Life's lessons in design

Philip Ball

So long as it avoids a Panglossian view of nature, the science of biomimetics has the potential to enrich many areas of technology. But accurate mimicry will require greater understanding of natural mechanisms at the molecular scale. As this continues to unfold, emulation may increasingly give way to assimilation of biological machinery.

There is such a long and colourful history of engineers, scientists and artificers gaining inspiration from nature that one could be forgiven for thinking that all the best ideas have been spoken for. In the nineteenth century, biomimesis was at least as much an aesthetic as a practical pursuit. Artists and architects delighted in Ernst Haeckel's drawings of radiolarians for their beauty alone. When the French designer René Binet conceived of the elaborate entrance gate to the World Exposition in Paris in 1900, he told Haeckel: "everything about it, from the general composition to the smallest details, has been inspired by your studies"[1] (Fig. 1).

But others recognized the inventiveness, economy and sound engineering of nature's structures. The Wright brothers took flight after watching vultures swoop, giving a nod to Leonardo da Vinci's explicitly aviamorphic flying machines. Joseph Paxton is said to have paid tribute to the ribbed stem of a lily leaf in his Crystal Palace, which housed the Great Exhibition of 1851. Gustave Eiffel's tower supports its own immense weight along elegant curves inspired by bone structure. D'Arcy Thompson[2] tells how in 1866 the engineer C. Culmann in Zürich, pondering on the design of a new construction crane, wandered into the laboratory of the anatomist Hermann Meyer who was studying cross-sections of bone. Observing how the trabeculae of the porous material traced out lines of tension and compression, he cried out: "That's my crane!"

This rich heritage means that the diverse array of scientists and technologists who today take their lead from nature may feel they are immersed in the paradigm of an earlier age, with its traditional-sounding considerations of morphology, stress distribution and hydrodynamic forces. And yet the materials and devices emerging from biomimetics are unmistakably forward-looking: new solar cells, smart sensors, advanced robotics and aerospace materials.

But today, biomimetics has something much more dramatic to offer than an aircraft wing or an anti-drag surface coating modelled after some natural example. One of the biggest obstacles to taking full advantage of what nature has to offer is that the living world has an awesomely elaborate means of construction. There is no assembly plant so delicate, versatile and adaptive as the cell. But as modern methods of investigation and analysis decode and elucidate the cell's molecular machinery piece by piece, this disparity between the natural and synthetic art of manufacture begins to diminish. When biomimicry proceeds at the molecular scale, as it is now beginning to do, its entire basis is transformed.

And the inevitable corollary of molecular biomimetics is a new conceit, which one might call biosynergic engineering: merging nature's machinery with synthetic constructs to develop a new kind of synthetic methodology at the molecular scale. The scattered, primitive beginnings of such a movement already reveal that nature may have even more potential than it displays in the wild.

Small is beautiful

Biomimetics has encompassed some grand engineering, but it is undoubtedly small science — indeed, often budget science. The reasons are clear: nature does not employ exotic materials, nor extreme energies or high pressures. The living world comes almost with a guarantee of economy, for that is evolution's exigency. Maximum return for minimal (metabolic) outlay: this is the stipulation that keeps nature lean and, in some sense, optimal.

Yet in what sense, exactly? The engineer must consider that carefully. It would be foolish to assume that natural selection stands proxy for the testing laboratory or the market, refining a design in just those ways that a new product demands. The complex of compromises that shape the fitness landscape of evolution is likely to bear only incidental correspondences with that which determines the contours of technological and economic viability. This, after all, is why we seek to mimic and not to duplicate. One of the attractions, as well as one of the main challenges, of biomimetics is that it demands creative solutions. Nature's pool of ideas is valuable only if it can be translated into terms that the technologist can work with, particularly in terms of materials and processing methods.

