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Phil. Trans. R. Soc. Lond. A 2002 **360**, doi: 10.1098/rsta.2001.0923, published 15 February 2002

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Systematic technology transfer from biology to engineering

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Published online 11 January 2002

Solutions to problems move only very slowly between different disciplines. Transfer can be greatly speeded up with suitable abstraction and classification of problems. Russian researchers working on the TRIZ (Teoriya Resheniya Izobretatelskikh Zadatch) method for inventive problem solving have identified systematic means of transferring knowledge between different scientific and engineering disciplines. With over 1500 person years of effort behind it, TRIZ represents the biggest study of human creativity ever conducted, whose aim has been to establish a system into which all known solutions can be placed, classified in terms of function. At present, the functional classification structure covers nearly 3 000 000 of the world's successful patents and large proportions of the known physical, chemical and mathematical knowledge-base. Additional tools are the identification of factors which prevent the attainment of new technology, leading directly to a system of inventive principles which will resolve the impasse, a series of evolutionary trends of development, and to a system of methods for effecting change in a system (Su-fields). As yet, the database contains little biological knowledge despite early recognition by the instigator of TRIZ (Genrich Altshuller) that one day it should. This is illustrated by natural systems evolved for thermal stability and the maintenance of cleanliness.

Keywords: TRIZ; creativity; innovation; biomimetics; ideality; technical evolution

1. Introduction

When we innovate we commonly fail to take advantage of the solutions and practices of other sciences and technologies or to recognize the similarities between our technical problems and the solutions to similar problems in otherwise alien technologies. In particular we fail to tap in to the four billion years' worth of 'R&D' in the natural world. We introduce here a systematic means for integrating this natural technology into humankind's technology using a method developed in Russia over the last 50 years—Teoriya Resheniya Izobretatelskikh Zadatch (TRIZ)—roughly translated as the theory of inventive problem solving. TRIZ provides an objective framework for accessing solutions from other technologies and sciences (Altshuller 1999; Salamatov 1999).

TRIZ is remarkably successful at integrating knowledge from physics, chemistry, mathematics, engineering, management and political science. It is successful largely because that knowledge is in a form accessible to all users. The key is *functionality*.

For example, an O-ring is a specific solution to the functional requirement ‘seal’. By assembling all knowledge relating to this function, a designer is able to access all methods of achieving the function, irrespective of industrial or intellectual boundaries. But the efficacy of TRIZ is not only in showing where the solutions lie but also in establishing boundaries for the search. Thus not only is a good solution to a problem found very quickly, but time is not wasted trying to find a solution where none exists.

By including data on how biology achieves the function ‘seal’, it will become possible for all designers to access *biological* knowledge as well, a development which was foreseen by Altshuller not only as inevitable but as a way of *significantly improving* and *enriching* the method (Altshuller 1999, p. 213). To illustrate the potential which biology-based technology (biomimetics) has in suggesting new approaches, most of the following concepts have been taken to patent and some into production.

1. Strain gauging based on receptors in insects (Skordos *et al.* 2002).
2. Deployable structures based on flowers and leaves (Guest & Pellegrino 1992).
3. Tough ceramics based on mother-of-pearl (Jackson *et al.* 1989).
4. Drag reduction based on dermal riblets on shark skin (Bechert *et al.* 1997).
5. Tough composites based on fibre orientations in wood (Chaplin *et al.* 1983).
6. Underwater glues based on mussel adhesive (Holl *et al.* 1993).
7. Flight mechanisms based on insect flight (Ellington 1999).
8. Extrusion technology based on the spinneret of the spider (Knight & Vollrath 1999).
9. Self-cleaning surfaces based on the surface of the lotus leaf (Barthlott & Neinhuis 1999).

Velcro (1955), is the commonly quoted total success story of biomimetics. George de Mestral’s dog got some burs entangled in its fur, which made de Mestral (an inveterate inventor) realize that here was the nub of a novel joining technology. After several years’ experimentation to develop a production process, Velcro was commercialized in the middle of the last century, and is now the subject of over 1700 patents. And of course the Eiffel Tower and the architecture of Santiago Calatrava and of Frei Otto owe large amounts of their novelty and utility to the designs of natural world.

Ideas in waiting include the following.

1. Wood cutting based on the wood wasp ovipositor ‘drill’ (Vincent & King 1996).
2. Soft robotic actuators based on worms (Osada *et al.* 1992).
3. Highly insulated clothing based on penguin down (Dawson *et al.* 1999).
4. Novel joining technologies based on hooks in nature (Nachtigall 1974).
5. Helmet design based on toughening mechanisms of antler bone (Hansen 1999).

