Putting Biology into TRIZ: A Database of Biological Effects

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Our goal is to make biological information available for engineers via a 'biological patents' database in TRIZ. However, biological functions need to be co-ordinated simultaneously at many levels of organization – from cell organelle to population to ecosystem. Each function has links with other functions on different organizational levels. To account for this, we made auxiliary 5D 'conflict' matrices for biological structures and environments, and for causes and limits of actions; these allow us to resolve data about organisms into engineering-like chunks of information and cover the primary TRIZ constituents of 'function', 'effect' and 'conflict'. In this way we can also provide a framework for the rationalization and quantification of bionics.

Introduction

As with any fundamental science, biology involves observation, description, classification and analysis. Engineering, on the other hand, acts, prescribes, utilizes and manages. The transition from science to technology, or from theory to practice, which is the course of design, is difficult since there is often not enough information about *all* the relevant effects and the *conditions* of their manifestation. In other words, a designer requires a bridge between ideas and their physical implementation. This bridge should make knowledge transfer more predictable, reliable and manageable.

Methods and procedures are therefore required to give us an answer not only to the question *'what to do?'* but also *'how to do it?'*. We consider that the most appropriate method to play the role of this bridge is TRIZ – the Russian Theory of Inventive Problem Solving – or perhaps a new, integrated, method based on TRIZ.

TRIZ was originally developed within the physical and chemical domains of matter (mechanical, geometrical, electrical and chemical phenomena) and engineering. More recent applications have been in management, advertising, architecture and business consulting. However, those developing and adapting TRIZ have ignored the vast area of biology. This comprises numerous components at various levels of organization, e.g. biosphere, landscape, population, individual, organ-system, organ, tissue, cell, organelle, etc. One unfortunate result is that there is hardly any literature on TRIZ and biology that is not trivial. We are therefore expanding the existing TRIZ framework to incorporate biological data and biomimetic thinking (Bogatyrev and Bogatyreva, 2003).

TRIZ and Biology

The underlying concept is that billions of years of 'research' have gone into natural systems as life on the planet has evolved. This 'research' is, *a priori*, very likely to provide novel solutions to existing technical problems (1, 2, 3). Our goal is to make this biological information available to engineers by cataloguing and classifying the effects of any given action, mechanism or function, in all biological systems.

To accommodate this information we needed to adapt the structure of biological information to suit the established structure of TRIZ. We started our work with the 'contradiction' matrix of functional conflicts which is the usual, relatively easy, first step in using and understanding TRIZ. This method of defining a problem goes back at least as far as Plato, who pointed out that at the heart of

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every problem there is a conceptual or functional conflict of the type: ‘It must be stronger but may not be heavier’ or ‘It must be both waterproof and porous’. Once the problem has been stated in the terms of an apparent impasse, TRIZ provides a method for the resolution of the conflict by presenting ways in which similar types of conflict have been resolved by other people, often in other areas of science or technology. If the nature of the conflict is sufficiently generalized, it is possible to use resolutions from a wide variety of disciplines with the increased possibility of a better and more innovative solution.

This method necessarily involves loss of detail in the interest of generality, which implies that until the detail of specific functions and observations has been smoothed, not to say glossed, over, those functions and observations cannot be accommodated within the system. However, since the functions performed within and by living organisms are by and large different from, and more complex than, those with which we are familiar in technology, we need to analyse and distil those functions very carefully to make them compatible with the systems and methods of TRIZ. This analysis and distillation is not a trivial process. Initially, we designed auxiliary conflict matrices for biological structures and environments, and for causes and limits of actions. These allow us to break natural data into engineering-like chunks of information and cover the primary TRIZ components of ‘function’, ‘effect’ and ‘conflict’.

The matrix we are building is therefore five-dimensional – it takes account of:

- an object and its parts (which are accounted for in the TRIZ contradiction matrix) and in addition;
- the ultimate purpose of action;
- the environment in which the object operates;
- the limits and causes of action;
- the resources and auxiliary systems involved.

It incorporates the ideas of several TRIZ tools within a single context, and is thus not only a database of physical effects, but also a database of intention and motivation.

Another TRIZ concept of which we make much use is the system operator. This rather pretentious term simply means that there are levels of hierarchy above and below (and before and after) almost any object being studied. These have already been mentioned for biology (organelle, cell, tissue, organ, organism . . .), and that the level of the object under scrutiny is always referred to as the system. The super-system represents the assemblage of which the system is a part (for a cell it is a tissue; for an organism it is a population) and the sub-system represents one of the components of the system (for a cell, an organelle; for an organism, an organ). Increasingly we are finding that this classification – which in TRIZ is usually regarded simply as a way of expanding the conceptual approach to a problem – is an integral part not only of understanding the problem but of divining where the solution to the problem might lie. In some instances in the following discourse, the term ‘entity’ is used instead of ‘system’.