Take wood, for example. There has been relatively little serious attempt to produce an artificial analogue, for the simple reason that wood itself is already an almost peerless structural material for certain applications:

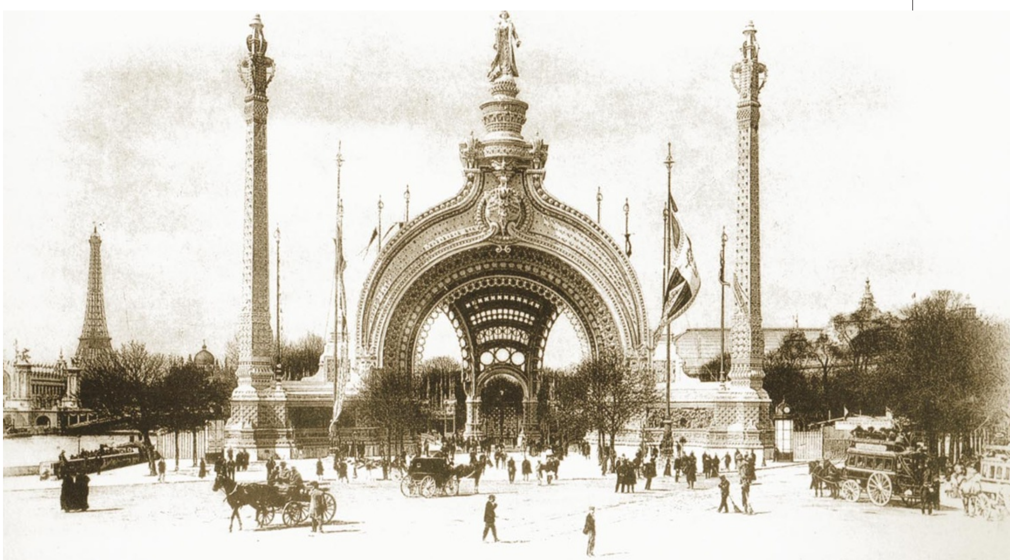

Figure 1 **René Binet's entrance to the World Exposition in Paris, 1900, inspired by Haeckel's drawings of radiolarians.**

cheap, lightweight, tough, mouldable and easily shaped. But it is not perfect, especially in terms of durability in the face of damp and pests. Yet which features of wood's enormously complex structure are the most salient for mimicry in a synthetic version?

The material developed 20 years ago by Gordon and Jeronimidis[3] latches onto the fibrous structure to capture fracture-resistance, and so uses glass fibre in a resin matrix. The low-density cellular structure is only crudely imitated in this material, by corrugating some of the laminated layers — this suffices to keep the material light without sacrificing too much robustness.

But there is more to be learned from the natural engineering of wood. Many engineering materials must be punctured for joining purposes. But it is one of the oldest principles in the engineer's handbook, notorious ever since Inglis worried nearly a hundred years ago why British ships were breaking in half, that holes produce stress concentration and so allow cracks to nucleate. The fibres that reinforce wood's glassy lignin matrix are severed and rendered structurally ineffective where a hole is drilled in timber.

The tree, however, drills no holes, even though it must disrupt the trunk's wood where a new branch pushes through. The solution is obvious to see in planking: the fibres deform around a knothole, remaining continuous. This simple solution avoids a significant reduction in fracture strength, yet has been little exploited in fibrous composite materials. Jeronimidis is now proposing to do so[4].

High fracture strength is also the alluring aspect of the abalone shell nacre, in many ways the type specimen for biomimetic materials science. Nacre combines several of the features recognized as characteristic of how the properties of superior materials are engineered in natural substances. It is a composite material, and incorporates both inorganic (here calcium carbonate) and organic compounds. The microscopic structure is finely wrought: plates of the hard mineral interleave with sheets of proteins and other macromolecules. The mineralization process is highly controlled, promoting the less thermodynamically stable crystal polymorph (aragonite rather than calcite) with crystallographic planes aligned in different platelets and the crystal morphology constrained to flat sheets. Some of these features recur in bone, eggshell, tooth enamel and the exoskeletons of diatoms and radiolarians.

The macromolecules are presumed responsible for guiding nucleation and growth of the mineral, but beyond that much is mysterious. The idea that acidic groups in the protein sheets provide a template for the aragonite crystal planes now looks overly simplistic; soluble acidic proteins instead seem to be a major determinant of crystallization[5]. But the growth process is not just a matter of engineering growth in the places and shapes it is required; it also demands that nucleation is suppressed elsewhere in a fluid that is supersaturated with the salt.

