

Applications — Influence of Biology on Engineering

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Abstract

Examples are presented showing the way in which biological systems produce a range of functions which can be implemented in engineering, such as feedback-control of stiffness (muscles and nervous system), the design of fault-free structures (trees) and damage-tolerant materials (wood) and high performance insulation (penguin feathers) and shock absorbers (hedgehog spines).

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1 Performance criteria; philosophy

If engineers are going to be able to use ideas from biology (and it's not always easy to convince engineers that they should), it cannot be stated too often that the biological system must be understood before allowing ideas to be transferred into the engineering environment. The classic example, again, is flight where there was insufficient appreciation of the scaling problems in powering flapping flight. For instance, structural control and feedback. Many animals could be equated with low loading structures with feedback to give the impression of infinite stiffness and stability. As an example, imagine yourself holding a glass in your outstretched hand with your arm held horizontal. Much to your delight, someone decides to fill the glass with your favourite drink (in my case, of course, that would be water). To the surprise of the engineer who is watching, your outstretched arm does not sag with the addition of this extra load. Obviously you are contracting muscles on the upper side of the arm and these are counteracting the weight. But to the engineer it appears as if you have an arm that does not deflect on loading — it is infinitely stiff! When computing power becomes cheaper than concrete (and that point may already have been reached

if we were to do our sums in terms of global accounting) it will be cheaper to make a lighter structure with less material and to make it capable of bearing loads by the simple expedient of controlled stressing — just like your outstretched arm. It would also be just the sort of structure for the armed forces, since it would be light weight and easily transportable, could rapidly adapt itself to new or changed conditions, lean into the wind on an exposed site, *etc.*

2 Adaptation and computation — different means to the same ends

A topic introduced earlier concerning laws of scaling and allometric growth suggested that plants and animals have an intrinsic “knowledge” of how big and heavy they should be, by measuring deflections. If the deflections are too great then more material can be added locally until the deflections come within the allowed range. That range will have been evolved by a process of natural selection to be within a safe limit for the structure and the material of which it is composed. Some materials such as bone are being continually remodelled, so material is not only deposited in areas of greatest displacement (= greatest load) but also being resorbed where the displacement is less than the design optimum. Other materials such as wood are not capable of being resorbed, being chemically outside the

metabolic pool once the cell walls are lignified and insoluble. With trees, therefore, material can be added but not removed. There are several finite element packages and programs that can deal with the necessary calculations. One of the first people to apply these ideas was Claus Mattheck, a materials scientist specialising in fracture mechanics working at the Nuclear Research Labs at Karlsruhe. Claus has shown that the concept of a constant and evenly-distributed stress at the surface of biological structures can be accepted as a significant design rule in animals and plants ^[1]. This is also a characteristic of good mechanical design, since there can then be no stress concentrations from which a fracture can start. His idea was to make use of this attribute to test shapes of structures for particular loading situations for producing structural shape optimisation of engineering components. For engineering purposes the optimum is to have sufficient strength for all relevant loading cases whilst maintaining a minimum weight. This can be further refined by saying that the structure will be designed to resist best those loads that it faces most commonly. We have already seen that wood conforms to this general performance characteristic — perhaps some clues can be obtained from its structure as well. Before computers became available, Baud in 1934 experimented to find the optimum shape for the joint of a cantilever beam to a strut. To do this he filed pieces of celluloid by hand and checked the homogeneity of stress by placing the specimen between crossed polars and loading it. In those areas where the strain is non-uniform, the plastic is slightly more stretched and the molecules slightly more aligned, thus appearing coloured in polarised light. Empirically, Baud was able to derive contours for the joint area, which turned out to be different for compressive and tensile loads. Claus Mattheck showed that Baud curves are found in many contexts in natural structures such as branching trees and antlers. He then examined the way in which trees respond to changes in loading, which is to change the distribution of the outermost layer of the wood. This is, of course, the only option open to the tree since the wood is added from a growth layer around its periphery. He modelled this in the computer by allowing his finite element model (q.v.) to develop a thin, uniform outer covering of very low

stiffness. This could then register more sensitively the non-uniformities in the distribution of surface stress. He allowed this layer to swell in those areas where the stress was greatest. The new addition to the shape was then given the properties of the bulk of the material and the process repeated. Claus has applied this approach successfully to a range of structures, including simple beams bent in various ways, links of a chain, a crane hook, a rubber bearing and, most satisfyingly for biologists, the design of a novel thread form for the screws used to fix metal plates onto bone (Fig. 1). Claus walks with a limp due to a poorly executed repair on one of his legs, so he has some personal interest in this particular improvement in design. There is an interesting and important outcome. The design books may recommend a minimum radius at the point where a lug or tooth sticks out from a piece of metal, in order to reduce notch stresses. Claus's designs produce far smaller surface stresses even though the change of direction can be made with a far smaller notch radius. So it's not the size of the notch that matters as much as its shape. Again nature seems to be very good at designing holes. Some of these ideas have been proved in practise, and are, for example, contributing to safer design of the front suspension of Opel cars.

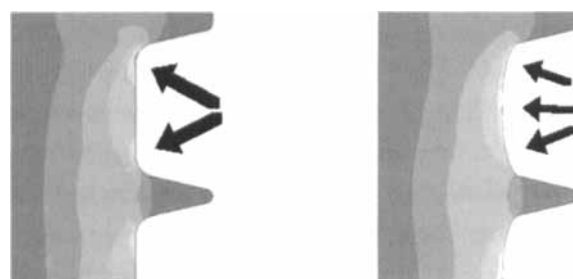


Fig. 1 A novel thread form on a screw. Arrows denote high stress, which is more evenly spread in the improved thread form on the right ^[1].

Whilst Claus Mattheck has shown why the shapes of nature offer design solutions to architects and engineers, that has not been a necessary step in the ability to use the ideas for real structures or practical design studies. After all, nature doesn't know why these structures are efficient or durable — that they result from the mechanisms of evolution is sufficient. So other architects and designers have taken the same path as

Mattheck, less analytically because the computational tools were not available. Robert Le Ricolais (1894–1977), a French engineer and architect, used the reticulated ceramic frameworks produced by the microscopic marine protozoa, the Radiolaria, as his inspiration (Fig. 2). He first came upon them in Haeckel's report from the Challenger expedition ^[2] at the end of the 19th Century. With rigorous logic he developed structural principles, with a research school at the University of Pennsylvania in the USA. The structures resulting were stiff, light and durable, yet made of only a few basic units. His target was, as he said, structures of "Infinite strength for zero weight". He also studied the corrugated shells of the scallop, *Pecten*, producing stiff plates and tubes made by assembling corrugated surfaces. More recently, Frei Otto at his Institute for Lightweight Structures in the University of Stuttgart followed a strict and extensive programme of bringing together biologists, architects and engineers (and palaeontologists, mathematicians and ecologists; even philosophers and sociologists) in order to extract useful ideas from biology. These ideas were clearly seen in the tensile web structures that he used to cover the Olympic Stadium at Munich (Fig. 3), amongst other structures. Such membranes are reminiscent of horizontal webs that are built under water by spiders such as *Argyroneta aquatica*, which they use, for instance, to retain air for

