TRIZ in Biology Teaching

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Introduction

As an initial part of a project aimed to bring TRIZ into biological sciences (and, of course, bring biological sciences into TRIZ!) we set a series of problems to a class of 2nd year biology students who had just had a course in the mechanical design of organisms, given as part of their degree course in Reading. The students had a half-hour introduction to TRIZ (given by JFVV), were then given a copy of the Contradiction Matrix, a list of the Inventive Principles with an abbreviated list of examples, and set to work for two hours (DM in attendance), in groups of about 8 students, to attack one of the following six problems. These problems, and solutions to which the students arrived, are presented here together with a few of our comments and suggestions.

The Nicaraguan Bull Shark

The problem . . .

At present the only shark which can re-invade fresh water is the Nicaraguan Bull Shark. Predators are therefore smaller and somewhat slower in the rivers than in the sea. Reduced availability of food (due to man's overfishing) drives shark back into fresh water. How can the fresh-water fish respond?

. . . and its resolution

In order to escape the shark, the fish must either outswim it or outsmart it. So they must be faster, or present a more difficult target, or be invisible (hide, disguise or camouflage themselves). A more risky strategy is to taste bad, be very slimy (like a hagfish) either as soon as the shark touches it, or after the shark has eaten it (a strategy suitable only for a population of fish, but not much use for individuals!) or to have poison spines.

…. and according to TRIZ:

A number of contradictions can be formulated:

Taking the 'outswim' route, the parameter the prey fish needs to improve is 'Speed'. The parameters which will tend to get worse as speed increases are most likely to be 'Energy spent', and 'Volume of Moving Object'.

Speed vs Energy spent suggests:

Anti-weight - this applies to both predator and prey, and could include making the digestive system smaller so that there is less food in the gut. But the fish then needs to feed more frequently. Another system whose weight can be reduced is the skeleton. Unfortunately the shark has adopted this strategy already!

Dynamics - leading to segmentation. Fish muscle is already segmented and it's this muscle which it uses for really fast swimming. It can also lose segments or other bits (parts of fins, for instance) if it's caught. This tends not to happen with fish, but happens with other animals as a response to predation. Common examples are brittlestars and various crabs and lobsters, which tend to drop bits off and escape whilst the predator ponders over its "catch".

Parameter changes - the skin could be made stronger or stiffer to transfer forces better. Shark do this (the skin is an "exotendon"), so perhaps the fish would also move faster if they reduced the importance of the skeleton for transmitting forces and used the skin instead. Parameter Changes (‘change the concentration or consistency’) also suggests ideas associated with making the fish slimy or in some other way difficult to catch/swallow.

Use strong oxidants - perhaps tap another or more powerful source of respiratory gas, or, in combination with Parameter Changes, perhaps suggests the manufacture and deployment of poisons.

Speed vs Volume suggests:

Pneumatics and hydraulics - there is much evidence that the shark is essentially a hydrostatic organism. This is important if the skin is to be used to transmit energy and store it elastically from one tail stroke to the next. But bony fish mostly have a swimbladder which is full of gas, so they have to conserve their volume unless they sink.. However, they could compress the body against the pressure of the gas in the swimbladder, reduce their volume and sink to the bottom to avoid predation.

Discarding & Recovering - perhaps suggests that part of the prey fish could become sacrificial - as with lizard tails.

Taking the ‘outsmart’ route, the parameter the prey fish needs to improve is ‘Adaptability’. The parameters which will tend to get worse as speed increases are most likely to be ‘Energy spent’.

Adaptability vs Energy spent suggests:

Mechanics Substitution - replace a mechanical means with sensory means - further suggestion of poisons or, perhaps, fields to counter the shark threat?

Periodic Action - suggesting that the prey fish could evolve to swim only at certain times of the day or night.

Other contradictions formulated and used by the students included:-

Productivity (thinking about use of increased production of young to outsmart the shark) **vs Energy spent** suggests:

Segmentation - the reproductive organs can be made of more (and smaller) units so that there will be many more, smaller, offspring which will give each individual a greater chance of survival. Each fish will also be a smaller and less worth-while meal for the shark, and they will be able to make greater use of the structure of the environment finding nooks and crannies in which to hide.

Universality - the prey fish can have sense organs in the skin so that they can tell when the shark is approaching. The lateral line organs already do this, but they can be proliferated, as in the shark and related fish such as catfish and the chimaera fish - the organs of Lorenzini. They are very sensitive electrical and pressure sensors.

Shape vs Speed suggests:

Mechanical vibration - it is well known that organisms tend to have locomotory organs which work at a resonant frequency. Fish probably do this, though the idea hasn't been measured or tested. It seems

to work with human walking and running, and certainly is the case for insects flying.

Area vs Harmful Factors suggests:

Colour Changes - camouflage

Two legs good

The problem . . .