Gathering and Presenting the Data

The database is available on our web site, http://www.bath.ac.uk/~ensab/TRIZ/. We have not yet made this open for the addition of data, but will later allow people to register so that we can moderate the additions. Initially it consists of a series of forms that prompt for information by asking specific questions. The reports generated from the answers to these questions (the database) can also be accessed and, with suitable security measures, edited. Computationally, it is a suite of server-side C++ classes and functions running on Bath University’s UNIX systems that record and search the data, and a set of client-side HTML forms and Javascript programs for checking consistency and completeness of the input. These run in any browser (Bowyer et al., 2003).

Specific Features of the Database

In order to be compatible with existing TRIZ tools, the database needs to have the following features that currently exist as fields in records or links between records within it.

Definition of Function and Effect

Because of the recent growth of interest in interdisciplinary ‘function-design’ problems, and because of recent advances in the philosophy of the analysis of function within biology (as a result of the development of behavioural science, where one cannot avoid the words ‘goal’ and ‘purpose’), we can finally lay to rest any fears about teleology (Bekoff and Allen, 1995).

Biological systems are without doubt teleological. Their goal is a condition that is in some way useful or desirable, enhancing survival of the individual. We can thus define the function of the biological system to be ‘the action needed to achieve a useful or desired condition’.

In technical systems, the achievement of this goal is delegated to a technical device. The goal still remains the future condition of the system. Therefore, the function of a technical system is 'the action needed to achieve a useful or desired condition *with the help of a technical device*'.

This apparently pedantic reframing allows us to say that the result of the function of a technical system in a particular environment is a technical effect, and the result of a function of a biological system in a particular environment is a biological effect. The technical effect is equivalent to the use of tools, a phenomenon observed in many mammals, birds and insects. Technology is not a uniquely human product. Note in passing that the definition of effect includes the observer.

From the engineer's point of view, a biological effect is usually defined as a resource that could be used in a technical system. We have a different point of view – an effect is not a resource. The biological effect should be a description of the system, as we always need to know the hierarchical level of functioning and its past, resources used, and future (goal) (Bogatyreva et al., 2002). Any given effect could cause many other effects at many levels of biological organization – from cell organelle to animal population and ecosystem functioning. Conversely, it could be caused by yet other causes and effects on many other levels!

For example, running can be said to be an effect of legs moving fast (we see this at the organismal level). But running has other effects at the sub-system level: increases in pulse rate and breathing, etc. These subsequent effects of 'running' are consequent upon 'movement' but are non-specific for a particular function – they occur while swimming too. In this network of causality we therefore need some points of reference, some special rules that will help us to build the framework for the database. To simplify matters we suggest:

> **Rule 1** – systems exhibit 'goal directedness' that allows us to trace a line of effects through the network of causality. For example, the movement of a fish's fins (a system of organs) affects the fish (the super-system) that then moves through its environment, water.
> The user of this effect is the fish: the effect arises from the interaction between the system and the environment. So, we come to
> **Rule 2** – one sees an effect in the super-system, one or more levels up the hierarchy from the working system.
> The next rule is about resources. The system cannot be its own resource – sky hooks never work. So,
> **Rule 3** – resources can be obtained only from other external systems.

Table 1. Characteristic Causes and Effects

Cause	Internal
	External
	Static
	Dynamic
Effect	Object changes
	Medium or other object changes
	Both change
	Reciprocal
	Not reciprocal
	Static
	Dynamic

Cause and Effect

An effect, as defined in TRIZ, is because of an obvious cause under particular conditions. In biology on the other hand, we may see an effect, but must search for causes, and can only guess about goals. This is because biological systems have as their goal a useful or desirable future condition.

In the database, therefore, some differentiation is necessary (Table 1). We consider that:

- causes and effects can be static or dynamic;
- effects can be reciprocal or non-reciprocal;
- some effects can be result of several sub-systems acting together in (inner or outer) contact, or without contact.

The Medium

We now define in which of eight types of medium an entity lives and functions – air, ground, water, or their combinations, or in the biotic environment (i.e. living on, or from, another organism – such as a parasite or tree-dweller).

Interactions between Entity and Medium

In defining the system, we want to describe how the entity or system of interest interacts with the medium in which it functions and how it interacts with other objects. We make these distinctions here.

Sub-entities, Super-entities and Resources

In this field we indicate the relationship of the sub-system and super-system to a given system. The characteristics of biological systems we take into account are:

1. *The hierarchy*, which regulates resources, energy distribution and the capacity of the system in space and time.