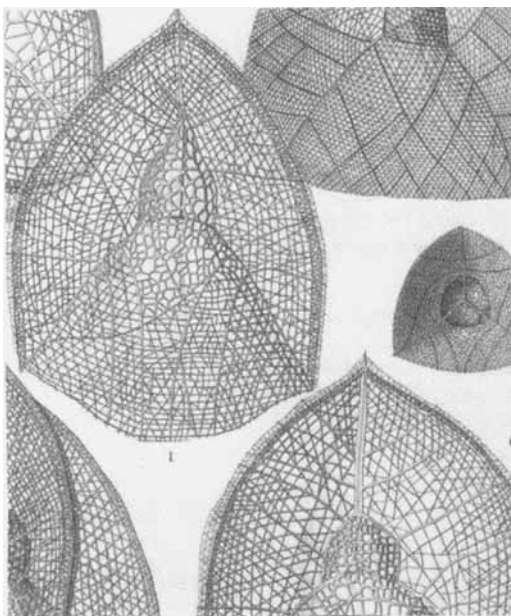


Fig. 2 Radiolaria — the skeletons of *Callimitra* spp. ^[2].

the subaquatic development of their eggs. This concept was used more literally by Jacques Rougerie in a design project for an underwater village to house 250 divers (Fig. 4).

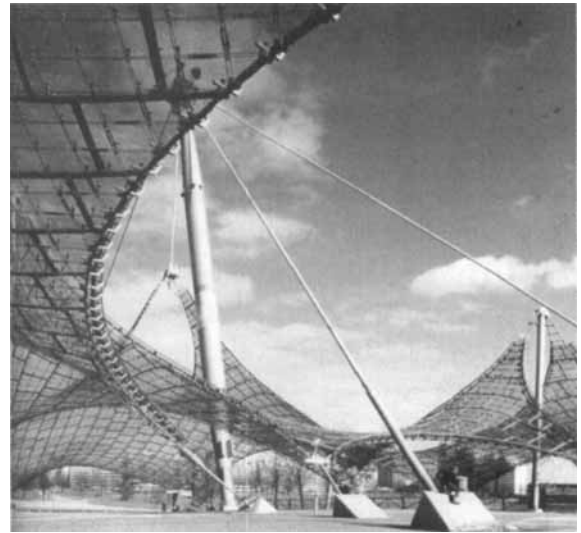


Fig. 3 Part of the Olympic Stadium at Munich.



Fig. 4 Jacques Rougerie's underwater village ^[24].

3 Wood

Wood is still the most efficient structural material in terms of its cost, its stability, its safety and the weight it can support. The largest aircraft ever made — Howard Hughes' "Spruce Goose" — was made out of the only possible material for its construction. Wood. And the highly successful DeHavilland "Mosquito" was also made of wood ^[3]. In fact wood should never have been abandoned as a material for making aircraft. Aircraft started being made of metal as a combination of idleness and prejudice. Idleness because the mechanical properties of wood are not totally uniform, so wood (especially

for a critical application such as making aircraft) has to be carefully graded and chosen. Prejudice because, with no evidence from experiment or experience, metal was considered to be less flammable than wood, lighter than wood for a given stiffness, cheaper than wood and more durable than wood. Well, metal in general may burn less well than wood, but aluminium burns very well if an aircraft catches fire for any other reason, as experience has shown. Structurally wood is far more efficient than metal, more especially being much better at making large panels ^[4]. The invention of stressed-skin construction in the 1930s allowed the external plates of metal to be smooth and carry significant loads, but also made them more likely to buckle. Even so, metal aircraft were still more expensive than wooden ones, and they continued to be made of metal only because of an irrational faith that mass production would make them cheaper ^[5]. And wood is durable if it is cared for as much as metal is. Both wood and metal deteriorate if damp, but metal, being technologically more “sexy”, has attracted more effort and technology to assure its reliability.

Basically, though, wood is not always predictable, metal is, even though its properties are inferior for aircraft construction. This has resulted in a culture into which the introduction of fibrous composites, many of them wood-like, is more difficult, even though those composites, like wood, can have a superior mechanical performance. If the compromise is well calculated it is possible, in artificial composites using the same morphology, though on a much larger scale, to increase the toughness by a factor of ten or more over “traditional” fibre-resin composites at the expense of only a moderate decrease in axial stiffness (Table 1). George’s analysis

of the fracture of wood as the co-operative tension buckling of a population of spirally wound straws led to a novel material that uses this mechanism ^[6]. Early forms of the models were assemblages of straws of spirally wound glass fibres stuck together with resin. But these are not very easy to wind and glue together, although weight-for-weight they are five times tougher than any other man-made material (Table 1). There is a cheaper and easier way. We now use sheets of parallel fibres of glass in an uncured resin matrix (these can be bought as a standard item) which are then folded and glued in a mould to produce a corrugated structure looking like corrugated cardboard ^[7]. The cunning part of the plan is to arrange the fibres at an angle (about 15°) to the long gaps between the corrugations, so producing something like the spiral windings in the wood cell wall (Fig. 5). This material is being developed for protection against explosives and against knives and bullets. It is particularly well suited for use in clothing since it is so light, being a cellular material. It is certain that there are more mechanisms available in wood, since only one of its morphological characteristics — the cell wall — has been properly investigated so far, and then only in coniferous woods.

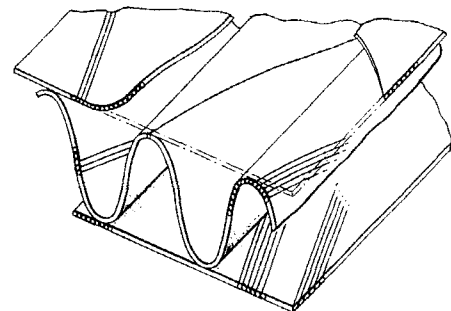


Fig. 5 Using the technology of corrugated cardboard to make a wood analogue ^[7].

Table 1 Comparison of metals and some fibrous composites

Material	Specific gravity	Stiffness (GPa)	Specific stiffness	Toughness (kJ/m ²)	Specific toughness
CFRC	1.6	140	87.5	1	0.6
Oak	0.68	10	15	7	10
G's W (corrugated)	0.61	11	18	10	33
Tough aluminium	2.7	70	26	400	150
Tough steel	7.8	206	26	1220	156
G's W (tubes)	0.65	11	17	500	820

CFRC — Carbon-fibre Resin Composite; Oak — a dense wood; G's W (corrugated) — wood analogues as shown in Fig. 5; Tough aluminium — Structural, ASTM B247/2018 (4% Cu; 0.8% Mg; 2% Ni); Tough steel — U.S. A1S14340, oil quenched from 830 °C, tempered at 600 °C; G's W (tubes) — wood analogue made with tubes of GFRP wound at 15° to the long axis.

Another intriguing topic is why certain hardwoods (woods from broad-leaved trees as opposed to conifers) resist impact forces so well. When we started work on this area (as part of a project to develop new ways of toughening artificial composites) we found that although many people had worked on what gives wood its longitudinal mechanical properties, the source of its properties across the grain had hardly been looked at all. One or two trivial things emerged, such as the effect of repeated loading, at high or low rates, which collapses the cells longitudinally so that the outer surface has a higher density. This explains why cricket bats have to be “played in” (they undergo a form of work hardening — in metals this can be done by firing steel balls at the surface that makes the fault lines within the crystal of metal move until they can go no further and are said to be “pinned”. In this way the ductility of the metal is removed making it harder but more brittle). A more interesting and general mechanism emerged from looking at the way in which the presence of large vessels — tubes up to 500 μm in diameter — within the matrix of smaller fibres. The way in which these holes improve the toughness of wood has been described in the second essay in this series ^[8]. But if we are to make use of this phenomenon we need to dissect it, understand it, and then to implement it in a variety of other materials.