These topics have been arrived at more or less adventitiously. In most instances the concept was made available to the engineering community only through the medium of a biologist. The framework provided by TRIZ makes such information more readily available so that it will be easier to identify areas of biology likely to yield useful information for specific problems. As a corollary, the method also provides a framework into which biological knowledge can be integrated for biologists. The facility with which TRIZ can combine disparate inputs and ideas will increase in importance in the biological sciences as the incidence of genetic manipulation increases and we develop genetic manufacturing. The area between living and non-living materials, where biology meets engineering (bioengineering, biomechantronics), will also benefit. TRIZ will provide the creative underpinning at this interface and be a major part of the engine for innovation (Ball 2001).

The paper describes case studies to illustrate the likely benefits to engineers and biologists of integrating biological knowledge into the TRIZ framework. We begin, however, with a brief review of some of the key concepts contained within TRIZ.

2. The tools of TRIZ

The method uses four main tools: a knowledge database arranged by function, analysis of the technical barriers to progress (contradictions), the way technology develops (ideality) and the maximization of resource usage.

(a) *Function*

A database arranged by functionality allows us to access solutions and identify the most appropriate ones. The TRIZ-based Invention Machine ‘TechOptimizer’ software is the most comprehensive functionally classified knowledge-base available. It contains over 6000 physical, chemical, mathematical and engineering solutions; for instance, there are 30 ways of achieving the generic function ‘reduce drag’, only four of which originate in the aerospace sector. The database tells us that the chemical industry commonly uses ultrasound as a way of reducing drag. Incorporation of such solutions into an aerospace context offers significant improvements and patentable ideas. But this database contains no biology. Drag reduction is found in shark skin (ribbed dermal denticles or teeth covering the body), teleost fish (secreted mucus), penguins (a turbulator at the base of the beak) and saw fish (the teeth on the ‘saw’ are turbulators). The nautical industries were probably first to exploit the shark skin mechanism, with aerospace second and—most publicly known—swimwear (the Speedo Company) third. Incorporation of these drag-reducing solutions into a systematic, functionally arranged knowledge-base would provide a means for all engineering sectors to access and benefit from these and other techniques for drag reduction. Biologists might also discover previously unsuspected drag-reducing adaptations in organisms.

(b) *Contradictions*

In TRIZ, problems are represented by pairs of conflicting parameters enabling us to access the good solutions of inventors who have successfully overcome the conflict in question. For instance an aircraft nose-cone has to be light but sufficiently

strong to protect the components inside the nose. The contradiction is strength-versus-weight. TRIZ identifies solutions with the same contradiction and, using the ‘contradiction matrix’ (a two-dimensional matrix which lists all currently recognized pairs of contradictions), identifies the relevant two or three of the 40 ‘inventive principles’ on which TRIZ is based (Altshuller & Shulyak 1998). Any newcomer to the method finds it difficult to believe that only 40 principles can cover the innovation represented by 3 000 000 patents. Nevertheless, it is a reasonable result which, more importantly, works well.

As with the functionally arranged knowledge-base, none of the good practices found in nature have thus far been incorporated into the method, although preliminary research has suggested that nature is bound by the same 40 principles (Vincent & Mann 2000). However, for the strength-versus-weight contradiction, TRIZ currently fails to make any connection to the way birds and insects have evolved their lightweight structures, or to the way a spider’s web overcomes the parallel need for low weight and high strength. Initial work on whether nature uses the same inventive principles under the circumstances of a particular individual contradiction type suggests that it does not. This has important implications for the way in which problems are tackled and, given the massive amount of data represented by naturally evolved inventive solutions, suggests that nature has much to offer in terms of providing inventors with new perspectives on the ways in which problems are solved. A general rule which is emerging is that the solution of technical problems within a taxon (family, order, etc.) is a process of optimization in TRIZ terms, whereas the interphyletic differences between the solutions to particular technical problems are more akin to differences between inventive principles. If it is real and can be quantified, this sort of difference might make a contribution to the quantitative understanding of evolution and phylogeny.

(c) Ideality

In analysing the patent database, TRIZ researchers have shown that technical systems evolve in predictable ways, most notably an over-riding trend to increasing ‘ideality’ (Kowalick 1997). This is very much like biological adaptation in that technology develops towards systems which maximize the good (functional benefits) and minimize the bad (‘cost’ and ‘harm’). The concept of ideality suggests that the use of an external system of any kind is non-ideal, and that ultimately the system should evolve to be self-serving or self-actuating. The word ‘self’ is very important in the evolution of technical systems, as ‘things which do things for themselves’ represent solutions making very good use of existing resources. Mann (2001) details the limits of engineering’s attempts at ‘self’ oriented design solutions. The lotus effect (see below) provides a good example of a natural solution where the requirement to have a clean surface is achieved without the introduction of a separate cleaning mechanism.