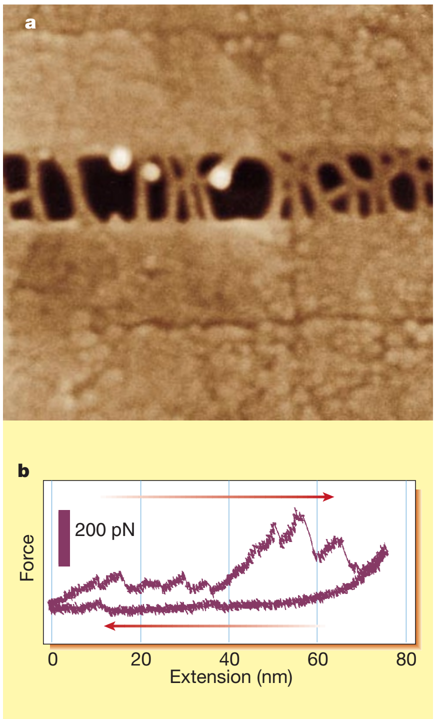

Figure 2 **Molecular-scale toughening of nacre a, Strands of proteinaceous material between the mineral layers. (Photo: J. Vincent, Univ. Bath.) b, The force curve for individual protein molecules, measured with the atomic force microscope. (From ref. 9.)**

It seems quite possible that the soluble proteins act in a manner comparable to that of the antifreeze proteins in cold-water fish, which can both inhibit and promote ice nucleation according to taste. These proteins are thought to have repetitive hydrogen-bonding groups commensurate with the lattice spacings in ice.

Understanding the molecular-scale mechanisms of the nucleation and growth (two distinct phenomena, don't forget) of crystals promises dividends in the industrial preparation of metastable polymorphs, or the suppression of degradative mineralization on engineering structures. *De novo* design of crystallization regulators is still at an early, exploratory and largely empirical stage[6], although combinatorial methods including immunization techniques for raising crystal-binding antibodies[7] look encouraging.

The toughening mechanism of nacre — crack deflection and energy absorption at 'weak' interfaces — is now well established, and has been demonstrated in synthetic laminated materials. But close inspection shows that there is more to it than that, reminding us that nature is cautious and generally seeks several simultaneous solutions to a challenge. As the mineral plates are pulled apart during deformation and fracture of the shell, tiny strands are pulled out from the intervening organic layers[8] (Fig. 2a). Single-molecule measurements of the force–extension curve of these strands with the atomic force microscope show that they lengthen in 'modular' fashion, producing a series of sawtooth jumps[9] (Fig. 2b). By combining relative stiffness (before each jump) with large extensibility, this creates a high work of fracture (equal to the area under the force curve). The same principle seems to be at work in the titin molecule, the elastic cord that prevents the interdigitating sarcomeres from separating when skeletal muscle is highly extended. Here the sawtooth pattern has been shown to have a clever structural origin: the protein consists of a series of identical globular domains that unravel one by one[10].

Ant strategies

To appreciate that nature does not necessarily have all the best ideas, we need only point to the wheel. Nevertheless, most of the problems of controlled motion and manoeuvrability have been explored and elegantly resolved in the living world. The Wrights and Otto Lilienthal drew comfort from the evident fact that they were not attempting the impossible.

Yet nature shows too how all flight is not the same. The smaller an airborne creature gets, the more manoeuvrable it typically is, which tells the engineer at once about the importance of Reynolds number: in a medium of fixed viscosity, aerodynamic phenomena have a particular size scale. It is becoming gradually clear that this allows insects access to different tricks, and thus different flight patterns, than buzzards and gulls.

Specifically, insects are conjurors of the vortex. With deft flappings and rotations of their wings, they are able to manipulate the vortices shed from the edges to control their motion in ways that flight engineers can only dream of: taking off backwards, for example, or landing upside down. By such means, insects subvert the 'conventional' aerofoil principles of flight, giving rise to the canard that the bee is aerodynamically impossible. In essence, the flight of the bumble-bee is a flight beyond the dynamical steady state: lift is generated at particular, exquisitely timed moments during the flap cycle. By rotating the wing so that it is parallel to the ground on the downstroke but perpendicular on the recovery stroke, an insect is able to recapture energy from the vortices shed from the wing edge[11]. This reveals a new mechanism for flight that one could hardly have deduced from first principles, and which might be adopted for the development of miniaturized robotic flyers for remote sensing, surveying and planetary exploration.

