Rings* film trilogy made use of similar technology.

Ant colony optimization (ACO) is a population-based algorithm that can be used to find approximate solutions to difficult optimization problems. It was developed by Marco Dorigo in 1992 and was inspired by the foraging behaviour of ants. When an ant finds a food source, it marks the path with pheromones. This attracts other ants to that path, leads them to the food source, and prompts them to mark the same path with more pheromones. This is known as stigmergy, i.e. a small change by a group member causes other members to behave differently, leading to a new pattern of behaviour. Over time, the most efficient route will become the superhighway, as the faster and easier a path is, the more ants will reach the food and the more pheromones will be on the path. Thus, it looks as if a more intelligent being chose the best path, but it emerged from the tiny, simple changes made by individuals.

In ACO, a set of software agents called 'artificial ants' locate optimal solutions by moving through a parameter space representing all possible solutions. Just as real ants lay down pheromones directing each other to resources while exploring their environment, the simulated 'ants' similarly record their positions and the quality of their solutions. Consequently, in later simulation iterations more ants locate better solutions. One variation on this approach is the bees algorithm that mimics the foraging behaviour of honey bee colonies.

Today, there are many different variations of ACO and each of them has particular strengths and weaknesses. One of these variations, called stochastic diffusion search, has been used to determine the location of wireless masts for communication networks. Here the objective was to minimize the number of sites while maximizing area coverage for users. Airlines have used ant-based routing to assign aircraft to arrival gates and to optimize aircraft boarding rules to minimize turnaround times.

Particle swarm optimization (PSO) is a computational method that originally was developed by James Kennedy and Russel Eberhart in 1995. Their goal was to simulate the social behaviour and choreography of birds flocking around food sources. Later, they realized how well their algorithm worked on optimization problems. The basics of the algorithm are that over a number of iterations, a group of variables have their values adjusted closer to the member whose value is closest to the target at any given moment. Imagine a flock of birds circling over an area where they can smell a hidden source of food. The one who is closest to the food chirps the loudest and the other birds swing around in his direction. If any of the other circling birds comes closer to the target than the first, it chirps louder and the others veer over towards him. This tightening pattern continues until one of the birds happens upon the food. PSO is an algorithm that is simple and easy to implement.

A major application of swarm intelligence is the control of swarms of robots and drones. Researchers at Georgia Robotics and Intelligent Systems created a small swarm of simple robots that can spell and play the piano. The robots cannot communicate but, based solely on the position of surrounding robots, use an algorithm to determine how to complete their

task optimally. A Chinese company, Ehang, created a swarm of one thousand drones that lit the sky with colourful and intricate displays while autonomously troubleshooting any errors. Not surprisingly, swarm intelligence is of great interest to the military establishments of many countries. Drone applications include intelligence gathering, missile defence, precision missile strikes, and enhanced communication.

7.3 Human Swarming

In horseracing, the 'favourite' to win a race is the one on which the most money has been bet. The favourite is not necessarily the horse that most people think will win because the odds are biased. One person betting £100 will dominate over 90 people betting £1 on another horse. Even if the betting were taken out of the equation, the 91 people still might not pick the winner because the result would simply be the average of their individual choices. However, if the 91 people were to act as a crowd ('human swarming') there is a much greater chance that they will make the correct decision about the likely winner. This is a relatively simple example but the principle has been adopted for complex decision-making and is based on a platform called SWARM that mimics bees.

When a honey bee swarm emerges from a hive, the bees initially do not fly far. Rather, they gather in a nearby tree or object and cluster around the queen while 20–50 scout bees are sent out to find suitable new nest locations. An individual scout returning to the cluster promotes a location she has found by using a dance to indicate direction and distance to others in the cluster. The more excited she is about her findings the more excitedly she dances. If she can convince other scouts to check out the location she found, they may take off, check out the proposed site and promote the site further upon their return. Initially, different sites may be promoted by different scouts but after a period of time a favourite location emerges from this decision making process. When all scouts agree on a final location, the whole cluster takes off and flies to it.

SWARM was developed by Louis Rosenberg and his Silicon Valley-based company, Unanimous AI, uses it to support human decision making by crowdsourcing opinions online. It lets hundreds of participants respond to a question all at once, pooling their collective insight, biases and varying expertise into a single answer. Answering a question with the SWARM tool involves moving an icon to one corner of the screen or other – pulling with or against the crowd – until the 'hive mind' converges. Individuals must constantly vie with other members of the group to persuade them to edge towards their preferred solution.

A number of academic studies have shown SWARM to significantly improve the accuracy of insights generated from human groups. For example, a study conducted at California Polytechnic administered a standard subjective judgement test to over 283 people using an online survey. Each test included 35 questions, thereby generating approximately 10 000 survey responses. The survey results were compared to 66 small groups of 3–5 people answering the same questions using SWARM. On average, the small groups using SWARM outperformed 92% ($p < 0.001$) of survey respondents. As a follow-up, five of the small groups were selected at random. When their results were aggregated their performance was in the 96th percentile (top 4%) of the survey responses.

Furthermore, this group of 18 people achieved a more accurate score (by 1.6%) than if all 283 surveys were aggregated statistically. In other words, using 1/16 the number of participants, the SWARM platform generated better results.