(d) Trends of technical evolution

As with biology, competition leads to optimization. All the other trends observed by TRIZ researchers are subsets of this trend to ideality, for instance the well-established trend for systems to develop from one to two to three dimensions. Trivially, this is seen in lower organisms—algae have evolved from single cells to fila-

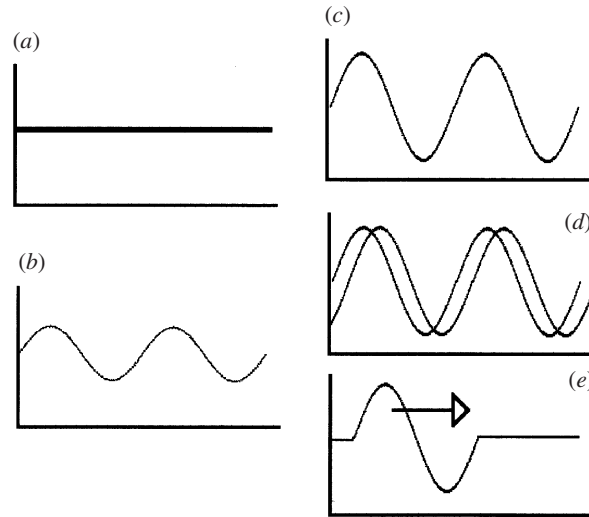


Figure 1. A TRIZ evolutionary series on the coordination of rhythm. The effectiveness of the action increases from (a) to (e), or from left to right. (a) Continuous action; (b) pulsating or periodic action; (c) resonating action (larger output for the same input); (d) several actions at once (two are shown); (e) travelling wave. More information in the text.

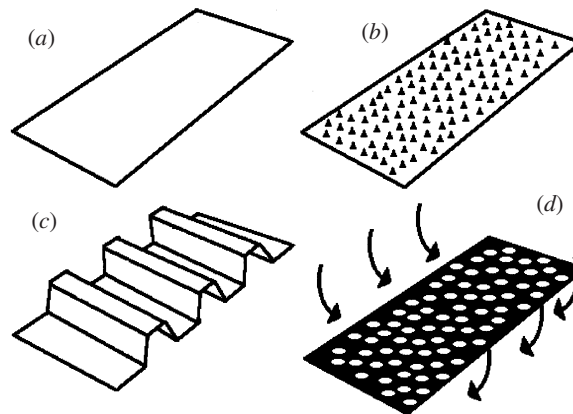


Figure 2. A TRIZ evolutionary series on surface segmentation. (a) Flat surface; (b) surface with protrusions; (c) rough surface; (d) surface with active pores. More information in the text.

mentous to bulk tissues. It may occur elsewhere. Another trend in technology is for rhythmic coordination to progress from continuous actions to pulsed actions to resonance to the use of a standing wave (figure 1). This is found in animal locomotion progressing from amoeboid crawling (continuous) through jellyfish swimming and insect flight (pulsed, possibly resonant) to walking and running in mammals (probably resonant); a standing wave is found in peristaltic transport mechanisms and crawling soft animals such as worms and snails. Classical TRIZ incorporates eight patterns of evolution of technical systems.

TRIZ trends provide problem solvers with useful suggestions as to the evolutionary potential of systems. The surface segmentation trend (figure 2) has many examples in

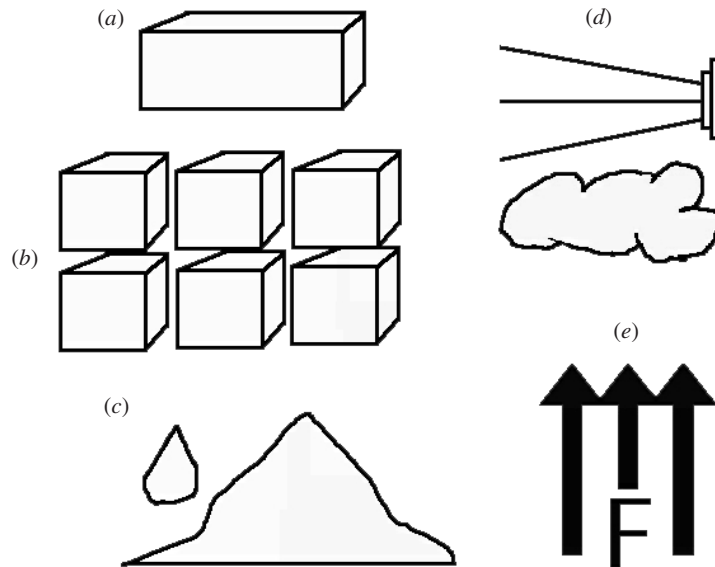


Figure 3. A TRIZ evolutionary series on segmentation of substances or objects. (a) Monolith; (b) monolith has been segmented coarsely; (c) fine segmentation to liquid or powder with increase in surface area; (d) gas or plasma; (e) force field. No biological analogues have yet been proposed for this series.