The actuators and sensors needed to drive and direct robot motion can benefit from studies of nature. Here an important part of the motivation may be simplicity. There has been a tendency to overdesign robots, imbuing them with actuators that permit every conceivable mechanical rearrangement of limbs and with sensors that provide exhaustive information about the surroundings. Nature, always seeking economy, makes do with far less. An understanding of how animals navigate — by landmarks, trail laying, geomagnetism or mental integration of the path already covered — should indicate the minimal requirements in different landscapes. And the articulation of moving parts often provides a lesson in creative simplification. Instead of having active control mechanisms for movement in each direction, limbs are often moved by the passive properties of the hinge materials. In insects, for example, the wing hinge is not attached to the flight muscles at all. Rather, these muscles deform the elastic, resilient cuticle of the thorax, which translates its change of shape to a wing oscillation[12]. This mechanism, which permits small strains to give rise to large-amplitude motion, is surely instructive to engineers wondering how to extract large displacement from the generally small strains available from piezoelectric smart actuator materials. In fact, a similar principle is already used in the crescent-shaped 'moonie' actuators devised by Newnham and co-workers[13], and in the piezoelectric heads in some dot-matrix printers.

One of the most striking messages for robotics coming from the study of animal motion is that some tasks are more efficiently conducted by many small, simple entities than by a single large and complex one. Approaches to robot design that attempt to search 'design space' in a pseudo-evolutionary way rather than to impose a preconceived strategy[14] may now include the option of fragmentation: of allowing for a distributed solution[15]. This is, of course, how an ant colony operates as a kind of 'super-organism' when foraging.

A recent study of ant-mimicking division of labour in a swarm of 'cooperative' robots lacking decentralized control showed that this does indeed provide an efficient foraging strategy[16]. The robotic swarms exhibit an optimal size, reminiscent of the size selection seen in animal colonies: for larger groups, the (programmed) tendency to avoid other robots begins to inhibit a thorough search of the territory. Social insects often operate task recruitment, whereby one communicates with another to draw it towards a resource-rich area. The inclusion of such a capability in the robot swarm boosts its ability to exploit clustered resources.

Search algorithms derived from those of ant colonies confer benefits not only in real-space tasks, but also in computation. Of course, the original 'biomimetic' computer application is the genetic algorithm. But some search tasks, such as trawling a large database (as in a web search engine), lend themselves to schemes that implement a kind of trail-laying, like the pheromones deposited by foraging ants[17]. 'Evaporation' of the trail is essential to prevent chasing of false leads or movement towards depleted sources, and the efficiency of the search can be highly dependent on identifying the optimal evaporation rate.

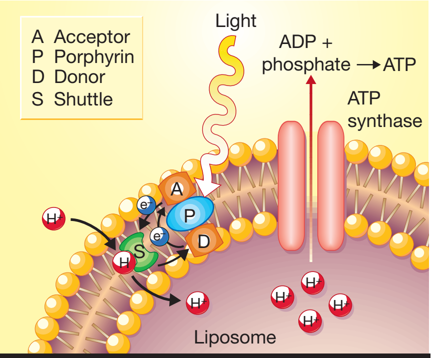

Figure 3 **Artificial photosynthesis driving ATP formation in liposomal membranes. A light-harvesting molecular triad transfers an electron to a shuttle molecule in the membrane, which ferries protons into the liposome's interior. The resulting proton-motive force then powers ATP synthesis by ATP synthase.**

Search for systems

Engineers interested in flight, or in tough materials, do not find it hard to know where to look in nature (even if the answers they find are subtle and hard to tease out). But the routes of technology transfer from biology to engineering sciences are not always so obvious. There might be a myriad of good ideas buried in the living world for an engineer searching for innovation in a particular area — but how to find them? "In nature there are lots of hidden patents," is the rather mercenary but nevertheless apt way that the Russian engineer Genrich Altshuller expresses it.