4 Ceramic composites

Biological ceramic composites (bone, nacre) are mostly significantly tougher than man-made ones, so there is a distinct advantage in making similar materials. Their stiffness is dictated by the amount of ceramic present, but nature can pack more ceramic into a composite material than we can, so biological ceramic composites can be much stiffer. This may be to do with the fact that nature uses crystals and platelets rather than round particles, which can then be packed much more closely. Mother of pearl, for instance, can contain 95% ceramic whereas we can manage only 50% or so with spherical particles. Another advantage of using platelets is that the matrix material is much more evenly distributed between the particles; spherical particles will be very close at some points on their surface, with large volumes of matrix material in other places. Thus nature

can get away with using only a tenth of the polymeric material that we need, which would reduce our reliance on oil-based materials if we could copy it. There have been several attempts to make ceramic composites using small particles. Various people have tried producing composites of silica in silicone rubbers, cobalt in various polymers, copper or cadmium sulphide in polyacrylonitrile, and copper in cellulose. In these systems the polymer often constrains the size of the inorganic particles so one can say that the product is a “nanophase” material, itself an advantage (small particles can be more reactive since there is more surface area per unit volume, and they can also provide more effective reinforcement). However, we still have no control of shape or orientation of the particles, the uniformity of their size or their interaction with the surrounding matrix that is essential for the effectiveness of the material. It seems that nature provides three fundamental requirements for the manufacture of these materials:

- (1) The matrix material is organised — this requirement could readily be fulfilled by liquid crystalline polymers;
- (2) There are strong interactions between the matrix material and the inorganic phase — this could also be provided by liquid crystalline materials;
- (3) The rate at which the polymer matrix and the inorganic material are supplied to the reaction area is carefully controlled.

Many people have tried to form crystals of calcium salts in solutions of various organic materials. Dilute solutions of polypeptides made from a single type of amino acid (homopolypeptides) seem to be able to influence the morphology of the hydroxyapatite crystals formed ^[9]. These “organoapatites” contain only 2%–3% of the homopolypeptide. When the organic phase is poly(L-lysine) the crystals are exceedingly thin plates whereas poly(L-glutamic acid) encourages much larger crystals to form. This suggests that the lysine derivative favours growth of the crystal in only one plane, inhibiting growth in the other planes. A weakness of this approach is that the reactions of nature occur in concentrated solutions. And under these conditions liquid crystalline materials are far more likely to form ordered structures.

Bill Clegg, who worked at ICI with Derek Birchall, one of the major innovators in the area of biomimetics, developed a platy ceramic based on nacre. Nacre has a tenuous protein matrix between the platelets of aragonite. Clegg's idea was to use the platelets, but with different matrix materials in the sandwich. By adapting the technology used to make multilayer capacitors from electrical circuits, he made the production cheap and simple. Ceramic powder is mixed with a polymer and formed into sheets about a fifth of a millimetre thick. This is formed into sheets like pastry, coated to give the right interfacial properties, pressed together to give the desired shape and cooked at 1000 °C without pressure. When the ceramic is silicon carbide and the sheets are coated with graphite (which stops them sticking together), the material has a work of fracture of the order of $6 \text{ kJ}\cdot\text{m}^{-2}$, several times greater than nacre. However, this material still has problems, being weak in tension and tough in only one direction, when the crack is made to progress across the layers. The graphite does no more than separate the plates, so the material is also weak in shear or fatigue tests. Even so, the material was used to make a prototype combustor liner for a gas turbine. The current metal version has fine holes through which cooling air is blown, but this air can combine with unburned fuel to give local hot spots. A combustor made from a single thick layer of silicon carbide broke the first time it was used, but the toughness of the laminated version showed a dramatic improvement in resistance to thermal shock. The graphite is still a problem, though, since it tends to burn away at the high temperatures. It's important to allow the plates to move against each other as the platelets heat and cool, so the interlaminar layer has to be significantly softer than the platelets. So the graphite was replaced with a layer of the same material as the platelets, but with holes in it. The holes are made by mixing starch granules in with the ceramic paste, that burn away when the material is heated. Starch comes in a variety of shapes and sizes, depending on its origin, is cheap and disperses readily in water. The separated plates can store a charge between them in the same way that a capacitor in an electrical circuit can. The ability to store charge depends, amongst other things, on the distance between the plates and the state and nature of the

material between them. If these change, as might happen when the material is deformed, then the capacitance will change, can be measured, and used to monitor loads and damage in service in a non-invasive manner.

Nacre's trick of dividing the brittle calcium carbonate crystals into tiny plates can be used with other brittle ceramics — metal carbides for instance. Liu, Li and Li at the Tsinghua University of Beijing in China made multilayers of titanium carbide (TiC) and a number of metals (iron, chromium, cobalt, nickel, copper, aluminium, *etc.*) that mimic not only the structure of nacre but manage to do it at the same scale ^[10]. By heating a correctly proportioned mixture of Ti and C in a vacuum, the constituent atoms are knocked off at high energy and can be deposited onto the surface of a substrate material (in this instance silicon). This is known as sputtering and allows very fine control of the thickness of the layers. The layers that were produced in this study were very much thinner than those found in nacre (less than 10 nm — the thickness of a platelet in nacre is about 500 nm) and the total thickness of the multilayers (alternate layers of the carbide and a metal) was only about 1000 nm. So it's an expensive way of making a material (the basic kit does not come cheaply) and you can't make much anyway. For that money the material has to have an outstanding performance. But how to test it? With nacre it's difficult enough to make a test piece for a normal materials test — here we have a sample so small it can't be seen with the naked eye! A micro-hardness test was adapted in which a pointed (often pyramid shaped) diamond is pressed into the surface of the test material. The force required to do this, and the size of the indentation, allow stiffness and toughness to be estimated at very small scales. In this instance the test developed involved pressing the diamond into the surface of the test material at increasing loads until the first crack along one of the indented ridges could be seen. The load at which this occurs reflects the ability of the material to stop cracks spreading through the multilayers. For the uncoated silicon substrate this load was 12 g. For TiC on its own it was 25 g, and for the multilayered carbide / iron coating it was 60 g. The best result was obtained with a carbide / aluminium multilayer, when the load was 240 g. Multilayers were then made with

titanium nitride (TiN) and platinum (Pt) which, with judicious choice of the thickness of the layers, could be made harder and tougher than either of the two starting materials on their own^[11].

This is a powerful alchemy. In most composite materials the hardness is some sort of average of the individual components. But (presumably) by controlling and inhibiting the way cracks spread at a size scale near to the molecular level the properties of materials can be brought much closer to some sort of theoretical maximum. The moral is that if we can control the way materials fall apart, we can very much improve the way they stay together. Nacre is not the only tough ceramic found in mollusc shell — it just happens to be the one that has been studied the most.

