Better design using nature's successful (no-compromise) solutions

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Abstract

The paper describes a programme of work aimed at identifying and codifying design solutions from the natural world in which a trade-off or compromise has been reduced or eliminated in an inventive manner. A conflict elimination structure enabling users from other disciplines to take advantage of the compromise elimination strategies evolved in nature in a systematic manner is described. A number of case study examples highlighting the differences between the manner in which nature resolves contradictions and the manner in which designers attempt to achieve the same goal are also presented.
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1. Introduction

The Soviet-originated Theory of Inventive Problem Solving, TRIZ (Altshuller [1]) and its more recent systematic innovation successors (Mann [2]) have together analysed close to three two million successful design solutions from across all areas of human endeavour. The research has showed that one thing 'successful' solutions have in common is that the designer has sought to eliminate the trade-offs and compromises that everyone else has assumed to be fundamental. The research has also demonstrated that, so far, these three million compromise-eliminating solutions have emerged from the deployment of just 40 strategies. This is not to say that there aren't more, but simply that so far only 40 have been uncovered.

More recent studies of the natural world by Timokhov [3] and Vincent [4] successfully demonstrated that the natural world also evolves solutions in which trade-offs and compromises are eliminated or at least become significantly reduced. A subsequent, more detailed, programme of analysis of the natural world aimed at finding additional inventive strategies has been conducted during the period 2000 to 2003 and the findings are reported here for the first time. This research has thus far shown that nature has used exactly the same 40 strategies as have been used by human designers. Conversely, this research has also shown that for a given conflict or contradiction situation, nature very often uses a different selection from the 40 than the human designer has typically used.

The paper describes the programme of research to construct and populate a 'conflict elimination' tool based on the best practices found in nature. The paper is divided into three main sections. The first section describes the task of configuring the conflict elimination tool. The second part details a number of examples of the natural world evolving conflict-eliminating or conflict-reducing solutions and compares the strategies used with the equivalent best practices used by designers. The final section of the paper describes the ongoing programme of research to integrate together the best of the natural and human-designer worlds in order to enable designers working in all fields to have access to the best possible set of trade-off and conflict elimination strategies for any given situation.

2. Conflict Elimination Tool Structure

Working through the 1950s and 60s, the original TRIZ researchers gradually evolved and expanded a simple tool to permit the ready transfer of successful conflict-eliminating solutions from one engineering discipline to another. The most well known of the versions of this tool is the 'Contradiction Matrix' published by Domb [5]. This tool features the 39 most commonly used engineering design parameters (size, shape, strength, manufacturability, reliability, etc) arranged in a two-dimensional matrix. A portion of this Matrix is illustrated in Figure 1.