engineering systems, from car tyres to table-tennis bats to wing design. The biggest practical use of the trends occurs when the current technology does not lie at the right-most end of the trend so that each remaining step represents the potential for a new generation of system. For instance, light bulbs have glass with a smooth surface. The trend suggests that there are definite evolutionary opportunities by texturing the surface of the glass in first one and then a second direction. While the benefits of doing so may not be immediately obvious, the method suggests that they will exist if we look hard enough, perhaps changing the dissipation of the light, giving the ability to change colour, self-clean, and so on.

The TRIZ trends of evolution form a very powerful collection of problem-solving tools. Two more are shown (figure 3, ‘segmentation’, and figure 4, ‘dynamization’) without explicit reference to analogues from nature. Several companies use the trends to identify gaps in the patent database to generate intellectual property. Comparisons between the technology trends uncovered by TRIZ and nature are still sparse. The likelihood is that nature has much to teach in terms of both examples of the trends in action and existence of additional trends thus far not uncovered in a technical sense. Thus, formal study of nature’s evolutionary trends may usefully extend TRIZ trends. By corollary, where there are instances of natural systems which have not evolved to the right-hand side of the TRIZ trends, there is the potential, from a biomimetic perspective, to evolve designs which are capable of ‘improving’ on natural solutions.

(e) *Use of resources*

While the preceding discoveries could undoubtedly have been uncovered anywhere by anyone with the patience and dedication shown by the TRIZ researchers, the resources concept is probably uniquely Russian. The concept is very simply about

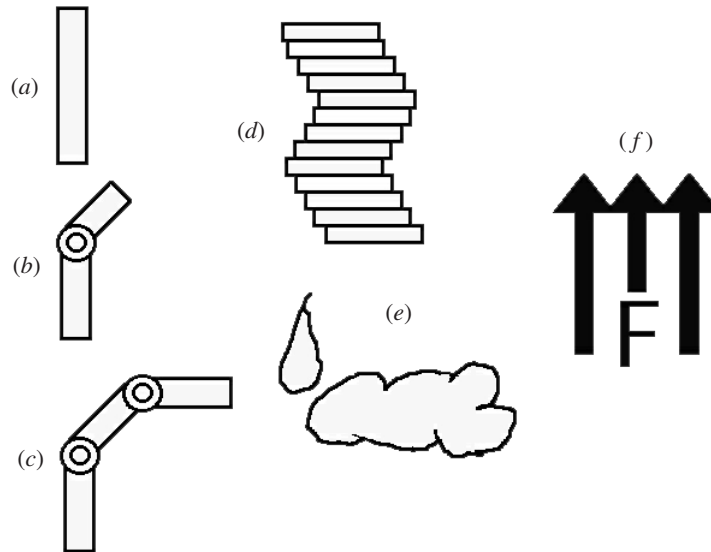


Figure 4. A TRIZ evolutionary series on dynamization. (a) Immobile system; (b) a joint in the system; (c) several joints in the system; (d) proliferation of joints leads to a soft elastic system; (e) further proliferation of joints leads to a liquid or gas; (f) and finally a force field. This series echoes changes seen in the evolution of a number of phyla where an initially heavily armoured organism evolves more joints and eventually loses the armour totally. As far as we know the further evolution of organisms to gas and force field has not occurred, though such transformations exist in science fiction, itself a fertile source of ideas for both technology and TRIZ.

making maximum use of the things that exist in and around the systems we design. Typically in the west, we have been very wasteful in this regard, tending to adopt the approach ‘if it’s broke, fix it by adding something’ rather than trying to make the existing system do the job for us. Encouraging designers to use resources effectively is a key element of the overall TRIZ process. Taken to extremes, TRIZ further encourages designers to think of even the bad things as resources. Resonance is a good example of an under-used resource; pressure would be another where, given an increasing pressure we wanted to seal against, our usual response would be to increase the duty of the seal to better fight the pressure, TRIZ would encourage us to use the pressure to help form the seal. Nature, of course, through the medium of competition for resources, has been rather more effective in its drive to make best use of the least amount of resources, and thus probably has important lessons to communicate to the TRIZ method.