5 Spines and quills

The foam-like structures down the centre of hedgehog spines supports the thin outer walls against local buckling, allowing the structure to bend further without failing. Lorna Gibson and her student, GN Karam, both of the Dept of Engineering at the Massachusetts Institute of Technology have “solved” hedgehog spines^[12], which I and a student (Paul Owers) had shown a few years before to be highly efficient struts^[13]. Like us, she distinguished several different internal structures to the basic tubes (Fig. 6) — an isotropic three-dimensional core (porcupines such as *Coendou* and *Erithizon*), the same, but with added solid ribs running longitudinally down the tube (the porcupine *Hystrix*), orthogonal longitudinal and circumferential stiffeners in a “square honeycomb” (European hedgehog,

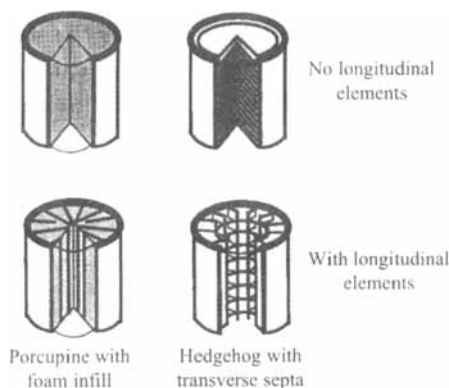


Fig. 6 Internal structures of some porcupine quills and hedgehog spines (adapted from [12]).

Erinaceus and the spiny rat, *Hemiechinus*) and last, thin septa very closely spaced (as in the tenrec, *Setifer*). These four structures were analysed as cylindrical shells with a compliant (soft) core. The theory of cellular materials^[14] shows that the ratio of the stiffness of the cellular structure to that of the material from which it is constructed (E_c/E) is the ratio of the densities (ρ_c/ρ) raised to a power whose size depends on the geometry of the cellular structure. In the spines of hedgehogs and porcupines this ratio is between 0.05 and 0.1. Karam and Gibson were able to calculate the degree to which the cellular structures stabilise the tube of the spine against buckling when it's loaded on end like a strut — the most likely form of loading for these structures. The porcupine quills performed more or less the same as hollow cylinders in buckling as struts with an axial load; in bending they are 40% or so better. But the spines of the hedgehog, with their square honeycomb core and longitudinal stiffening, supported three times the load that they would without the core. For a given bending stiffness the mass of the tube can be reduced by increasing the relative radius. This basically gives the tube a greater second moment of area, I , and therefore a greater flexural rigidity, EI . But it then runs into the problem of the tube going flat at the point of highest force (Brazier ovalisation — Fig. 7) and of local buckling. The foam core alone can resist the ovalisation, but local buckling demands radially orientated material for its resistance. This reinforcement is thus best provided

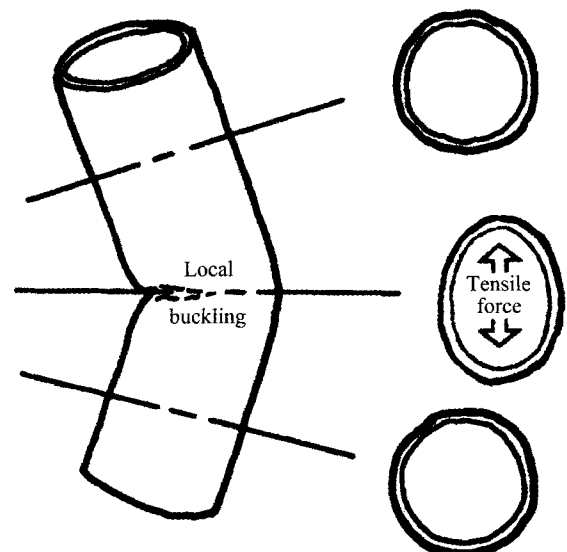


Fig. 7 An end-loaded tube going flat at the point of highest force (Brazier ovalisation).

as longitudinal, circumferential or orthogonally stiffened. If these stiffeners are sufficiently massive they can also do the job of the foam core, that can be removed with no reduction in mechanical performance. Additionally, material in the central part of the core will have a low second moment of area and provide much less support in proportion to its mass. It can therefore safely be omitted from the structure. The recent development of a process that allows the production of cylindrical metal shells with an integral foam-like or honeycomb-like core means that the excellence of this design, previously confined to nature, can be extended to lightweight tubular struts such as are found in the suspension of racing cars.

6 Molecular machines

The development of mechanisms for doing directed work at the molecular level has proceeded from at least three directions. The first, that can be immediately dismissed (at least in the present context, though many would dismiss it totally) is the concept of scaling down machines to the molecular level. The main proponent of this approach — Eric Drexler — has the concept of a factory being reduced to the size of a microscope slide. Precisely what such a factory can make, and how productive it can be compared with the “full size” version is not stated. It may open up the possibility of production of materials at the molecular scale, with the associated advantage of perfection, but output per machine would be low. Obviously if some of the machines could be programmed to make more machines (a concept of some antiquity, proposed in some detail by von Neumann) then millions of machines could have an effect similar to that of bacteria, that were responsible for many commercially exploited deposits of iron. One of the possible outputs at this level that has been suggested is the construction of crystals such as diamond by the individual placing of atoms and molecules by these machines. It would still take a long time, however, since although there might be millions of machines, they all take up a finite amount of space, necessarily several times larger than the molecules that they are manipulating, and so would be jostling for space around the growing diamond, queuing to place their atoms on the pile. How can this

can be quicker or more efficient than diffusion-based chemistry. And where does the energy come from to do all this? How is it fed into the individual machines? Do they store it in a battery or pick it up from sliding contacts like a train? The concept of the machine includes molecular bearings and conveyer belts. But if Eric knew any biology he would know that at the size range he is talking of diffusion is as fast as anything else. One has merely to set up a source and sink for a particular molecule that one wishes to transport and let it be guided by the concentration gradient. The surface of the crista of a mitochondrion is not far removed in concept from a line of work stations along a conveyor belt. The enzymes that are to do the chemical reactions are arrayed in order, fixed to a surface, and the substrate molecules move from one work station to the next. The ideal machine — no moving parts.

Now Eric Drexler is a lecturer of great charm, clarity and persuasion, and like many proselytes he achieves many instant converts who, on reflection, decide that the new religion is perhaps not all it seemed to be. I numbered myself among the converted for an hour or so after listening to his lecture but, happily, lapsed soon after when I realised how much more powerful biology is.

The other two lines towards molecular machines converge from chemistry and biology. Both are based on chemical potential in swollen gels; the chemical route is the older. Both have the potential for converting chemical, thermal, optical and other sources of energy into mechanical work. They are therefore much more versatile than Drexler's machines (Drexler does not say much about how he intends to feed power into his mechanisms) and much more robust (Drexler does not admit that bits might drop off his gear wheels or chains). Both types of machine transduce energy as changes in molecular conformation associated with changes in hydration. The change in hydration is effected by controlling the charged groups to which the water binds. A simple system is a polyacrylate gel whose pH is changed. At an acid pH (4 or so) the material is close to its isoelectric point, so that the internal charged side groups, negative and positive, are balanced out and there is little net charge. Water will not be readily bound and may

even be expelled (depending on the starting condition) so that the gel will occupy a small volume. At a more alkaline pH (10, for instance) there will be many more positively than negatively charged groups and large amounts of water will be bound into the gel. Unfortunately this change in volume, on its own, does not achieve very much. The gel is intrinsically soft and weak. Some way has to be found of turning this volume change into useful work.