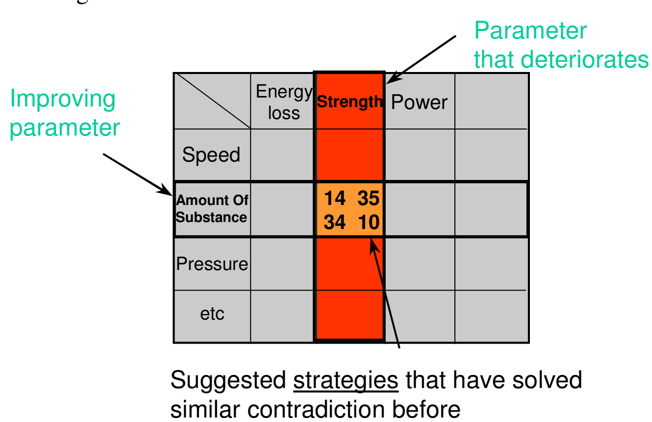

Figure 1: Sample Section of Contradiction Matrix of Classical TRIZ

The basic method of operation of the Matrix involves identification of an attribute (or attributes) that a designer is looking to improve, followed by another attribute that is preventing the improvement. This pair of conflicting parameters is then looked up in the Matrix using rows for the improving parameter and columns for the worsening parameter. The intersection of improving and worsening parameters is a box containing a series of numbers. These numbers relate to the most commonly applied inventive strategies used by designers, engineers and scientists that have successfully challenged that particular conflict pair. Thus, in the example in Figure 1, the Matrix identifies Inventive Strategies 14 ('Increase Curvature'), 35 ('Change Material Parameters'), 34 ('Discard and Recover') and 10 ('Add some form of Preliminary Action') as those most commonly used in situations where a designer has successfully reduced the amount of material used in a structure without reducing the strength. More details of the meanings of these Inventive Strategies can be found in Mann [2]. The main underlying concept of the Contradiction Matrix tool is the creation of a structure that allows rapid transfer of successful design practice from one discipline to another – such that, as soon as a designer is able to recognise that he /she is facing a conflict between amount of material and strength, the Matrix will identify the best practice of everyone else that has previously succeeded in creating an effective solution to that conflict pair.

This Contradiction Matrix was effectively frozen by the Soviet researchers in 1973. An extensive programme of research to evaluate the Matrix based on present day innovative practices was completed in 2003 by Mann et al [6]. This work examined large numbers of patents and design solutions emerging between the years 1985-2003 and resulted in the expansion of the Matrix from 39 to 48 parameters, and a complete updating of the priority sequencing of Inventive Strategies in each of the matrix boxes. New parameters introduced into this Matrix included things like noise, aesthetics, safety, compatibility, and harmful emissions – all issues that take a much more prominent role in the life of the designer than they did in the early 1970s.

In terms of the most appropriate form of this type of contradiction matrix for design solutions found in the natural world, the research programme has thus far identified the following parameters for which it has been possible to locate a statistically significant number of conflict resolution solutions:-

Weight	Stress/Pressure
Length	Strength
Area	Stability
Volume	Temperature
Shape	Illumination Intensity/Brightness
Amount Of Substance	Function Efficiency
Amount Of Information (Memory)	Loss Of Substance
Duration Of Action	Noise
Speed	Harmful Effects On System
Force	Adaptability
Energy/Power	Durability/Robustness/Life

Repairability/ Healing	Productivity/Reproduction
Security/Protection/Vulnerability	Complexity
Harmful Effects By System	Ability To Detect/Precision

Figure 2: Matrix Parameter Relevant To Natural World Design Solutions

3. Conflict Elimination Case Studies From Nature

During the course of the research into conflicts and contradictions solved by nature, several thousand examples have so far been identified and codified. The consolidated output of all of this research is expected to be published by Mann et al as described at [7]. This section highlights some of the examples included in the research, the process of mapping them into the Matrix, and comparisons with the recommendations made by human designers.

3.1 Substance versus Strength Solutions

The 'amount of substance' versus 'strength' conflict pair highlighted in the previous discussion is one of the most common conflicts found in nature. This should not come as too much of a surprise since evolutionary pressures continually drive life-forms to make best possible use of the resources they possess. Three examples of nature tackling this substance versus strength conflict are described below:-

The Locust – manages to maintain sharp cutting surfaces on its mandibles without having to use a very hard (and hence biologically 'expensive') material. The adult *locusta migratoria* solves the problem by configuring the outer surface of the left and the inner surface of the right incisor to be twice as hard as other areas, thus providing a self-sharpening mechanism as the softer material wears away [8]. This solution represents use of Inventive Strategies 3 ('Local Quality') and 25 ('Self-Service').

Birds – all flying birds have a strong evolutionary incentive to create the strongest possible structure with the smallest possible amount of materials. Weight is the critical issue here, and the load-bearing skeleton is the main focus of the conflict. As is fairly well established these days, birds resolve the substance/strength conflict by using hollow bone structures featuring different sizes of 'holes' in different parts of the bone according to load-bearing requirements. Birds have thus evolved solutions using inventive strategies 3 ('Local Quality' again) and 31 ('Porous Materials').