Altshuller has attempted the apparently oxymoronic task of systematizing creativity in technical innovation. By analysing over a million engineering patents, he has identified 39 'principles' on which particular engineering problems hinge. The problems then arise from situations in which one of these principles or parameters has to satisfy conflicting requirements. The 'contradiction matrix' thus contains 1,482 (39×38) 'standard technical conflicts', which Altshuller suggests can be addressed by a series of 'standard solutions'. He calls this the Theory of Inventive Problem Solving, denoted by its Russian acronym TRIZ[18].

Altshuller claims that almost all innovation requires knowledge already available, if sometimes from disciplines far removed from the immediate one. TRIZ claims to ease that process of information retrieval. Julian Vincent has considered how TRIZ fares if applied to the engineering problems faced by living organisms[19]. The assessment, while anecdotal, is revealing.

First, it is possible to identify natural analogues of all 40 of the standard solutions, which include such things as segmentation of parts, asymmetrical design, nesting of objects, multiple functionality and porosity. This in itself implies some kind of mapping between biology and technology. Yet nature does not seem to use the same contradiction matrix to solve problems[20]. For example, the drag-reducing properties of shark skin make it one of the archetypal examples of natural engineering. But identifying on the TRIZ matrix the contradictions that arise in this hydrodynamic problem suggests that appropriate solutions should involve weight compensation, moving parts or changes in some ambient parameter such as compliance. In contrast, shark skin uses a solution not included in Altshuller's list: surface conformation. The microscopic ribs of the shark's scales suppress turbulence in the boundary-layer flow.

This does not imply that TRIZ is a useless concept. Rather, it suggests that human ingenuity is a restricted resource: several thousand good engineering heads cannot compete with the billions of years that evolution has had to experiment, select and refine. In other words, says Vincent, nature may be a treasure trove for that small but vital fraction of engineering problems that, in Altshuller's reckoning, require genuine innovation and even fresh discovery.

Biosynergy

Yet the question remains: are nature's solutions practically accessible to us? It might not be fruitful, or even possible, to isolate and imitate one aspect of a functioning organism while neglecting the dynamic system in which it is embedded, and which is responsible for its fabrication, maintenance and adaptation. Silk is a sobering example.

No one expected that simply mimicking the amide linkages in the polymer chains, as in nylon, would generate a material quite as appealing. But Kevlar, the aramid fibre in which intermolecular hydrogen bonding creates a degree of liquid crystallinity similar to that in concentrated silk solution, deepens the mimesis and greatly improves the strength. Shear-induced alignment of polyethylene during the extrusion process, copying that which occurs in the silk spider's spinneret, produces the high-strength fibre known as 'rocket wire'.

Best of all, one might think, is to take mimicry to the point of plagiarism, and copy the silk protein exactly. But although silks have been sequenced and silk genes spliced into the bacterium *Escherichia coli* and goats (which express the protein in their milk), synthetic silk is still not a mass-produced, high-strength technological material. The crucial aspect of mimicry is not, it seems, in the protein composition but in the processing. It is the weaving of strands in the spinneret that gives them their strength. The details of this process are not understood; but it may be that not until we can build an artificial, miniaturized spinning mechanism will silk be an industrial material.

This is why biomimetics must reach down to the microscopic and ultimately the molecular scale. Some of nature's best tricks are conceptually simple and easy to rationalize in physical or engineering terms; but realizing them requires machinery of exquisite delicacy. "The smaller the scale [at which mimicry is conducted], the better the prospects for emulation," says Steven Vogel, who points out that nature's artefacts are made in factories smaller than their products[21]. It is precisely this 'bottom-up' approach to fabrication that is being sought within the field of nanotechnology — which, ever since its beginnings in Richard Feynman's famous talk[22], has acknowledged the inspiration and guidance that biology offers.