3. Functional classification: some examples

(a) *Staying warm*

Examination of an existing TRIZ knowledge-base for the specific functional requirement to ‘stay warm’ requires an abstraction of the definition in order to ensure maximum access to solutions from other fields of industry and science. In this case, ‘stabilize thermal parameters’ is the generic functional classification adopted by TRIZ

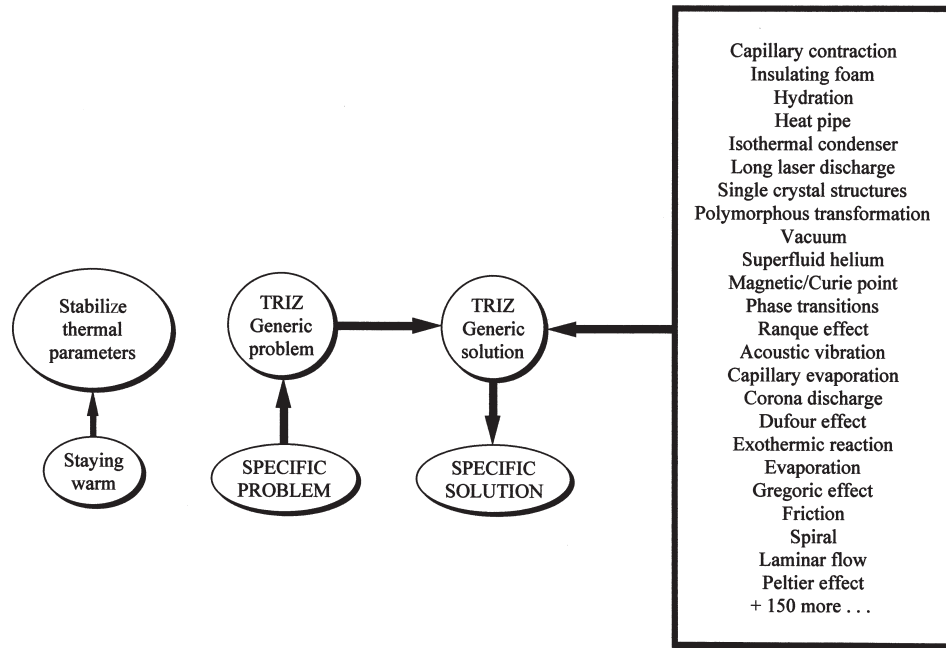


Figure 5. Steps in partial solution of the problem 'staying warm'. The TRIZ generalization is 'stabilize thermal parameters'. TRIZ then lists over 150 ways of doing this. Obviously, not all these are represented in biology, but it may also emerge that there are some biological solutions to this problem which have been unexploited, perhaps (for instance) because we lack the materials or technology to fabricate the necessary morphologies or control systems.

researchers. Provided we are able to make this abstraction, the current database reveals a host of solutions from a variety of sources (figure 5).

The database contains no biological solutions to the problem, despite the fact that nature contains many examples which offer much potential for effective exploitation in engineering systems. These include feathers, especially those of the penguin (figure 6), fur (in which the air responsible for insulation is as much within the hollow hairs as entrained between the hairs in the pelage) and 'hair' and scales found on insects (Heinrich 1993). Some long fur, such as that found on the polar bear, may be self-ventilating, as the hairs move when the animal runs (C. Dawson 2000, personal communication). Such multifunctionality is rare in engineered insulation but can be tracked in figure 7, which suggests that self-ventilating fur is highly evolved. Sub-cutaneous fat insulates by restricting blood supply to the skin surface (C. Pond 1998, personal communication). Note that these are all passive 'low-energy' solutions to the requirement to keep warm. There is also a large range of nests and burrows, many of which provide some sort of heat amelioration of an otherwise hostile environment (Hansell 1984). Once constructed, these could also be considered passive, and are attracting a lot of attention from architects wishing to make buildings with low-energy consumption.

We do not include a discussion of homeothermic or central heating systems or countercurrent heat systems (*rete mirabile*), which are relatively common in nature.



Figure 6. (a) Feather of the penguin *Pygoscelis papua* showing the prominent after-feather (scale bar is 5 mm).

(b) *Cleaning or washing*

Conventionally, a washing powder company would seek to deliver the function ‘clean clothes’ using its capabilities in engineering a more effective washing powder than its competitors. Abstracting the ‘clean clothes’ function to one of ‘remove solid substances’ enables companies to see how other industries have delivered similar functions. The function database illustrates that there are many possible alternative ways to deliver the ‘clean clothes’ function other than washing powder (figure 8). The database, however, contains no biological data.