At this point we take a lesson from plants, which manage to get work out of a liquid by putting it into a stiff membranous bag of cellulose. The movement of water can now be made to exert very high forces indeed. Plants can grow through concrete and their roots can destroy buildings; they can change their shape in various ways, slowly or quickly, by changing the turgidity of their cells, which they do through control of the osmotic potential in the cell. Plants are machines whose potential for inspiration we have hardly begun to exploit. With their highly modular design and low energy input they represent some of the best of all models for biomimetic exploitation. This is not the only way of transducing volumetric change into useful work. The muscles in your body are connected into the tendon by a sheet of collagen fibres — the perimysium — wound into a crossed helical pattern very much like the skin of worms. This arrangement has the same structural properties as the worm's skin, so that the volume and aspect ratio of the cylinder are inextricably linked with the fibre angle (Fig. 8). Remembering that the maximum volume is obtained with the fibre angle at about 54° , one can start with a long and thin cylinder (to the left of the maximum volume) or a short fat one (on the other side of the peak). With the first cylinder, increasing its volume will cause it to contract along its length, with the second the cylinder will expand. Since we are working with a system of fibres, which are intrinsically ill-designed for supporting compression, the second type of cylinder is probably best forgotten. The contractile cylinder, however, could function as a muscle and be powered by a gel whose volume is changed by adjusting pH. Increase the pH in the presence of water and the gel will swell forcing the fibres to move towards the maximum volume angle and shortening the cylinder.

This caused some consternation when it was first demonstrated, since the gel experts involved were chemists to whom mechanical interactions were not always obvious. The idea of a swelling gel getting shorter was counterintuitive to them.

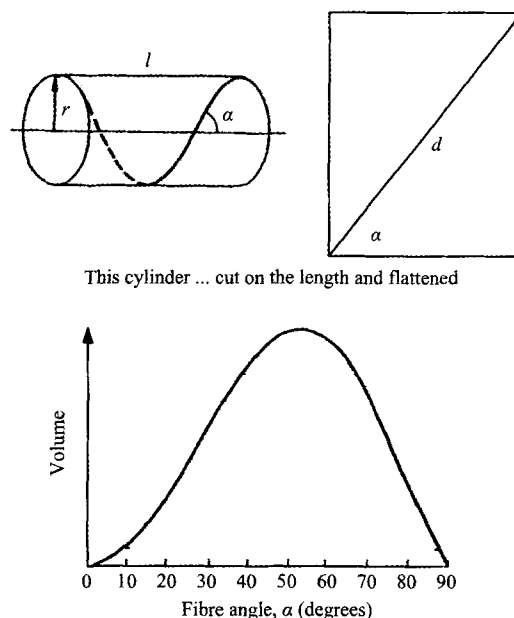


Fig. 8 The volume and aspect ratio of the cylinder are inextricably linked with the winding angle of the fibre ^[25].

There is a robotic muscle available that works on this principle, but actuated by air. This has two major disadvantages. First, the power source is external to the effector (the helically wound bag) necessitating pipes working at pressure; second, gas is compliant, so just like a soft material stretched to a great extension, compressed air can store large amounts of strain energy, which is intrinsically dangerous if the bag is damaged — it will pop like a balloon. Hydraulic systems are much safer from this point of view since the liquid is pretty much incompressible. Even so, there are still pipes containing liquid at high pressure. The gel muscle system described here has the advantage of the muscle which it copies, which is that chemical energy is converted to mechanical energy only exactly where it is required, and any pressure developed is confined to the helically wound bag. Much safer, much more adaptable. This system (at least in its preliminary state) produces a contractile force of about 0.1 MPa. Although this is only a tenth of the force produced by the most powerful muscle known — the anterior byssus retractor of the

mussel.

Other types of chemomechanical system based on gels have also been developed. For instance, a gel derived from poly(N-isopropylacrylamide) will shrink to a third of its original volume when heated above a critical temperature. An electric field of only $0.5 \text{ V}\cdot\text{cm}^{-1}$ will cause a polyacrylamide gel in an acetone / water mix to shrink. In theory, an electric field of $5 \text{ V}\cdot\text{mm}^{-1}$ (i.e. 100 times stronger) could shrink gel particles $1 \mu\text{m}$ across to 4% of their original size within a millisecond. Unfortunately, of course, it's not easy to make such gels and keep them uniform. Once they start to bear a load (i.e. do useful work) the gel particles have to butt up against each other to transfer the load and the diffusion pathways for liquid to move in and out are partially blocked, slowing down the response. Some of these gels, with pore size controllable by pH, for instance, can be used to release drugs in a controlled manner or act as an adaptive filter, allowing filtration of solvent mixtures containing molecules of different sizes. In another system, the gel just absorbs the solvent, leaving the concentrated solute behind. If a strip of PAMPS (poly(2-acrylamido-2-methylpropane sulphonic acid)) gel is suspended between two electrodes in a dilute solution of a surfactant and a voltage is applied across the electrodes the surfactant molecules, which are positively charged, move towards the negative electrode. They encounter the negatively charged surface of the gel and stick on to it, preferentially to the side facing the positive electrode. In so doing they displace water and make the gel contract on that side so that it curls up. When the electric field is reversed, the surfactant molecules are first released, allowing the gel to straighten out. Then the surfactant is caused to bind to the other surface of the gel and bends in the other direction (Fig. 9).

Using this simple system, Professor Yoshi Osada of the University of Sapporo has made demonstrator models of "caterpillars" which will move along a saw-tooth (ratchet) beam at a speed of up to $25 \text{ cm}\cdot\text{min}^{-1}$ and a robotic tadpole. Speed is one of the main problems in all work with gels that swell. They rely on diffusion for the transport of the swelling solvent in and out, and diffusion takes time. But muscles also rely on diffusion, at least for the last part of their chemical pathway within

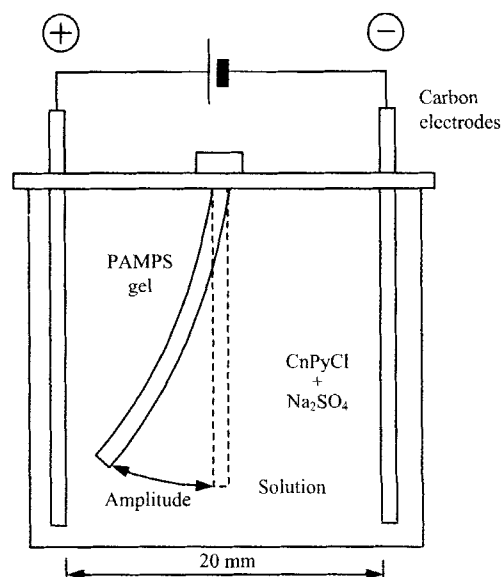


Fig. 9 Making a gel move in an electric field [26].

the cell, and many muscles are far larger than the gels with which we play. How do they manage, especially when (as can be both calculated and measured) they develop internal pressures when they contract? In animals with a blood supply contained in vessels, which can therefore be supplied under pressure, this pressure can be used to deliver nutrients to within a few micrometers of the target. But with animals with an open blood system, such as insects (and especially the flight muscles of insects which have an exceedingly high rate of metabolism) how can metabolic supplies arrive quickly enough and the breakdown products be discharged?