Butterfly Wings – all insects have a strong incentive to achieve lifting surfaces capable of generating high lift-forces without being heavy. Butterflies have evolved several effective strategies to the substance versus strength conflict. Figure 3 illustrates typical examples courtesy of Hey [9] showing a variety of corrugated structures (inventive strategies 14 and 17) and use of air spaces (strategy 31).

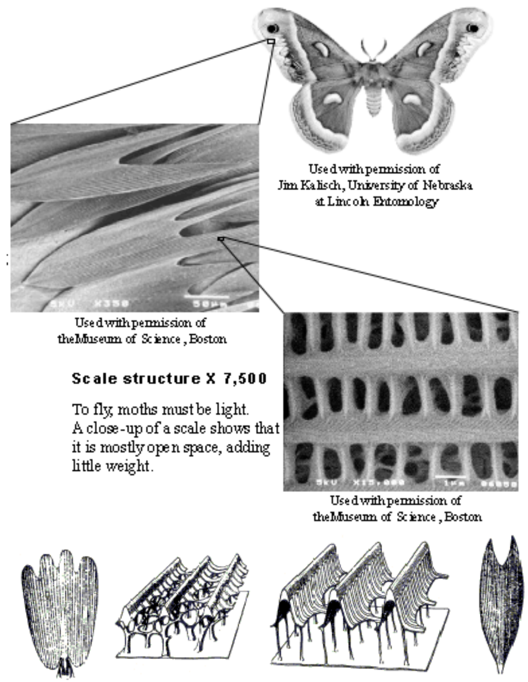

Figure 3: Butterfly scales and micro-structure

Thus, taken together, we observe nature using almost completely different inventive strategies (3, 14, 17, 25, 31) to the top-four used by human designers as illustrated in Figure 1 (10,14, 34, 25).

3.2 Brown Bear

The design of its fur allows the Brown Bear to solve a contradiction between wanting the fur to provide excellent heat insulation in cold weather, and also to be able to dissipate large quantities of heat when the animal is running and hunting. The conflict being solved here again involves the ‘amount of substance’ parameter, but this time it is in conflict with temperature rather than strength, The conventional Matrix highlights the use of inventive strategies 3, 17 and 39 as the most commonly used human solutions to the problem. As illustrated in Figure 4, the brown bear, uses strategy 3 (‘Local Quality’ again – here the non-constant cross-sectional area of the fur fibre), but in conjunction with strategies 8 (‘Counter-Weight’ – the thickness of the fur at mid-span is greater than that at the root, thus creating a means of introducing a highly dynamic motion) and 19

(‘Periodic Action’ – in that the rhythmic, co-ordinated motion of the fibres that creates an effective heat pumping mechanism)

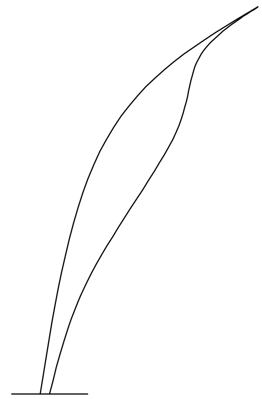

Figure 4: Brown Bear And Sectional View Of Single Fur Fibre

3.3 Tengmalm’s Owl

Tengmalm’s owl successfully achieves fully-three dimensional location of it’s prey without adding more complexity to it’s hearing systems than other birds (which can usually only achieve x-y directional information). The conflict being resolved here is one between the desire to acquire positional information (best matches in the Matrix; ‘Length of Moving Object’ or ‘Ability To Detect’) and system complexity (already featured in this form in the Matrix). The Matrix records inventive strategies 1, 19, 26, 24, 15, 10, 37 and 28 as the eight most commonly used by designers. Tengmalm’s owl, on the other hand, makes very effective use of strategy number 4, Asymmetry – Figure 5.

