Solving materials design problems in biology and technology – a case study

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ABSTRACT

In a series of studies we have reclassified the TRIZ categories of ‘contradiction’ and ‘inventive principle’ derived by Altshuller and his colleagues and show that the hierarchical relationships of the parts of a problem are important, such that at low levels of hierarchy, materials and structure predominate, but at high levels, it’s information which is important.

By identifying the functional conflicts in its design, the cuticle of arthropods can be shown to cope with IR and UV irradiation in the same manner as our technology – by controlling spectral properties. However the skeletal properties of cuticle are integrated with demands for sensing, movement, etc, by controlling the local properties of the material rather than by changing global parameters (which would be the technical solution). The biomimetic similarity of cuticle with technology is only about 20%, suggesting that we can learn from the design of arthropod cuticle.

INTRODUCTION

The definition of a problem as a conflict in design requirements, and the solution of the problem as the resolution of the conflict, was used by Genrich Altshuller it in his system of inventive problem solving (“TRIZ” – Theoriya Resheniya Izobreatatelskikh Zadatch). The resolutions were derived from successful patents, and so represent a collection of best practice [1]. In comparing the resolutions provided from TRIZ with those provided from biology, we can measure the similarity between technology and biology, and test whether the emerging study of biomimetics is likely to provide novel practical solutions to technical problems.

TRIZ was conceived, derived from and perfected in the environment of things artificial, non-living, technological and engineering. But biomimetics operates across the border between living and non-living systems. And since the reason for looking to nature for solutions is to enhance technological functions, it is necessarily true that TRIZ does not contain many of these functions, and probably doesn't have the means for deriving them. Despite the fact that TRIZ is the most promising system for biomimetics, we still have a mismatch. This is conflated by a number of factors that are currently not normally observed in a technical system. For instance, the more closely an artificial system is modelled on a living system prototype, which is typically complex and hierarchical, the more frequently we have emergent effects, which are classically unpredictable, therefore mostly unexpected and often harmful. Furthermore, one of the basic features of living systems is the appearance of freedom of will or action (depending for its effect on the complexity of the living system). This gives living systems great adaptability and versatility, but at the expense of the predictability of the system's behaviour by an external observer.

The outer covering of arthropods – the cuticle – provides functions such as shape, structure, hinges, barrier, filter, etc. [2] Some of these functions are apparently mutually incompatible. It is thus possible that we can learn about the balance and integration of various functions from understanding the resolution of these design conflicts. Our studies show that biology and technology are similar only to the order of 10%, that there are thus more functions in biology whose technically novel design principles can be adapted to technological ends, and therefore that biomimetics can offer novel and valid alternatives to technological problems.

Conflict resolution

The first technique learned in TRIZ is the solution of problems by first identifying the conflict at the heart of the problem, then using a look-up table to identify a resolution to that conflict which has proved successful. The conflict is defined by a pair of properties that are apparently mutually incompatible: for instance if one parameter (e.g. strength) is improved it may compromise another (e.g. lightness). The table (the 'Contradiction Matrix') has been derived from the examination of millions of successful patents and the conflicts they resolve. It relies upon stating the conflict in stylised terms (there are 39 conflict topics provided, ranging from mass, length, time and their combinations, to less well defined topics such as reliability or ease of use) and then classifying the resolutions (currently 40, numbered, 'Inventive Principles' or I.P.s) which encapsulate all currently recognised manipulations, such as changing the temperature (I.P. 35), dividing the object into subunits (I.P. 1), using composite materials (I.P. 40), etc. The ideal resolution requires that there is a solution in which a material can (e.g. in the example above) be stronger but not heavier.

The data from technology and biology present a continuum of variables and contradictions at different levels of complexity. The biological data have to be structured into a framework that is compatible with technology to operate with this large amount of very varied information. We defined a functional framework that says "Things do things somewhere". This established six fields of operation (Table I) in which all actions with any object can be executed: "Things" (*substance*, *structure*) includes hierarchically structured material, i.e. the progression sub-system – system – super-system; "do things" (*energy*, *information*) implies also that energy needs to be regulated; "somewhere" (*space*, *time*). These six operational fields (Table I, column 1) re-organise and condense the TRIZ classification of the Features used to generate the conflict statements (Table I, column 3) and of the Inventive Principles (Table I, column 4). Although this blunts the "Contradictions" tool of TRIZ, it makes other processes easier (for example Functional Analysis in TRIZ, or "SU-Field" system) and is more logical and easier to use than the 39 "Contradictions" system. Moreover it is more complete.