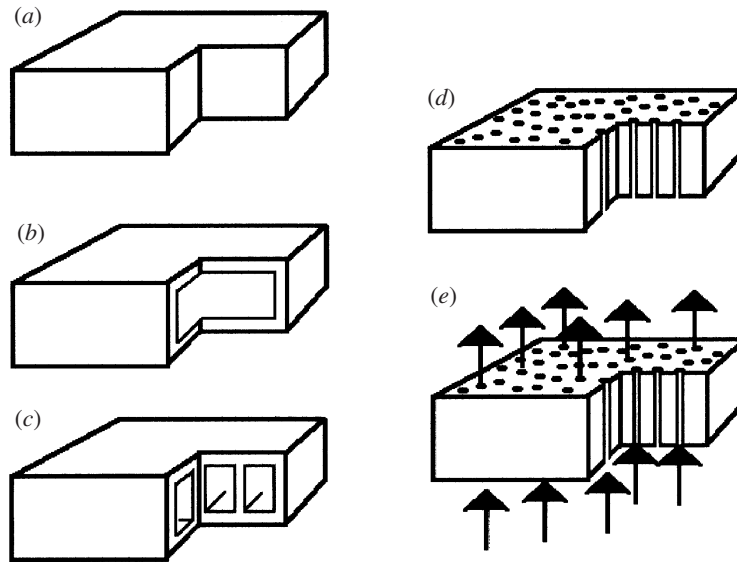


Figure 7. A TRIZ evolutionary series on the segmentation of space, with notes on its relevance to thermal insulation of fur. (a) Monolithic system (a solid hair); (b) system with a cavity (hollow hair); (c) system with multiple cavities (hair with foam filling); (d) capillary or porous system (this may have an equivalent); (e) system with active capillaries (the pelage is ‘active’ and can modulate insulation independently of its structure; for instance, the pumping action of hairs moving up and down while the animal is running, ventilating the skin and reducing overheating). ‘Segmentation’ as a possible solution would emerge from its identification as the relevant inventive principle to be explored.

Biological systems perform similar functions. Examples of nature’s ways, which will eventually be included in the TRIZ database, include various types of grooming by licking, spreading cleaning or conditioning liquid over the surface (Kovac 1993), or by picking off individual items (Mooring 1995). Arthropods, whose sense organs are commonly on the outside of their stiff skeleton, rely more crucially on a clean external surface (Becker & Wahl 1996). They have a variety of cleaning mechanisms (hooks and brushes) including special ‘windscreen wipers’ to keep the surface of the eyes clean in foul conditions on a muddy substrate. Such cleaning bristles could form a prototype for a better toothbrush, whose ‘bristles’ are routinely made of nylon filaments with no surface sculpture or functionality.

Companies making washing machines have been interested in such mechanisms, trying to reduce the amount of water a dishwasher uses by incorporating a licking action. Although easily achieved by the household dog, such a trick has not yet been incorporated into a machine, despite surprisingly intensive effort.

A more passive cleaning effect, which therefore (presumably) requires less energy, is the ‘lotus effect’ (so far found on certain plant leaves and the wings of insects, see [http:// www.botanik.uni-bonn.de/system/bionics.htm](http://www.botanik.uni-bonn.de/system/bionics.htm)). The leaf of the lotus is hydrophobic to the extent that water running across the surface of the leaf retains particles of dirt which it gleans as it goes. This effect is achieved by a combination of hydrophobicity due to a thick layer of wax on the surface and the sculpture of that surface (figure 9). This forces droplets of water to remain more or less spherical when