In Swift's "Gulliver's Travels" the Houhenhyhms are horses which are gentle, wise, and can talk. They are the top animal. Perhaps they could evolve further and walk on two legs rather than four (shades of Orwell's "Animal Farm"). What adaptations might they develop, both in order to achieve bipedalism, and as a consequence of it?

. . . and its resolution

The main problem here is going to be stability - how can an animal keep its centre of gravity over the much smaller area where its feet contact the ground? The area can be enlarged by enlarging the feet (which is why bipedal animals such as birds, bears and humans tend to be "plantigrade", placing their feet flat on the ground, rather than digitigrade, which means walking on tiptoe like all hoofed animals. Many dinosaurs were bipedal but were never totally plantigrade, though large areas of their toes were on the ground when they walked). The advantages are that bipedalism is more efficient than quadrupedalism in terms of energy required for movement (this is an experimental result, but there is no current explanation) and that with the forelimbs free they can be adapted for other functions such as manipulation of the environment in various ways. Bipedalism is probably a requisite for the development of high intelligence. Another problem will be the strength of the legs since the hind legs will have to take rather more than twice their previous load - the fore legs of a quadruped take the high load since they have a head and neck extending forwards as well as having to support the front part of the trunk.

…. and according to TRIZ:

The conflicts identified and investigated by the students included:-

Stability vs Weight suggests:

Segmentation - which could suggest increasing the length of the toes, a very noticeable tendency in birds which tend to have their legs placed relatively far back on the body but need to keep their overall weight as low as possible. The long toes increase the area on the ground over which the centre of gravity can fall, so stability is less of a problem. Flightless birds such as the ostrich can afford to have much more robust feet. Also the weight of the body could be redistributed so that the centre of gravity is lowered.

Change of parameters - a bit more obscure. Increasing the stiffness of the foot might improve the long-toed model, but a hoof is stiff so in the absence of an increase in contact area with the ground, a more compliant hoof might be more stable. Perhaps the stiffness of the leg could be reduced by allowing it to flex, thus allowing a larger amount of control over posture and hence better balance (cf. Chimpanzees walk with bent legs). The stiffness of the backbone can be changed by putting extra curvature into it, so that it is permanently buckled (using Euler's theory to calculate its stiffness) but at a higher order than normal for a quadruped. The load-carrying capacity increases as the square of the order of buckling (double buckling carries 4 times the weight, etc). Such a modification can be effected in the lifetime of an animal, since the spine grows into its shape in response to the forces acting upon it. In the 1920s a Dutch veterinarian, Slijper, reared a goat which had been born without forelimbs. It developed a double-curvature spine like our own, purely in response to its upright stance.

Stability vs Energy suggests:

Do it in reverse - Can the animal get its stability from the environment? Perhaps through dynamic interactions (see below) or by getting support by taking to the water. This is reminiscent of Sir Alastair Hardy's ideas of the 1960s that man was more aquatic in the past.

Periodic action - allow balance to be achieved between the strides rather than when the strides are made. The feet are in contact with the ground for only a short time and can push in the proper direction to increase stability.

Stability vs Strength suggests:

Transition into a new dimension - change the shape of the body. Balance could be achieved by adding mass in some area such as the tail, to counterbalance the weight of the front end of the body. Obviously the more nearly vertical the animal can get the less it will need a counterbalance, so this transition implies a rotation of 90 degrees of the long axis of the body (the spine). This implies remodelling of the pelvis.

Prior counteraction - such as taking some of the force in tension. This can change the course of force through the structure and effectively move the position of the centre of gravity. In animals this is done by muscles but would be rather tiring. We gain some stability when standing by allowing the knee joint to go “over centre”, thus locking it in position. The back of the knee, rather than the front, is then under tension.

Dynamic interactions with the environment - hints at the possibility that in a densely wooded environment the trees can support the animal, so that it can ricochet from tree to tree and gain "balance" as a periodic action! ‘Dynamics’ can also be interpreted locally within the foot to imply that the form should be changeable according to the function being performed at any point in time.

Area vs Weight suggests:

Asymmetry - evolution of the foot geometry away from a basically ‘round’ hoof to something more like the human or bird’s foot.

Area vs Speed suggests:

Flexible Shells & Thin Films - again suggesting something like a bird type design.

Pneumatics & Hydraulics - increased use of liquids and/or air to assist in the load spreading and cushioning function. Example; human heel comprises fatty cells which act as a hydraulic cushion.

Migration

The problem . . .

The continents are drifting apart at an ever increasing rate, and islands are disappearing due to global warming. How do migrating birds cope?

. . . and its resolution

This is probably the most difficult of these six problems since flight is the most demanding method of locomotion and many migrating birds already exist on the limits of the physiological possibilities. The overall opinion of the class to this problem was that there were two main solution directions: either improve efficiency of flying or adapt by interspersing flight with swimming or resting.