FUNCTIONS OF ARTHROPOD CUTICLE

A list of functions and associated characteristics of cuticle was generated partly by reference to literature (e.g. Neville, 1975) and partly from personal experience with insects over the years. There is no guarantee that this list is exhaustive, but it was generated, as far as possible, with no apparent bias. The functions were then arranged such that each was placed in apposition to those functions or characteristics that might be expected to compromise it. Thus a table of conflicting functions was generated (Table II). Against each pair of conflicting functions was listed the method by which the conflict is resolved in cuticle, and this was expressed as a standard TRIZ inventive principle, whose index numbers are also shown. Two functions are considered in more detail to illustrate this process.

Table I. Classification of variables in the TRIZ Contradiction Matrix

Field of operation	Field definition	Contradiction Matrix Features	Inventive Principles
Substance	Adding, removing or changing material properties	Weight of moving and stationary object (1, 2) Loss of substance (23) Quantity of substance (26)	Copying (26) Colour change (32) Homogeneity (33) Parameter change (35) Phase transition (36)
Structure	Adding, removing or regrouping of structural parts	Stability of the object's composition (13) Manufacturing precision (29) Ease of manufacture (32) Device complexity (36)	Segmentation (1) Taking out (2) Local quality (3) Merging (5) Universality (6) Nested doll (7) Abundance (16) Intermediary (24) Discarding and recovering (34) Composite materials (40)
Space	Changing of special position or geometrical form of system or the shape its parts	Length of moving and stationary object (3,4) Area of moving and stationary object (5,6) Volume of moving object (7) Volume of stationary object (8) Shape (12)	Asymmetry (4) Spheroidality, curvature (14) Flexible shells and thin films (30) Porous materials (31) Another dimension (17)
Time	Retardation/ acceleration of the process, or changing an order of the actions.	Speed (9) Duration of action of moving and stationary object (15,16) Loss of time (25) Productivity (39)	Preliminary action (10) Beforehand cushioning (11) Dynamics (15) Periodic action (19) Continuity of useful action (20) Rushing through (21) Cheap short-lived objects (27)
Energy	Changing energy source or kind of acting field (magnetic, electric, acoustic, etc)	Total force (10) Stress or pressure (11) Strength (14) Temperature (17) Illumination intensity (18) Use of energy by moving and stationary object (19,20) Power (21) Loss of energy (22)	Anti-Weight (8) Preliminary anti-action (9) Equipotentiality (12) Mechanical vibration (18) Mechanics substitution (28) Pneumatics & hydraulics (29) Thermal expansion (37) Strong oxidants (38) Inert atmosphere (39)
Information	Changing the interaction or its regulation (information exchange) of a system or system elements	Loss of information (24) Reliability (27) Measurement accuracy (28) Object-affected and object-generated harmful factors (30,31) Ease of operation and repair (33,34) Adaptability or versatility (35) Difficulty of detecting and measuring (37,38)	The other way around (13) Blessing in disguise (22) Feedback (23) Self-service (25)

Stiff skeleton

A major function of the cuticle is to provide a stiff foundation for the animal:

- attachment for muscles
- mechanical protection
- control of shape

However,

- a uniformly stiff skeleton does not permit movement, so hinged areas are needed (I.P. 3)
- stiffness requires complete cross-linking of the cuticle protein, which militates against the use of the cuticle as a labile, resorbable chemical energy store (important for insects which feed only intermittently, such as *Rhodnius prolixus*, a blood-sucking bug) (I.P. 2)
- an external skeleton is a barrier to transmission of sensory information about the external environment, a function provided by sensory hairs and holes (the functional basis of the campaniform sensillum and slit sense organ). Note that translucent cuticle, needed for photoreceptors, can be cross-linked and stiff (I.P. 31)
- the animal recycles as much of the old cuticle as possible when synthesising the new one at the moult, which stiffness will compromise since it requires extensive cross-linking. Larval and nymphal cuticles are less cross-linked than adult cuticles (I.P. 9).