A method for making gels respond quickly, which rather side-steps all these issues, is to embed small magnetic particles in them. They can then respond to changes in a local magnetic field, moving with no volumetric changes and therefore no problems with diffusion. However, the external power source is rather large by comparison with the chemical or temperature changes which are all that is needed with chemically responding gels. Another way is to make hybrid gels. Polypyrrole gels are conducting, but do not swell very much. However, they are sufficiently compliant to be cast into a gel that will swell, and so could be cast into a hole down the middle of a polyacrylic gel (which swells well but slowly) and increase the electrochemical gradient pulling water into the gel. At the time of writing I have not seen the results of this idea, though I have heard

that others have thought of it and implemented it besides myself.

Elastin forms the basis for yet another family of successful molecular machines. This is the work of Dan Urry, a Southern gentleman of the old school who did new things in the University of Alabama at Birmingham. Elastin is a highly hydrophobic protein. It is a characteristic of hydrophobic materials that they are more hydrated, and more expanded, at lower temperatures than higher ones. Urry has designed and developed model elastin proteins which enhance and control this effect, changing from more random to more folded over a temperature difference of 15 °C, but over temperature ranges between 0 °C and 60 °C. They are based on α -elastin, being made of poly(VPGVG) which goes to a spiral structure at higher temperatures. The crosslinks are introduced by use of γ -irradiation from a cobalt-60 source. When a band or sheet of the elastic protein is warmed through the transition temperature it contracts with such force that it can lift a weight one thousand times heavier than itself. The temperature range over which this conversion occurs can be controlled by changing the chemistry of the polymer — the greater its hydrophobicity the lower the transition temperature. Other variables such as pH, salt concentration, pressure or electrical energy can also be transformed into mechanical work by these elastin analogues (Fig. 10). This sounds as if the gels made from elastin-like polymers are

more versatile than the other gels mentioned, which are mostly made from polyacrylamide-based materials. This may, however, be a hidden advantage of the biomimetic route. The molecular structure of elastin is much more regular and predictable than the other polymer systems (which are inherently random, and whose mathematical models are based upon random conformations), so its interactions can be predicted and understood that much more easily.

The basis of the mechanism whereby elastin converts a change in temperature to a change in conformation (doing mechanical work in the process) is the difference in hydration between the hydrophobic (nonpolar or apolar or uncharged) and the hydrophilic (polar or charged) amino-acid side chains^[15]. Around the apolar groups the water molecules arrange themselves into internally bonded pentagonal structures — something like 12 pentagons will surround an apolar group such as methane (CH₄). These pentagons are associated with two quantities of energy — heat is released as they form (so the pentagon represents a minimum energy state and is locally stable) but the other quantity works in the other direction, related to the increasing order amongst the water molecules. There is a balance as the temperature is raised through the transition temperature at which the elastin contracts and does its work. The pentagonal water becomes less ordered but the polypeptide chain folds on itself and becomes more ordered. The reaction to temperature goes the way it does because the increase in disorder of the water is greater than the increase in order of the model protein. The temperature at which this occurs can be reduced by increasing the amount of polar groups: groups such as COO⁻ have such an affinity for water that they can disrupt the order of the water, so less heat is required to drive the transition. The response can be driven in the opposite direction by stopping the formation of COO⁻ as a charged group and keeping it as COOH by reducing the pH. Since the reaction of a side-chain with water can also be affected by its immediate environment, the reaction does not depend only on the number of polar or apolar groups, but also their position along the molecule. All this contributes towards the possibility of a much more tailor-made molecule than is possible with random gels.

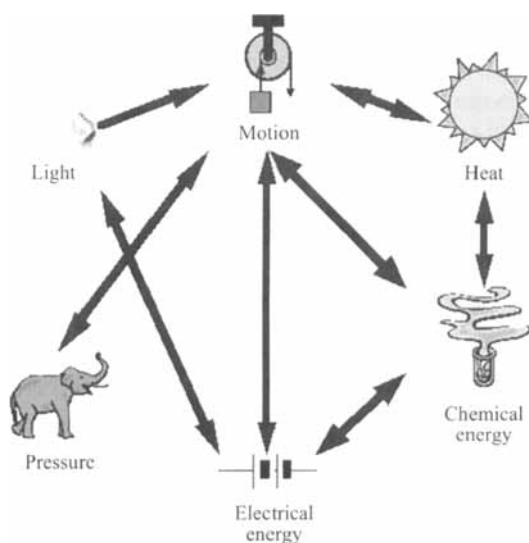


Fig. 10 Energy transductions by hydrophobic gels^[15].

Another type of chemomechanical engine (Fig. 11) was invented and demonstrated by Aaron Katchalsky working at the Weizmann Institute of Science in Israel. This depended on the contraction of collagen when it is treated with 8 M lithium bromide in water. When so treated, collagen will shrink to about 2/3 of its original length or, if held at its starting length, will generate a stress of about 5 MPa. The machine could generate only a few mW at the output shaft, but still served to illustrate the thermodynamic principle inherent in these gel engines, which has not been measured in any of the other systems. The specific power output was shown to be about $0.8 \text{ J} \cdot \text{g}^{-1}$ of collagen fibre although only half that was available as useful work. In the machine a long collagen fibre is wound around a pair of truncated cones that are set at a slight angle to each other. As the collagen shortens it works its way down the cones, rotating them as it goes. The rotation is also used to transport the collagen from the salt-containing bath to one of distilled water, in which the salt is removed and the collagen regenerates its length. It is then reeled back into the salt bath to drive the machine again. Ultimately, of course, the machine winds down as the concentration of salt in the two baths becomes more similar. Other salts can be used such as chlorides of lithium, calcium or magnesium.

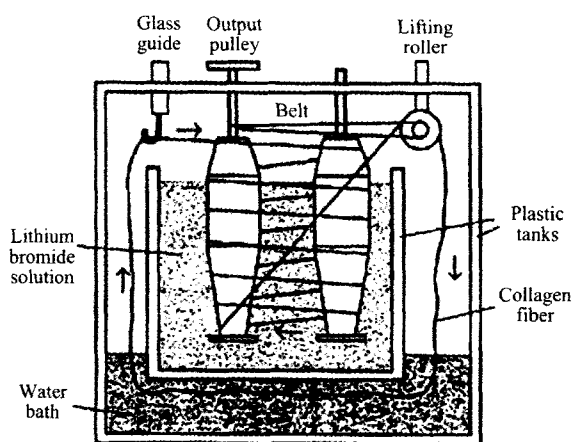


Fig. 11 Another type of chemomechanical engine. The collagen band contracts over the tapering part of the cylinders and turns them.

7 Repair mechanisms

The ability of animals and plants to repair and regenerate themselves is a source of great envy for engineers.

If materials could be made not only to detect and quantify damage (which they can do) but to diagnose the fault, rectify it and repair the damage, then design would be easier and structures more efficient. Robert Ker, working on the leg tendons of the wallaby, showed that they are susceptible to fatigue damage at loads only one tenth of their strength. From this he deduced that our tendons are continually breaking down in use and continually being repaired. It has been known for many years that there is a continual turn-over of tissues in the body, but this was the first time it had been associated with any other function. The difficulty comes in understanding how the cells can detect damage and “decide” how to rectify it. For a start, the cytoskeleton has to be considerably more organised than the vague “sol/gel” model would allow. Repair mechanisms for materials (concrete and polymeric matrix materials) are based on the fracture of a container of “glue” (matrix monomer, rubber, *etc*) embedded within the material^[16], or upon hollow fibres that contain repair chemicals^[17]. The latter is a better option since material can be brought to the fracture site from a much greater distance (the length of the fibre), and thus repair larger breaks.