It's important to realise why birds migrate. With all animals, life revolves around food and sex. The tendency is for all animals (including smaller ones such as insects) to migrate to cooler areas in summer, which keeps their environmental temperature more constant, there's usually more food available, and their offspring will be larger if reared under cooler conditions (Dyar's Law). A larger animal has advantages of strength and longevity, both of which will increase its sexual success and therefore the spread of its genes through the population.

Another consideration is that the flight speed for migration is higher than the flight speed for minimum energy usage, but it is nonetheless a particular speed. So flying faster will use up more energy per unit distance because of the increase in parasitic drag, and an increase in speed can be achieved by reducing drag. Increasing penetration (e.g. by higher wing loading) will increase energy usage. The nature of scaling of flapping flight means that there is an upper limit to the size of a bird, but that under certain conditions it can glide very efficiently (the albatross) and that smaller birds can fly far more efficiently

Conflicting requirements are the weight of the bird, its speed (drag), endurance, adaptability (the environment is changing), energy storage.

Contradictions identified and investigated by the students included:-

Duration of Action v Weight

Periodic Action - changing the frequency of wing-beat (and probably therefore, wing-size)

Combining - altering the way the birds fly in formation such that, for example, one bird flying behind another makes beneficial use of the vortices shed from the leading bird.

Duration of Action v Area

Local Quality - altering the profile of the bird feathers to induce greater lift generation efficiency (e.g. local features at wing-tips to reduce over-tip leakage). However the amount of work done by the muscles will remain constant.

Energy Spent by moving object v Adaptability

Partial or Excessive Action - again changing the frequency of the wing beat, and perhaps also combining the action with low level flight which can take advantage of energy transfer over waves, as the albatross does.

Power v Weight

Phase transitions - given enough stop-over places the bird could afford to carry less fat (the main energy storage material) and improve its power/weight ratio. Another way of looking at this is that they are *segmenting* their journey.

Porous Materials - the possibility that migrating species might reduce calcium load in their bone structure prior to migration in order to reduce weight. Seems a rather dangerous option.

Power v Productivity

Mechanical substitution - suggests the bird could fly higher where the drag is lower. But since the partial pressure of oxygen is lower at altitude it would need either to fly with less energy expenditure per unit time, or increase the absorptive area of its lungs or the oxygen-carrying capacity of its blood.

Of course, the bird could ultimately adapt by hibernating in the colder habitat. Many migratory insects do this, risking being eaten by hungry small animals or not finding a sufficiently sheltered place to overwinter.

Parameter Changes - suggests changing the way energy is stored, or, thinking about the architecture of the bird, reducing the stiffness of the system allowing more in-flight flexure and consequently less energy spent on maintaining a given shape.

Mechanical defences

The problem . . .

A species of caterpillar feeds on the leaves of a shrub. As a defence mechanism the shrub starts to develop a glassy-smooth and hardened bark. What might the caterpillar do in order to continue feeding on the plant?

. . . and its resolution

The problem is one of grip or adhesion, which resolves into force or strength. These have to be increased without compromising energy consumption, weight, durability or mobility.

Contradictions identified and investigated by the students included:-

Force v Use of Energy

Periodic Action - suggested a mechanism resembling the ribbon teeth of a snail which extended the length of the underside of the caterpillar generating a literal caterpillar track! Each tooth on the ribbon would be in contact with the tree periodically. In fact the hooked ends of the caterpillar's feet are very much like this, the track being regenerated each time the legs are swung forwards.

Another Dimension - give the caterpillar a sticky tongue, like that of a chameleon, which it can shoot out to stick on to a leaf then haul itself up. Caterpillars actually do this in reverse, dangling from the end of a silk line until they collide with another part of the plant. Alternatively the entire animal could jump from one part of the plant to another (a common solution amongst adult insects, though not many caterpillars jump). Admittedly these modes of movement are rather more random than a designer might like, but at the same time probably require much less energy than a directed mechanism and do not require the sophisticated sensory and ranging mechanisms which the glue gun would need.

Force v Convenience of Use suggests**:**

Self service - using a freely available or waste product to perform other helpful functions. The proverbial stickiness of dung, which the caterpillar produces, could modify the glass-smooth surface and make it suitably rough again. Alternatively the caterpillar can lay down a silken trail, using the adhesive properties of the silk. This is a common mechanism, especially amongst social caterpillars which lay down a path from an overnight nest area to the feeding area on the plant.

Force vs Weight suggests:

Segmentation - suggests similar ideas to the caterpillar track idea above.

Mechanical Vibration - suggests some kind of pulsed gripping action.

Force v Speed suggests:

Mechanics Substitution - 'replace a mechanical solution with a non-mechanical solution ' - a specific trigger to break out of the 'grip harder/better' and think about use of adhesion/ some form of chemical grip or possibly using some form of vacuum solution.