2. *The inertia*, which affects the likelihood of an effect being expressed on a different level of the hierarchy. The further the super-system is from the effector in terms of hierarchical levels, the less likelihood there is that the effect will be expressed. This causes cumulative properties of biological effects. An effect can be seen only in the super-system. And every super-system tries to compensate for the actions/effects of its sub-systems. But the only system that 'wants' to change is that which has a goal. The general inertia in biological systems opposes change. That is why an active effect is always violent at the levels of the super-system and environment.

These can be described in terms of resources (Table 2) that are essential for the effect characteristics. Resources can be obtained only from other external systems. They can be field (i.e. delocalized, such as sunlight) matter and information and can be obtained from sub-systems, super-systems and the environment. In the entry field of our database, we choose whether the field results from the medium in which the entity functions, from the super-system, or from the sub-system. We define whether it is dispersed in space or aggregated, and whether there is much or little of it (Table 3). We do the same for substance and information resources.

Table 2. Possible Interactions Between an Entity (= System, Object) and Other Objects or the Surrounding Medium

Object-medium interaction	Inner contact
	Outer contact
Object-object interactions	Fixed contact
	No contact
	Any contact

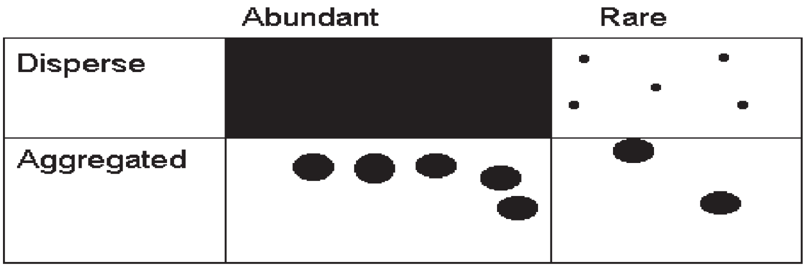
Table of Parameters

We must know what prevents, or makes difficult, the achievement of the effect. In this field we define how action or function starts and is stopped. One first selects a parameter, which 'causes' action, and whether this happens by its being decreased ('DOWN') or increased ('UP'). Then one selects a parameter that 'prevents or limits' action in the same way (example: for shivering, the event which 'causes action' would be 'energy change', 'DOWN', and the event that 'prevents or limits action' would be 'temperature change', 'UP'). One can select as many sets (of cause and limit) as one likes for a given entity (e.g. shivering can also be decreased for objects of high mass). The selection is considered a

Table 3. Types of Distribution of Resource

	From medium	**From super-system**	**From sub-system**
Field	I II III IV	I II III IV	I II III IV
Substance	I II III IV	I II III IV	I II III IV
Information	I II III IV	I II III IV	I II III IV

I, II, III, IV – space distribution description:



Notes: A *field* is a permeating resource such as ambient heat or a magnetic field, a *substance* is a discrete resource, *information* is an intangible resource such as a nervous signal. The resource may be distributed in a number of ways: I is 'dispersed/abundant', II is 'dispersed/rare', III is 'aggregated/abundant', IV is 'aggregated/rare' (the diagram indicates these differences). The resource can come from the medium, from the sub-system or the super-system.

complete entry when the last (LOW/HIGH) button is pressed. Up to that point, the combination can be changed without affecting the database.

So, in general, a biological effect is more complicated than a physical or a chemical one, partly because it includes both of the latter. This often gives it a non-predictable or 'emergent' quality. But we can make an analogy between effects in biologically emergent and the technically predictable systems of engineering, merely by recognizing that both biological and technical systems need a goal to pursue.

How to Use the Database

At present you need to be registered to add to the database, but please apply to the authors of this article for registration. The use of the database is rather restricted by comparison with its ultimate possibilities, when we have rather more data in it. However, you can interrogate it in a number of ways, asking what is known about an organism (a whale, for instance), or how you might achieve a certain effect (e.g. jumping – you can use muscles or springs, which have different adaptations). One use has already been to compare the overlap between technology (represented by the classic TRIZ matrix) and biological functions to achieve the same technical result. The overlap is only about 10 per cent, showing that 90 per cent of biological functions remain to be incorporated – biomimetically – into technology.

Searching

The software has not been written to look pretty – it is severely functional. To search the database, activate the *Search* button. There are no compulsory fields; one can fill in as many or as few as desired and the system will find all records that match. Leaving the form completely blank returns every record in the database. The result of a search for 'cells' growth factors' is shown in Table 4. The meaning of each field is indicated after the section that is to be filled in, and contains embedded examples.