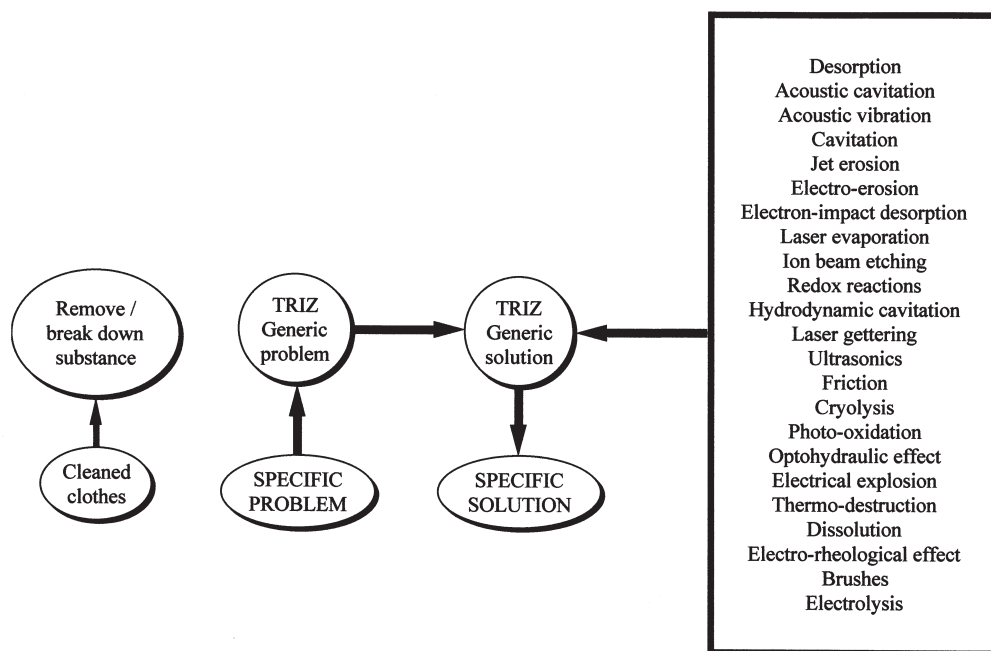


Figure 8. Steps in partial solution of the problem 'cleaned clothes' (or cooking utensils, etc.). The solution is restated as 'remove substance' and 'break down substance', for which there are many mechanisms. However, the lotus leaf, insect wing (and probably other biological surfaces) join the Teflon-coated kitchen utensil as a surface which cannot be contaminated. Experience suggests that biology will have a number of these mechanisms to suggest.



Figure 9. The epidermal structure at the heart of the lotus effect (downloaded from <http://www.botanik.uni-bonn.de/system/bionics.htm>).

in contact with the leaf, and reduces the tendency of other contaminants to stick to the leaf (Barthlott & Neinhuis 1999). This characteristic has been incorporated into an exterior-quality paint ('Lotusan'), which makes surfaces self-cleaning.

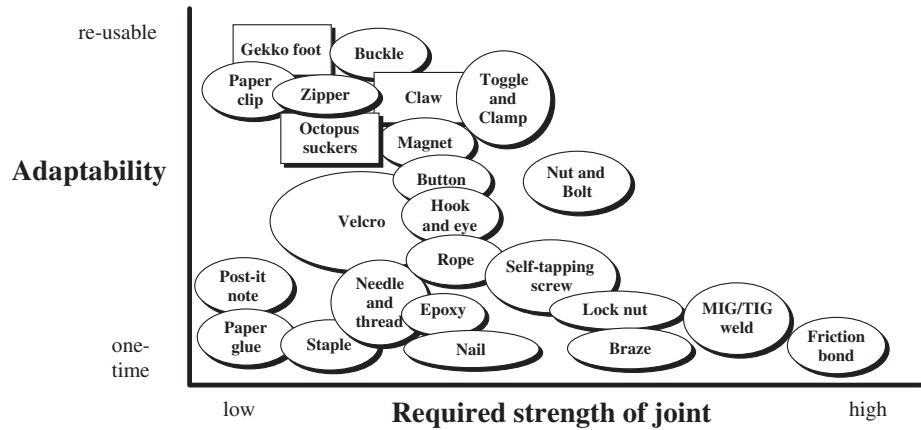


Figure 10. The technology of joining. Since strength and adaptability are probably mutually antagonistic, it seems likely that there will be a number of curves which become asymptotic to both axes. A few biological joining systems have been mapped into this space. The axes are as yet unquantified.

(c) Joining surfaces

Given an interest in joining objects or surfaces, it is likely that the strength of the joint will be significant to a specific problem. Physical size and adaptability will probably also be important. From these key factors, we can draw a graph describing the performance of different solutions (figure 10). If we then know the specific requirements of strength and adaptability for a given problem we can identify which of the ways of delivering the function are relevant. This is a novel approach which has yet to be quantified. Even so, while the engineering solutions seem fairly clearly distributed, the biological aspects are much more varied. As an example, consider hooks and claws as a class of temporary or semi-permanent attachment mechanism.

Hooks occur in nature as a vast array of designs and in a diversity of animals and plants (Nachtigall 1974) and have great commercial application, highlighted when Velcro was developed. No theoretical treatment of these bur hooks was made, the concept being developed towards producing the cheapest and most reliable hook-substrate combination (Velcro 1955). There are now over 1700 patents quoting Velcro, which are concerned either with novel uses of the material or with improvements.