These resolutions can be categorised in TRIZ terms by the inventive principles whose reference numbers are placed in brackets in the list above. Thus I.P. 3 – *Control of local quality*:

- Change an object's structure, or its environment, from homo- to heterogeneous *Use gradients instead of uniformity*
- Make each part of an object more adapted to its own purpose *Compartmentalise*
- Make each part of an object fulfill a different function e.g. *Pencil with eraser; hammer with nail-puller; Swiss army knife*

The other principles mentioned above are as follows. I.P. 2 is *Extraction*: extract, isolate or remove an interfering or necessary part or property from an object; I.P. 31 is *Porous materials*: make an object porous; use the pores to introduce or transport a useful substance or function; I.P. 9 is *Prior counteraction*: prestress the material in tension to allow the structure to take compressive forces, or provide protection before the challenge.

Protection from heat/radiation

Insulation can be achieved by absorption, reflection or re-radiation.

Absorption can be achieved by a combination of cuticular thickness and spectral absorption, implying the presence of a chemical (usually a phenolic derivative such as melanin which absorbs in the ultraviolet). However:

- Protection by thickening the cuticle is expensive in terms of material and energy required to move it around, so it has to be controlled geometrically (I.P. 14: *Spheroidality* - use curves instead of straight lines)
- Insulation can be achieved by introduction of many small air spaces, thus reducing conductivity and allowing reflection and re-radiation, so the cuticle can be made porous (I.P. 31: *Porous materials*) which will also lighten it

Function we want	*Conflict function*	*Cuticular trick*	*I.P.*
Keep poisons out	pass excretions	thin rectal cuticle	30
"	pheromones out	gland pokes thru' cuticle	31
"	CO2 out	diffuse via trachea	3
Stiff skeleton	allow movement	soft hinge areas	3
"	food store	non x-linked inner layer	2
"	pass sensory info.	hairs and holes	31
"	recycle materials	control x-linking	9
sound production	skeletal function	use non-loaded area	3
"		use same loading	5
light weight	cheap materials	"good" design (geometry)	14,30
transmit light	protect from heat	spectral separation	35
waterproofing	allow water in	control permeability areas	3
"	pass sensory info.	small chemosensory areas	3
"	change stiffness	crinkly waterproof surface	11
pass excretions	waterproofing	locally thin cuticle	14,3
pheromones out	waterproofing	glands thru' cuticle	3
"		waterproof surface	3
soft cuticle / hinges	waterproofing	folded surface membrane	3
"	mechanical stability	muscle across joint	9
pass sensory info.	skeletal function	use selected areas	3
cheap materials	recycle materials	resorb cuticle at moult	35
protect from heat	light weight	geometrical control	14
"	light weight	porous material	31
"	transmit light	spectral control	32
allow water in	waterproofing	selected areas	3
change extensilbility	mechanical stability	change water content	35
self-cleaning	var. surface props	rough, hydrophobic	3
fracture control	stiff skeleton	control loads & faults	40,14
colour (physical)	self-cleaning	smooth, hydrophobic	3

Table II. Design conflicts in arthropod cuticle.

The first column shows the desired function, the second column shows another function which conflicts or interferes with the first. The third column shows the resolution of the conflict that has been implemented in the design of the cuticle, and the fourth column shows the equivalent TRIZ "Inventive Principle" (I.P.)

Absorption of UV by melanin will obscure the dermal light sense (important for controlling the way the cuticle is laid down) and obscure the eyes, so spectral control is needed (I.P. 32: *Colour changes* - change the colour or transparency of an object or its external environment).

In order to compare these biological resolutions of a design conflict with those which technology would use, it is necessary to convert the functions identified in the cuticle into the conflict topics that TRIZ recognises. For instance the functions “change stiffness”, “protection”, “soft cuticle” and “stiff skeleton” are all reduced to feature number 11, which is defined as *stress or pressure* (compression, tension or bending). Similarly “keep poison out”, “self cleaning”, “surface properties” and “waterproof” all become feature number 30, which is *external harm affects the object*. The conflicting functions are similarly classified into the standard TRIZ features, which now allows the conflicts to be treated in the standard TRIZ system [3] and a direct comparison to be made between technological and biological solutions to the same problem.