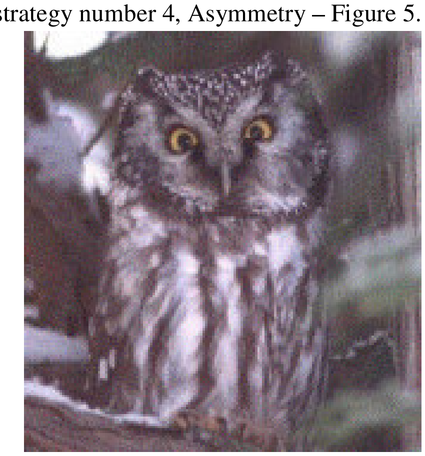

Figure 5: Asymmetrical Skull And Ear Structure of Tengmalm’s Owl

The asymmetrical positioning of the ears means that any sound made by potential prey reaches one ear out of phase with the other in the vertical (z-) direction and hence the owl achieves fully 3-dimensional location. See Mann [10] for more detail on this and other examples of the Asymmetry inventive strategy being used in nature.

3.4 Hoverfly

Insects often rely on the heat of the sun to generate sufficient warmth. Warmth can create several benefits, including the ability to spend more time finding food and mates, and also increasing the time taken for sperm and eggs to reach maturity. On the other hand, there is a danger of over-heating if too much of the sun's energy is absorbed. The marmalade hoverfly (*Episyrphus balteatus*) solves the temperature versus time conflict through its ability to change the ratio of black to yellow areas in its striped markings (Halpin [11]). The hoverfly is thus using inventive strategy 32 ('Colour Change') to tackle the problem. The conventional Matrix on the other hand suggests strategies 19, 35 and 39 as the most commonly used designer strategies. The solution evolved by the hoverfly recognises the importance of colour on the radiation emissivity properties of a surface. To the vast majority of designers (spacecraft design excepted), the use of colour change is a much ignored conflict-resolving opportunity.

4. Towards A Unified Conflict Elimination Tool

The biological examples described in the previous section serve to highlight some of the differences between the compromise-reducing or eliminating strategies adopted by nature compared with those used by human designers. These differences appear to be consistently repeated across the several thousand case study examples now present in the database. What is less clear at this stage is which of 'human' or 'natural' best practice gives superior output than the other. What can be said with some degree of confidence is that – at this point in time in the evolution of mankind's design capability – nature appears to be stronger in a majority of areas. An effective means of making comparisons emerges by looking at the state-of-the-art in terms of achieved ratios between pairs of conflicting parameters. In most such comparisons it appears clear that nature is still considerably more advanced than the best of mankind's abilities. We might think here of attribute ratios like substance-to-strength (where natural solutions like the aforementioned bird-bone or spider-web outclass the human designer by a significant margin), or (grip-)force-to-area ratio (gecko foot), or speed-to-power-applied ratio (shark, swordfish, most avians). In this latter case, although it is clear that man can achieve significantly higher speeds than nature, we still require proportionally much more power to achieve it, and thus nature can be expected to still offer useful design direction guidance. In certain other ratios – particularly in and around the world of design at the sub-atomic level – it would appear that man is able to exceed the best that nature has evolved.

Taken together, we might imagine that it is possible to generate a table of 'state-of-the-art' ratio performance for each of the boxes in the Matrix structure. In fact this task is currently being undertaken as a part of the next stage of the research. We are guided in this work by another aspect of the TRIZ philosophy; this time the belief that systems evolve towards what is labelled an 'ideal final result' (IFR) end-state. This end-point is traditionally defined as the ability to deliver a useful function with zero-cost and zero-harm. Generally speaking the IFR is used as a theoretical design attractor rather than a design goal that is practically achievable (although Mann [2] records certain specialised examples where the IFR has been achieved). A related TRIZ idea further suggests that as systems evolve towards this attractor the number of possible design options reduces as progressively more different strategies hit their fundamental limits. Evolution, in other words, is convergent. This is illustrated conceptually in Figure 6 below.