There are obvious identifiable alternatives to Velcro-type functionality in nature, such as the permanence and strength of the attachment and the type of surface with which the hook can interact. In many instances the surface is modified, as when a lepidopterous larva puts down a pad of silk fibres for the attachment of its cribellar hooks. Bedstraw (*Galium* sp.) is a creeping plant with hooks on its stem which can attach ephemerally 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. In Hymenoptera, hooks (hamuli) join the fore and hind wings each time the wings are deployed creating a single flying surface. Sea-lice (Copepoda, Crustacea) and flatworms (Platyhelminths) are parasites with hooks that attach them to the skin of large sharks and marlin travelling at high speeds. Different species of parasite are adapted to different species of fish with hooks specific to certain skin types.

There are many ways in which a Velcro-like mechanism based on a wider range of functionality could be used. The different types of attachment, ranging from permanent to ephemeral, lend themselves to a number of developments. The more permanent interactions could be used to replace sewing (instantly redesigning clothing, e.g. fashion clothes, one-size uniforms, moving pockets around for adaptability, etc.). A hooking mechanism with marked polarity (i.e. attaches when moved in one direction, detaches when moved in the other direction—a sort of directional friction) could be used with equipment used in climbing and bridging gaps in the way that *Galium* climbs hedges and can cross gaps, giving rise to the possibility of self-designing structures (smart hooks). The wing-hooking mechanism of Hymenoptera suggests novel types of zip mechanism.

4. Using TRIZ

In use, TRIZ requires some skill and experience. It is not a machine which accepts problems at one end and spews out solutions at the other. To this extent a computer program is probably not sufficient for really effective use of the system. This article is not the place to paraphrase the instruction books and courses on TRIZ. An initial exploration is easily made at the Web site <http://www.triz-journal.com>, at which there is a large searchable archive of articles which are instructive and analytical, and report success stories of its use.

5. Benefits to engineers

The growing importance of and interest in biomimetics suggests that engineers are beginning to realize that nature offers much scope for improving the way systems are designed. At the moment the process by which engineers are made aware of nature's solutions is largely ineffective. The functional classification concept offered by TRIZ provides a ready-made framework into which biological solutions may be expected to sit comfortably, to provide direct access to natural design solutions.

The further abstraction of natural solutions to identify evolution trends and the mechanisms by which nature tackles design contradictions offers further opportunities to assist engineers in deriving stronger solutions to meet the ever-increasing drive for innovative products, processes and services.

6. Benefits to biomimetics

A natural system evolves only to be 'good enough' to survive and thrive in its prevailing array of boundary conditions. Technological analogues of such natural solutions are likely not to be bound by the same boundary conditions ('growth', reproduction for example) and so, by using some of the TRIZ tools it should be possible in the future to engineer systems which take nature as a starting point, and improve on the way nature does things.

Nature is, on the basis of our current analysis, a relatively poor solver of contradictions, although it is good at optimization, and is prone to evolve down culs-de-sac from which it cannot return (figure 11), the blind spot in the human eye being a classic case in point. TRIZ points a way to engineer biomimetic solutions which overcome such constraints.

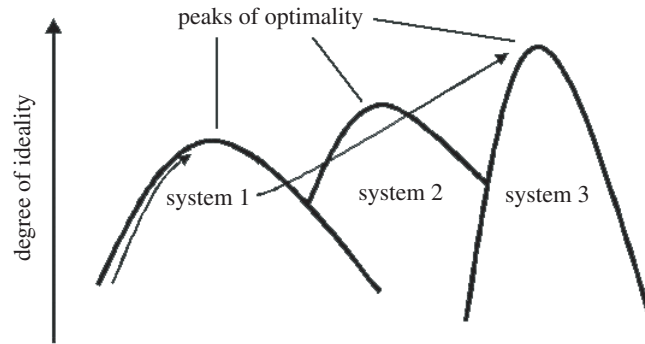


Figure 11. ‘Ideality’ is attained at the peak of a curve. Nature is probably good at finding local maxima but not very (if at all) good at ‘de-optimizing’ in order to find other peaks. Such local downgrading might be imposed by environmental factors.

7. Envoi

This paper is not particularly technical compared with its analytical fellows in this issue. This is because it is concerned with creativity and invention, two activities which have stubbornly resisted quantification, or even understanding. But it is our firm belief that the interface between biology and engineering will benefit from the slightest amount of regularization. Currently, transfer of information and concepts from biology to engineering is almost totally adventitious, and technology is consequently missing many advantages due as much to lack of communication across the disciplines as to ignorance and ineptitude. TRIZ seems to have the main qualifications of an effective bridge.

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