8 Velcro

This must be the best known of all stories in biomimetics — how Georges de Mestral, a Swiss inventor, invented what Velcro plc call “hook and loop fastener technology”. In the early 1940s, de Mestral went for a walk in the forest with his dog. Upon his return home, he noticed that his dog’s coat and his trousers were covered in cockleburrs. His inventor’s curiosity led him to study the burrs under the microscope, where he discovered the hooked ends of the bristles that stick out from the seeds. This became the basis for a zip, later developed into a unique, two-sided, fastener. One side has stiff hooks like the burrs; the other has loops like the fabric of his trousers (Fig. 12). The result was Velcro, named for the French words “velour” and “crochet”.

The challenge was then to make machinery that could produce textured fabrics that would work reliably. After considerable experimentation, de Mestral developed special looms and hook-cutting machinery. Currently Velcro Industries is (as their advertising literature

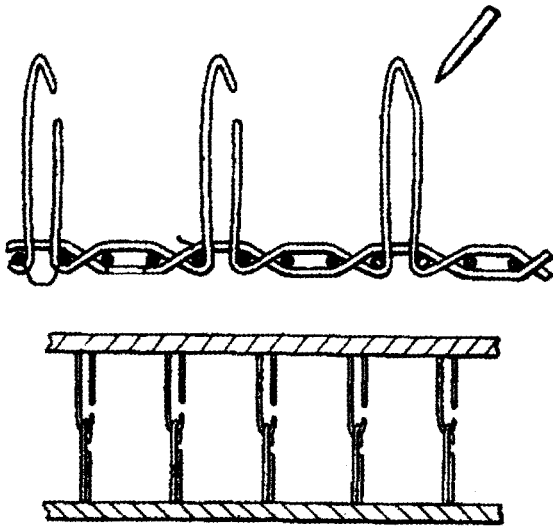


Fig. 12 An illustration from a Velcro patent ^[18].

assures us) a technically driven global organisation and the industry leader. It offers hundreds of different hook-and-loop products and fastening systems. They make fastening tapes of woven and knitted construction and custom-designed speciality fasteners made of various materials in different shapes and sizes. One problem that the company has never, it seems, solved is “silent Velcro”. Imagine a soldier out in the open, sitting in a bush or a hollow and camouflaged against the enemy sniper. “Time for lunch” he says, rips open the lunch pocket on his suit, and bam! The sniper follows the ripping noise of the Velcro and eliminates its source ^[18].

Nature’s hooks are many and various, but have received little treatment using engineering principles. Yet the design and implementation of joining systems is one of the core problems in the development and manufacture of reliable structures. Hooks occur in nature in a vast array of designs and in a diversity of taxa, involving animals and plants. The best summary of insect joining structures is by Stanislav Gorb ^[19]; a rather broader and much less analytical account was given by Nachtigall ^[20]. There are many semi-permanent hooking systems. For instance in some butterflies the pupa is attached to, and hangs from, a silken pad by hooks on the abdominal tip. The attachment must be strong and reliable since the pupa needs to hang for several months (many butterflies overwinter as a pupa) and the joint must be absolutely reliable (if the pupa drops it becomes prey to other animals, fungi, etc). Equally strong hooks are found in

sea-lice that are related to shrimps. These parasites can attach to some of the fastest swimming fish such as Black Marlin. However, different species of parasite are adapted to different species of fish because their hooks are specific to certain skin types. Hooks can work like zips as with the hooks that join the fore and hind wings of bees and wasps. These hooks have to be both strong and flexible and are necessary for flight by creating a single flying surface. They have to join two constantly moving objects while the insect is flying, yet make an instantaneous joint when the insect spreads its wings and break, probably with a very small force, when the wings are folded. And there are many more examples of hooks in plants. For instance bedstraw, a common creeping plant of the English hedgerow. The hooks on its stem can attach to a variety of substrates to permit the “creeping” growth pattern, both horizontally and vertically. Therefore the plant can reach sunlight without investing in a sturdy stem.

What ways could some of these designs be used? Can we break out of the Velcro mentality using more ideas from nature? Can we out-Mestral Mestral? Here are some possible applications summarising both the model system and the type of joining mechanism that could result.

More permanent interactions (possibly based on the Oleander butterfly pupal attachment) could be used to replace sewing (instantly redesigning clothing — e.g. fashion clothes, one-size uniforms, moving pockets around for adaptability, etc.). Less permanent interactions could be used for attaching external wiring and computing to clothing. A hooking mechanism with marked polarity which attaches when moved in one direction and detaches when moved in the other direction giving a sort of directional friction could give rise to a self-designing structure. It could be used with equipment used in climbing and bridging gaps in the way that bedstraw climbs hedges and can cross gaps.

9 Hairy or feathery clothes

Although feathers characterise flight, their original adaptive advantage was probably for insulation. An extreme modern example is the penguin, which can withstand extreme cold whilst fasting for up to 120 days

(during egg incubation) with a thermal gradient across a 2 cm thick layer of feathers of up to 80 °C. But in addition to keeping the penguin warm on land the feathers (Fig. 13) must also give a waterproof, streamline and non-buoyant coat when the penguin is diving. Under water the feathers are rotated by muscles at their base so that the feather lies against the skin, and the shaft or rachis is flattened so that it conforms better to the body surface. When the penguin emerges back onto land the muscles re-erect the feathers providing a thick air filled coat. However, only the shaft of the feather has muscle control. The rest of the feather parts cannot be actively moved. To achieve effective insulation it is important that the rest of the feather parts are able to “self organise” to give an effective, even insulation system.



Fig. 13 A penguin feather ^[21].

We have constructed a thermal model which shows how this feather prevents convection and minimises heat loss due to conduction and radiation ^[21]. The down layer represents about half the volume of the feather, and its barbs (attached to the rachis) are very long and thin and therefore bend easily. Barbules of diameter 6 µm emerge from the barbs, arranged spirally every 20 µm or so, and the barbules have spikes (hooks again!) sticking out which can engage other barbules, making up a spa-

tially stable three-dimensional feltwork of fibres. The insulation is achieved by the small size of the gaps between the barbules. Insulation is achieved by air, not the solid material, and air will not move freely through the network which penguin down provides. In addition the feather keratin is remarkably non-conducting. The lesson we learn from this exercise is that the holes in a fabric, through which the insulating air escapes, can be made smaller with finer and more flexible fibres. Presumably this is why natural fibres are warm — they are finer. A feltwork of microfibres, with roughened surface to retain the structure, would presumably make the warmest material.