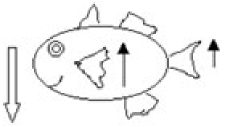
Adding Data

As an example, let us step through the procedure for entering data on a bony fish (teleost) moving in water. The form for adding data to the database can be reached via the *Add* button. There are compulsory fields that must be filled in, such as:

1. Author's name, 'Adrian Bowyer';
2. Entity description, 'Teleost fish' (action of the fins and tail in controlling movement);
3. At least one reference, 'R. McNeill Alexander *Locomotion of animals*, Blackie, Glasgow';
4. The entity's function, 'Move → Locomotion → Turn';
5. The entity's level of organization (molecule, organelle, cell (Procaryote, Eucaryote), tissue, organ, system of organs, individual, social organization, ecological system) – 'individual';
6. The medium in which the entity performs this function – 'water (liquid)'.

Other fields are optional. However more accuracy will help the project, such as defining super- and sub-entities. For example if 'fish' is the system, 'fins' and 'tail' are both sub-systems; 'fish plus its environment' is a super-system.

1. Cause and effect characteristics: cause is external to fish – interaction of its fins with water, effect is external and non-reciprocal.
2. Entity/Media interactions: 'outer contact'. All objects (fins, tail and fish body) are fixed and media is outside of them.
3. The table of parameters that cause and limit action.
4. Causal parameters: force on surroundings is increased (cause which is in media sphere), shape changing abilities of fins/tail (increasing) fins/tail strength.
5. Limiting parameters – high fish speed and high flow speed.
6. Resource is medium (water) viscosity (type III see table 2) and in the fins structure (substance) – partially flexible and partially strong – (type I see table 2).
7. A picture of the entity



8. The effect description. 'Undulation of fins and tail as parts of fish body in any combinations causes slow direct movement (manoeuvre) of the fish and the direction of the waves of undulation is always opposite to direction of movement'.
9. Links to physical TRIZ.
10. Any useful notes.

Conclusion

Our goal, to make biological information available for engineers via a database of the

Table 4. Record Details

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Author	Olga Bogatyreva
Creation Date	Mon Jul 7 17:11:54 2003
Last Modification Date	Mon Jul 7 17:11:54 2003
System	cells’ growth factors
Description	Stimulation of cells by growth factors triggers cascades of signalling that result in cellular responses such as growth, differentiation, migration and survival. The globular architecture of the growth factors is essential for receptor binding.
Reference	Nicholas J. Harmer, Dima Chirgadze, Kyung Hyun Kim, Luca Pellegrini and Tom L. Blundell The structural biology of growth factor receptor activation Biophysical Chemistry, Volume 100, Issues 1–3, Pages 545–553
Function	regulate inform signal
Level of Organisation	molecule
Living Medium	biotic
Cause Internal or External Contact	external
Cause Static or Dynamic	static
Effect Object Or Medium Changes	object changes
Effect (not) Reciprocal	not reciprocal
Effect Static or Dynamic	dynamic
Notes	Many growth factors signal through receptor tyrosine kinases, leading to dimerization, trans-phosphorylation and activation of tyrosine kinases that phosphorylate components further downstream of the signal transduction cascade. In general, weak binary interactions between growth factor and individual domains of receptors are enhanced by cooperative interactions with further receptor domains, and sometimes other components like heparan, to give rise to specific multi-protein/domain complexes. For example: nerve growth factor (NGF) is a symmetrical dimer that binds four storage proteins (two -NGF and two -NGF) to give a symmetrical hetero-hexameric 7SNGF organised around the -NGF dimer. It binds the extracellular domains of two receptor molecules in a similar way, so dimerising the receptor.

effects of action between system components or whole systems, will involve a great deal of data- gathering and analysis. We are looking for any ‘effect’ resulting from an object’s natural functioning and can find it in the object’s interaction with a particular environment.

Our database is therefore five-dimensional – it takes account not only of object parts (which are also accounted for in the classical TRIZ contradiction matrix) but also of the environment in which the object operates, the limits and causes of its action, the ultimate purpose of the action and the resources and auxiliary systems involved. It thus incorporates the ideas of several TRIZ tools within a single context and is not only a database of physical effects, but also a database of intention and motivation.

Acknowledgement

The studies presented here were financed by the EPSRC.

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Julian Vincent is a biologist, currently Professor of Biomimetics in the Dept of Mechanical Engineering at the University of Bath. His ambition is to make biological design solutions available to engineers, deskilling the process of transfer.

Olga and Nikolaj Bogatyrev are biologists with much experience in the behaviour of social insects; they are also probably the only biologists to have a formal training in TRIZ.

Anja-Karina Pahl is a facilitator who sees no barriers between the sciences and spends her life teaching others the same vision.

Adrian Bowyer is a Senior Lecturer in Mechanical Engineering with special interests in computing and technology transfer.