Photosynthesis, for instance, is a trick worth mastering. This is not a matter of efficiency: commercial silicon solar cells already do several per cent better at converting light to electrical energy than the chloroplast does in making the conversion to chemical energy. But the nanocrystal solar cells developed by Grätzel and co-workers[23] show the benefit of the chloroplast's design principles. Allocating charge generation and charge separation to different entities — in the leaf, to chlorophyll and to pheophytin, plastoquinone and other elements of the electron relay — reduces the chances of recombination of the light-excited hole and electron. In silicon solar cells, the semiconductor serves both ends, and recombination can limit the quantum efficiency of the process. Grätzel's concept was to capture the photon energy using dye molecules adsorbed to the surface of nanocrystals of titania. These semiconducting particles then ferry the charge to the collecting electrode. This helps to secure a respectable efficiency that, although by no means outstanding in itself, promises a competitive device when coupled to the very low manufacturing and materials costs.

But more transparently biomimetic is the liposome-based system developed by Moore, Gust, and their co-workers[24,25]. This is speculative mimicry — emulation without a current application — for the sunlight is here used to make ATP, as it is in the chloroplast, rather than to generate a flow of current. The motivation might therefore be construed as more akin to biocatalysis than photovoltaics: storing up photonic energy in a form accessible to biological systems. The liposomes mimic the thylakoid membrane of the chloroplast, anchoring and organizing the light-harvesting and energy-transfer molecules while also providing a barrier across which an electrochemical gradient can be established. The role of the photosynthetic reaction centre and antenna array is adopted by a synthetic molecular triad in which a photoexcited porphyrin passes energy to an electron donor, which releases an electron to an acceptor group. From here it is transferred to a mobile 'shuttle' molecule within the membrane, the surrogate for the electron carrier NADPH in photosynthesis. The electron-charged shuttle picks up a hydrogen ion too and carries them both to the inner face of the membrane. There it returns the electron to the triad, and releases the hydrogen ion into the liposome's hollow interior. This light-driven hydrogen-ion pump thus creates a proton-motive force, which is harnessed by ATP synthase embedded in the membrane (Fig. 3).

As a demonstration that a complex natural molecular process can be imitated in a self-assembling synthetic system, this work carries an encouraging message to deter any vitalistic suggestion that life's mechanics are incomparably intricate. But perhaps it stretches the definition too far to regard as genuinely biomimetic a system that uses molecules such as ATP synthase ready-made?

Of course, it is eminently sensible to do so, rather than trying to devise a proton-driven catalyst *de novo*. There is thus good reason to imagine that any molecular-scale engineering that seeks to achieve things at which the cell is already adept — such as energy conversion, construction or replication — will be wise to incorporate, rather than to imitate, biological machinery.

This sort of biosynergy has been elegantly explored with motor proteins. Work on wholly synthetic molecular motors is still in its infancy, and so far takes few cues from nature[26,27]. But the possibility of modifying motor proteins to do non-natural tasks is already apparent[28,29]. For example, Dennis *et al.*[29] have used immobilized kinesins oriented along corrugations in shear-aligned polytetrafluoroethylene films to transport microtubules across a surface with directional preferences. The development of peptides by *in vitro* selection that can recognize different metal[30] and semiconductor[31] surfaces suggests the possibility of using genetic recombination methods to append these selective hooks to motor proteins to transport and organize semiconductor nanoparticles (quantum dots) into arrays for information technology. In any event, molecular nanotechnologists would surely be short-sighted if they did not merely take inspiration but also working machines and devices from the cell.

Choices and challenges

Vogel[21] presents elegant and persuasive arguments for why it would be foolish to assume that nature has all the best ideas, which the engineer must then determine how to translate into workable solutions. The caricature of evolution in which nature explores all options and finds the best is still surprisingly pervasive. Nature has good reasons to avoid metallic components, for example, but this does not mean that human engineers should strive to do so.

Yet fundamental research on the character of nature's mechanisms, from the elephant to the protein, is sure to enrich the pool from which designers and engineers can draw ideas. The scope for deepening this pool is still tremendous. It is at the molecular scale, however, that we will surely see the greatest expansion of horizons, as structural studies and single-molecule experiments reveal the mechanics of biomolecules. If any reminder were still needed that nanotechnology should not seek to shrink mechanical engineering, cogs and all, to the molecular scale, it is found here. Nature's wheel — the rotary motor of the bacterial flagellum — never got any larger than this, nor is it fashioned from hard, wear-resistant materials, nor is it driven electromagnetically or by displacement of a piston. But it is efficient, fast, linear and reversible[32]. Somewhere there is a lesson in that.

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