Two features have been chosen as exemplars – conflicts engendered by the necessity for a stiff external skeleton (factor 11), and conflicts involved in the absorption (factor 17) and transmission (factor 18) of radiation of various wavelengths. When the comparisons are made (Table IV) the nature of the similarities suggests that at the molecular level (the spectral transmission properties of the material) there is little or no difference between the biological and technical worlds. This suggests that the resolution has been arrived at in the same way in the two technologies – presumably through a chemical pathway that provides specific spectral absorption of the potentially damaging wavelengths. But in terms of structures, and more importantly the versatility of structures, the solutions of biology are very different from those of technology. The data in Table III were chosen to show slight and strong overlaps; in the full comparison table (not shown here) there were 54 pairs of conflict and in only 10 was there any similarity between TRIZ and biology.

A comparison of the two (Table V) based on the entire set of comparisons (of which Table IV is a small sample chosen to illustrate two extreme comparisons) shows that while biology (column 2) controls material properties over a very short distance at a chemical and morphological level (I.P. 3 is used for 25% of resolutions), technology (column 3) tends to use a rather blunter, more global approach (I.P. 35 is the most used – 10% of resolutions) that involves changing a parameter such as temperature.

When the Conflicts and Inventive Principles are reclassified (see Table I), the distribution (based on about 2,500 biological cases which we have examined, in the same way as the cuticle examples shown in this paper) is as shown in Table III. The most noticeable trends are with Information (which increases from about a fifth to well over half the conflicts and principles as the level of hierarchy increases) and Substance, which trends in the opposite direction. Thus hierarchy should be considered in the application of ideas from biology into engineering.

Table III. Relation between hierarchy of structure and the type of conflict and resolution

%	organelle	cell	tissue	organ	system of organs	Individual	society	ecosystem
Substance	8.6	13.5	14.7	3	7.4	2.3	3	2.2
Structure	42.7	29.8	14.7	42.5	27.5	28.4	23.8	9.1
Space	12.5	23.3	25.1	3.5	4.5	15	16.2	15.6
Time	12.1	12.7	13.6	19	32	20.7	14	12.2
Energy	6.1	8.3	3.9	10	7.6	7.6	5	5.5
Information	18	12.4	28	22	21	26	38	55.4

Contradictions		Nature		T R I Z			
Improves	Worsens						
11	12	9		35	4	13	10
	13	**2**	9	35	33	**2**	40
	29	27		3	35		
	30	3		22	2	37	
	32	27		1	35	10	
	35	3		35			
	37	31		2	36	37	
17	2	**32**		22	35	**32**	
	18	**32**		**32**	20	21	16
	26	14	**30**	3	17	**30**	39
	30	**35**		22	33	**35**	2
	37	**31**		3	27	35	**31**
18	12	**32**		**32**	30		
	17	**35**		32	**35**	19	

Table IV. The first two columns of Table II have been transformed into standard functional conflicts of TRIZ and the similarities emphasised in bold. Design functions shown: stiffness (11) and the conflicting functions (12 – shape; 13 – stability; 29 – precision; 30 – external harm; 32 – ease of making; 35 – adaptability; 37 – difficulty of sensing) producing conflict pairs whose resolution in standard TRIZ (derived from technology) are given in the right hand column. Design functions 17 (insulate) and 18 (transmit radiation) are also shown, with their conflicting functions (2, 26 – light weight; 12 – mechanical stability; 30 – keep poison out).

Inventive Principle	**Nature**	**TRIZ**
3 (local quality)	25	5.65
14 (spheroidality)	14	0
30 (flexible shell)	13	3.39
40 (composite material)	13	3.39
35 (change parameters)	9.4	10.2
9 (preliminary anti-action)	4.7	0.56
31 (porous material)	6.3	1.13
27 (cheap, short life)	6.3	3.95
32 (change colour)	3.1	3.39
5 (merging)	3.1	0
2 (take out)	1.6	3.39
10 (preliminary action)	1.6	6.21
11 (pre-cushioning)	1.6	2.26

Table V. The percentage occurrence of Inventive Principles derived from Table IV. The numbers are those conventionally given to the principles in the TRIZ literature, together with a brief indication of the principle itself.