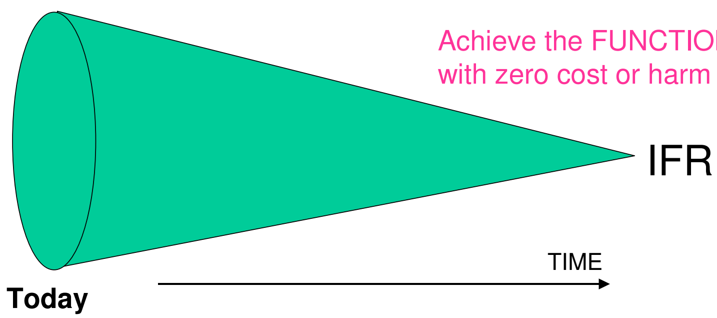

Figure 6: TRIZ-Based Global Evolution Schema

What the Figure 6 image allows us to do is compare and position natural and man-made design solutions in relation to a global optimum. So, to take a relatively simple example, in terms of thrust(force)-to-weight ratio, the IFR would consist of a ratio of infinity – i.e. the required thrust is delivered without any weight. The best of mankind's capability in terms of this ratio is typically between 1 and 2 for an overall system (state of the art aircraft is 2) or 15 for the propulsion system (gas-turbine engine). The recent emergence of so-called air-muscle actuator systems are able to achieve ratios of around 700-800. While clearly based on principles from nature, the air-muscles still fail to achieve the best of nature's capability (impulsive forces in locusts and crickets) by a considerable margin at either the propulsion mechanism or total system level.

Meanwhile, in the absence of this database of global 'best practice' of achieved ratios between conflicting parameter pairs, it is already possible to produce a version of the Contradiction Matrix combining the inventive strategies used by past and present designers and those being used by nature. Such a tool (to be published by Mann et al [7]) may not give designers guidance on which particular strategies are going to give the absolute best design outcome, but it does at the very least a) provide a systematic framework for thinking about trade-off elimination, and b) allow designers access to all of the strategies used by both man and nature to challenge those contradictions.

5. Summary, Conclusions and Future Work

The large majority of design practices across all areas of human endeavour involve strategies of trade-off and compromise. TRIZ research has shown that the most successful design solutions – the ones that deliver non-linear, disruptive advance – come from design strategies that seek to 'eliminate' those trade-offs and compromises.

The Contradiction Matrix tool provides a structure by which the best contradiction-eliminating strategies of others can be made available to others. The original Matrix was constructed by identifying 'best practice' and abstracting knowledge from it. The addition of contradiction-challenging examples from the natural world continues this philosophy. Since nature has to solve many of the same trade-offs that human designers have to work with, it is possible to combine the best of both fields in a Matrix structure featuring many of the same design parameters.

In the not too distant future, we anticipate that it will be possible to correlate the use of different inventive strategies to the effectiveness of the design solutions generated, so that in areas where nature is currently more effective (or 'ideal') than the best of man's endeavours, human designers can be guided to the inventive strategies being used by those datum-setting natural solutions.

In the meantime, and in parallel with this desire is a need to continue adding new data to the database. In human design as in nature, the drive for innovation usually emerges from an external evolutionary pressure. Considerable numbers of natural systems have evolved little in millions of years (e.g. crocodile) because there has been no pressure to evolve. A lack of pressure to evolve is equivalent to saying that there is no contradiction to be solved. The search for examples of contradiction-eliminating practice in nature thus needs to be focused on areas where such pressures exist. In practical terms this means identification and analysis of examples where an evolutionary 'arms race' is underway, or (increasingly often) in situations where nature is affected by sudden shifts in environmental conditions. The presence of a harmful effect, in other words, is a strong indicator of where we will find the best (contradiction-eliminating) design strategies in nature. To a large degree, the exact same concept applies in the human design environment.

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