10 Smart / intelligent materials and structures

The concept of Smart or Intelligent materials (and systems and structures) has been around for a number of years. Living cells and organisms represent “smart” concepts to a very high degree, and so have been used as a source of inspiration both for mechanisms and an idea of what functions may be possible. A “smart” material (system / structure — the one word takes all) interacts with its environment, responding to changes in various ways. A simple example is photochromic glass, used in up-market spectacles and many modern buildings, which darkens in response to sunlight. The literature is full of definitions of a smart material, most of which are irrelevant. We’re back in the material/structure duality, since in order to be responsive to its environment a material must at the very least have structure. It needs a receptor, a central processor that can differentiate between the inputs and integrate them into a single output, and an effector. This system could be considered as a material if it were integrated within a single lump of stuff (rather than having wires going from and to the central processor) and were being used or observed in a size range at least (arbitrarily) one hundred times larger than the size of the individual components. There are probably three main ideas of what function makes smartness — the simple response that follows on directly and inevitably from the stimulus; the if-then construct in which a decision is made based on balancing the information from two or more inputs; and the ability to learn, which is probably the smartest thing of all, since

learning can lead to a patterned model of the world (the brain is “stored environment”) allowing informed prediction of events. It can be argued that the successful organism is the one that knows what is going to happen next and that prescience is more important than smartness, or at least subsumes it.

Where does this get us? As much as anything it’s the autonomy and adaptability of individual organisms that gives a species its survival value. The biological implication is that this is the cheapest way to make a machine that will function in a range of unpredictable environments. How does this translate to the engineering environment? Consider a robot such as might be found in a factory. It is carefully designed so that the arm or arms are of the correct length and stiffness so that they can support their own weight, and the loads that they will have to manipulate, and not sag significantly. The joints are carefully made with no unnecessary play and give the arm(s) well-defined arcs and planes of movement. The animal equivalent (you, for instance) has arms of undefined length and controllable but undefined stiffness, joints whose accuracy can be variable but with very well designed bearing surfaces, and arcs and planes of movement that are relatively vaguely defined. You are much more adaptable than a robot. Although the robot can be more heavily engineered and deal with greater loads, you can be as reliable as the robot if you concentrate. The difference between you and the robot, in engineering terms, is that the robot was told how to use its limbs, whereas you learned how to do it. This put far fewer design constraints on your skeleton — its definition is not morphological but functional. Some people have particularly good skeletons and control systems and they find it easy to be athletic. Others (Toulouse l’Autrec comes to mind) have to make do with clumsier systems but make other adaptations to be successful and can be every bit as well co-ordinated. In learning to walk, you have a general aim (why should anyone want to learn to walk? Does anyone know?) and make adjustments until you manage it. But everyone does it differently, at least partly due to differences in skeletal design, and that is why you can recognise people by the noise they make walking. It reflects their individual technique and adaptations to their own particular

design of skeleton and the loads it has to take. Now make a robot along similar lines. Its structure needs to be defined only in terms of its load bearing ability and the positions and places in which it needs to hold or place things. To obtain reproducibility and ease of movement it is necessary to have very good bearings at the joints and where components might have to slide against each other in order that the spatial relationships between the components can be constant and little energy is lost in movement. But the material and structure of the arms and other parts between the bearing points are far less critical. So long as the robot can manipulate its world in the desired manner, it is successful. But you can’t teach it by entering three-dimensional space co-ordinates in a central programming unit, since there is no reliable way the robot can tell, *ab initio*, where the end of its arm might be. The only way you can teach it is by example. Move the bits of the robot to where you want them to be and let the robot remember how it did it. My suspicion is that with such a concept, based largely on biological design optimisations, it would be far cheaper to produce robots than currently. The question is — would the engineers feel that they were losing control of their machines? This is at least partially answered by work at the MIT robotics lab, where a humanoid robot has been learning how to use its limbs. The movements (accelerations, decelerations) are remarkably “human” in appearance since they have developed to use the minimum amount of energy. Compare this with current concepts in engineering, made necessary because of the “dumbness” of the materials and structures. The designer calculates a worst-case scenario based on the environment in which the machine is to be used, the quality of materials and the use and abuse to which it will be exposed. This will yield a system with large factors of safety comprising numerous reinforcements, redundant sub-units and back-up systems, and overall added mass. This design approach has been called “Defence in depth”. But still the designer does not know the trials to which the machine will be put, nor (more important) will the machine be able to benefit from its experience.

It is already possible to incorporate such features. Craig Rogers^[22] reported developments from his

research group at Virginia Polytechnic Institute which he directly ascribed to application of ideas from biology. He was particularly interested in the way in which muscles not only give movement but can redirect the loads in the skeleton by prestressing it in various ways, using antagonistic pairs. Structures were made with areas of high strain concentration across which piezoelectric actuators were mounted. These actuators could not only sense the strain but stiffen the structure locally. As the structure was flexed and the material fatigued in the high strain areas, the piezoelectric actuators adaptively stiffened those areas, retaining the performance of the structure and increasing its fatigue life by over an order of magnitude. Which is where this review started.

11 Multifunctional materials

Can we construct materials (structures) that can do several things at once? Yet again nature is asked to provide ideas and examples. The ideal multifunctional material would be intrinsically smart, self-healing,

self-diagnostic, electro-active, *etc.*, and be able to use its structure as a power source if necessary. Perhaps the spacecraft of the future will burn its fuel then burn the container, in much the same way that a freshly-emerged moth or butterfly larva will eat its eggshell. In this instance the reason is probably as much to ensure that it has a proper burden of gut organisms (the egg is smeared with maternal faeces as it is laid) as that the larva has a good meal to start its life. Probably the best natural example of a multifunctional material is skin, and the accompanying diagram (Fig. 14) shows how one might think of its attributes in a functional manner. The left side of the diagram shows some of the attributes of mammalian skin; the right side shows attributes of insect "skin" or cuticle which, because of its supportive and protective roles, has to be mechanically much more versatile than mammalian skin^[23]. How could we make such materials? Perhaps the technology of plastics points the way. Read the next, and last, exciting episode in this series of essays.

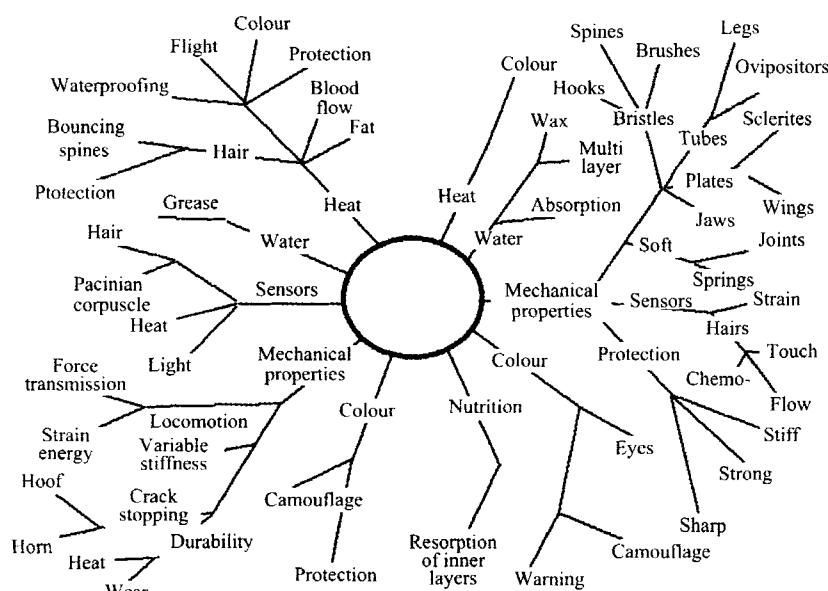


Fig. 14 Skin, a multifunctional material.

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