DISCUSSION

In technology one is presented with a problem and asked to find an answer; in biology one is presented with the answer (an organism) and asked to find out what the problem was. In biology this has led to internal comparisons of physiology and morphology and the recognition that functional problems in different organisms are similar but solved in different ways. For instance there are several types of organ for maintaining the ionic milieu of animals. But there has been little or no objective recognition that these organs are meeting apparently conflicting requirements, such as retaining liquid within a permeable tube. The answers to these problems are well known within biology, but their applicability often remains to be illustrated. TRIZ was developed to resolve such conflicts in technology, and its application in the present study emphasises the differences between biology and technology in the resolution of such design conflicts.

Thus the main outcome of this study is that biology and technology "solve" problem in design in rather different ways. More general studies (to be reported elsewhere) show that there is a 10% overlap between biology and engineering in terms of design solutions – i.e. the commonality of inventive principles used in biology and outlined in this paper to identify those principles in the biological context. The present study gives an overlap of a little less than 20%, nearly all of which is provided by the similarities in spectral filtering (Table IV). This suggests that the functional design of arthropod cuticle is relatively close to the technology of such materials – in this case, fibrous composites. Thus a major outcome of this study is that biology and technology "solve" problems in design in rather different ways. Specifically, insect cuticle becomes multifunctional by juxtaposing functions such that they interfere as little as possible. However, most of the functions of cuticle are provided by detailed control of properties over a very short distance. This suggests that technology should be aiming at producing not just very small components but integrated assemblages of components. An example of the success of this approach is given in a study of the design and integration of the campaniform sensillum into the cuticle [4]. The sensillum is a displacement sensor, relying on the deformation of a hole through the cuticle. The hole is formed by diverting the chitin fibres in the cuticle around it, rather than allowing the fibres to end blindly at the periphery of the hole, the equivalent of drilling the hole in a sheet of fibrous composite. This 'attention to detail' results not only in a far safer design (the stress concentrations normally associated with a hole are totally avoided) but an increase by a factor of 8 in the local amplification of globally applied strain, leading to increased sensitivity of the sensillum. Thus the proper integration of the strain sensor, rather than the current methods of sticking a foil gauge onto the surface, results in significant technical advantage. The deformation of the hole can be monitored in a number of ways, including current techniques of specialised embedded fibres, the additional advantage being the strain amplification provided by the hole.

The second and third most common TRIZ principles in Table V are spheroidality and spherical shells. These are both to do with morphology rather than materials, and emphasise another characteristic of biological structures pointed out with respect to hedgehog spines [5], that in biology material is more expensive (requires more energy to accrue) than shape. The tendency will therefore always be for the shape of a structure to be as efficient as possible and, unless the object is simply there for mass (e.g. the immovable shell of the oyster), this will allow reduction in the amount of material used. The fourth most common principle in Table V is the use of composite materials. In insects (and other arthropods), cuticle is a highly effective composite of chitin crystallites in a matrix made of a mixture of silk-like and globular proteins [6], which allows the cuticle to have highly localised properties and thus to support the close juxtaposition of functions (and thus of mechanical properties) necessary for I.P. 3 to work properly without the different functions compromising each other.

The application of TRIZ to problems in biology is not new [7], but has commonly been performed at a trivial level that purports to show how biology follows the lead of technology. If this were the true state of comparison, there would not be the current interest in biomimicry, nanotechnology, self-assembly, smart materials, etc., all of which have useful input from biology. The level of detail in the analysis presented here has not been attempted before, but is typical of the sort of case study that we are developing, allowing us to deconvolve biological functions and compare design solutions.

This general approach can be applied to any biological entity, from cell to ecosystem. The analysis of design at these different levels is the subject of further papers. However, it is worth pointing out that hierarchy, such an important factor in biological systems, is more or less ignored in technical systems, but is an important parameter in both the definition of problems and in their solution. The mirror of biomimetics shows how essentially 2-dimensional technology really is.

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