The use of SWARM has now moved beyond academia and is being used, for example, to improve the design of aircraft cockpits, predict sales of clothing lines, and to improve clinical diagnoses. In the latter case, studies have shown that groups of human doctors, when connected together by real-time swarming algorithms, could diagnose medical conditions with substantially higher accuracy than individual doctors or groups of doctors. For example, swarms of human radiologists connected together using the SWARM platform were tasked with diagnosing chest X-rays and demonstrated a 33% reduction in diagnostic errors as compared to the traditional human methods, and a 22% improvement over traditional machine-learning.

Suggested Reading

As noted at the beginning of this chapter, many books have been written on the topics covered here and, without exception, have been written for computer scientists and not biologists. The reader seeking more information is recommended to search for relevant topics in Wikipedia.

8

The Future of Biomimetics

Biomimetics has come a long way since Janine Benyus coined the term in 1997. There now are undergraduate courses and master's programmes at many universities including leading institutions like Imperial College London (UK), the University of Cambridge (UK), University of California Berkeley (USA), and Harvard University (USA). There now are journals devoted specifically to the subject (e.g. *Bioinspiration and Biomimetics*) and others that specifically cater for the kind of interdisciplinary science that constitutes biomimicry research (e.g. *Journal of the Royal Society Interface*). The ultimate sign that biomimetics has come of age is that there are now two International Organization for Standardization (ISO) standards for work in biomimetics. ISO 18458:2015 provides a framework for the terminology on biomimetics in scientific, industrial and educational projects and includes a description of the process of applying biomimetic methods from the development of new ideas to the design of the finished product. ISO 2015 18459:2015 is targeted at the use of biomimetics in the design and evaluation of load-bearing structures.

Back in 1997, there were virtually no products on the market that had been bioinspired other than Velcro: biomimetics was more of a concept than a realization. Today, as set out in previous chapters, there are many more products on the market, or about to come on the market. More important, we have a much better understanding of biological structures and biological processes to guide the development of new bioinspired products. This bodes well for the future. In this respect, it is worth considering what has happened in the field of biotechnology. In the late 1970s, biotechnology was synonymous with recombinant DNA technology (gene manipulation) and I was lucky enough to write the first textbook on the subject. Today, gene manipulation represents about 5% of biotechnology and comprehensive coverage would require a multivolume treatise.

In the introductory paragraph of Chapter 5, we discussed Peter Fratzl's analysis of the differences between natural and engineered materials. The first significant difference was that natural materials are made from just a few elements and largely ignore the metals favoured by engineers. Over the past few years there have been a growing number of publications describing biomimetic products made from natural polymers such as chitosan, silk, etc. So far, these materials have not been fabricated into composites with, for example, the capacity to replace timber but nobody so far has used them to make hierarchical materials. We are only beginning to understand the extent to which nature uses hierarchical materials so we can expect this aspect of biomimicry to be a major growth area. In Chapter 5, we

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discussed hierarchical steel that was inspired by the byssal threads of mussels (Section 5.2.2). However, the product still used metal. Hopefully, what we will be seeing is new strong materials made from natural polymers. This development should be facilitated by the range of modern fabrication techniques such as 3D printing. Finally, there are two advantages of using natural polymers in manufacturing biomimetic products that have largely been ignored. First, the synthesis of natural products requires little energy, unlike metals, i.e. they are environmentally friendly. Second, they are biodegradable.

Another key point made by Peter Fratzl was that natural materials, unlike synthetic ones, can respond to changing environmental conditions and have the capability of self-repair. A human who regularly lifts weights or runs long distances will develop muscles in the appropriate places. Trees that are constantly exposed to wind will develop stiffness by laying down the necessary new tissue. Can you imagine a bridge that of its own accord gets stronger as it is exposed to heavier and heavier loads? When we can build such a bridge then biomimicry really will have come of age. However, progress is being made. We already have seen the development of self-healing concrete (Chapter 4, Section 4.4) and glass bricks (Chapter 5, Section 5.3). There also has been development of materials that respond to moisture levels (Chapter 5, Section 5.4.1 and Chapter 6, Section 6.2.3). These are recent developments and in the coming decade we should see examples that are much more sophisticated.

Most of the examples of biomimetics described in this book are based on a single property of natural materials. For example, materials like Sharklet that resist fouling are modelled on the denticles of sharks (Chapter 2, Section 2.9). However, Sharklet-based materials will eventually develop a biofilm whereas healthy sharkskin never does. The shells of bivalve molluscs also remain free of extraneous growth as long as the structure is intact. In both these cases, the continuing freedom from biofouling is not dependent simply on the structure of the material. The animals also secrete cleansing solutions, i.e. there is not a single solution to a problem. The leaves of many trees contain noxious substances to deter herbivorous animals from eating them. Should the leaves still be attacked, the leaves will secrete volatile hormones that signal other parts of the tree, and neighbouring trees to increase the amounts of protective chemicals. Finally, the tree can self-heal by making new leaves. There has been little use of multiple technologies in current biomimetic products but this should change in the future. However, it will require the use of multiple technologies. A model for this approach is the laboratory of Alon Gorodetsky at University of California Irvine (USA), where they are combining electronics and optics to develop responsive materials (Chapter 3, Section 3.4). The future is bright!

Suggested Reading

Terrier, P., Glaus, M., and Raufflet, E. (2019). BiomiMETRIC assistance tool: a quantitative performance tool for biomimetic design. *Biomimetics* https://doi.org/10.3390/biomimetics4030049.

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