Dynamics - similar to mechanical vibration, but also suggesting other types of locomotion strategies involving multiple actions.

Area v Strength suggests:

Local Quality -keeping the feet the same overall size, but incorporating lots of small localised sharp protrusions. In fact many insects can walk on glassy surfaces using nothing stronger than van der Waals forces to keep them there. They have compliant hairs on their feet whose ends can conform to the surface and provide a surprisingly large area of contact. Since this area is not directly proportional to the weight (volume) of the insect, larger insects need to have disproportionately large feet.

Alternatively one could give the feet sharper ends. This makes them weaker, but is probably the equivalent of hooks which one finds commonly on insect feet.

If I ruled the World

The problem . . .

A single species of animal of about the size and longevity of Man dominates the world. It hasn't developed any mechanised form of transport but has managed to become a single interbreeding population. How *did* it do that?

. . . and its resolution

As an initial comment, none of the students calculated how long it would take a man to walk around the world, interbreeding as he went (the female of the species would tend to be less mobile - a commonly observed phenomenon. In general male gametes are many, mobile and minute; female gametes are few, fixed and fat). The answer is rather less than two years, or 15 global circumnavigations within the reproductive life of the average male. This problem also asks questions of history - how much of an interbreeding population was man world wide before the invention of mechanised transport? Probably more than many people would believe judging by the evidence from trading (look at the history of Palestine, one of the cross-roads of the World) and the distribution of gems and beads around the world, though in the absence of any information on the degree of isolation which would render a population into a reproductively separated species it is difficult to estimate how important prehistoric transhumance was.

Apart from the above, the obvious item to transport is the sperm rather than the egg (eggs tend to be heavier since they contain nutrient for the growth of the embryo. All the sperm has to carry is a few chromosomes) so that the animals would have to adopt techniques developed by plants. If the sperm is to be self-powered, then it can have problems with weight, reliability (durability) and energy which will tend to compromise distance travelled. Otherwise it can hitch a lift with another animal which might be travelling in the desired direction. This is common with diseases, when the animals are vectors, though the tendency is for the vectors to be more important for transmitting the disease from one host to another, rather than spreading the disease over large distances.

Some of the contradictions defined and investigated by the students:-

Speed vs Weight suggests:

Separation - the capsule can be degraded or used as fuel during transport, leaving the sperm intact. This could be combined with *Oxidation* since some beetles can produce an explosive mixture of phenols and super-heated steam which could project a sperm packet into the upper atmosphere.

Anti-weight - the sperm packet has wings or floats, commonly seen in marine and aerial plankton.

Weight vs Durability suggests:

Discarding and recovering - the water is separated from the sperm (i.e. the sperm is dehydrated) and the sperm rehydrated when they arrive. This will reduce the weight by an order of magnitude and has the advantages that the sperm will not need feeding and will be chemically more stable. This is a common mechanism in nature known as cryptobiosis or "hidden life" and allows simple organisms to be distributed over large distances and survive for long times. Thus reliability is served.

Porous materials - a way of reducing the weight of the container so that it will float.

Reliability vs Harmful factors suggests:

Cheapness - produce many more sperm than are required. This seems to be one of the main strategies of sperm throughout nature.

Intermediary - repeat of the suggestion that another animal should provide the transport. It may need hooks or glue (a sucker) so that it can adhere to a fish or bird. With plant seeds it is sometimes necessary for them to be eaten by the animal which transports it, but this is not likely to be relevant for sperm.

Problems with grass

The problem . . .

A gene escapes from a genetically modified plant into grass, where it raises the amount of silica from 10% to 50%. How do grazing animals cope with this?

. . . and its resolution

The silica in the grass is very hard and tends to wear the teeth down. But it is particulate and so probably doesn't affect the strength of the grass. Whether it affects the nutritional quality of the grass is a moot point, since the mechanical heterogeneity may actually help to break the plant cells open, releasing more nutrient with less chewing effort. But this could also lead to too high a rate of release of nutrient from the grass which could in turn lead to bloat due to the production of too much fermentation methane in the gut. In severe cases this can kill the animal. Cows and other ruminants tend to digest the grass fairly thoroughly;

but small mammals, insects, birds and fish can't "chew" so well, and many of the plant cells traverse the gut without being broken open. So a higher content of silica may be an advantage under some circumstances. Teeth for chewing grass tend to be very highly ridged and move across each other, so the action is a sort of reciprocating grinding.

The areas of conflict are therefore likely to be with the shape and material of the teeth.

Shape vs Area suggests:

Merging - the teeth could be merged to make one large tooth. This is rather like the solution achieved by the elephant, which has only one very large tooth functional on each side of its jaw at any one time. As that tooth is worn down it is replaced by the next one, so it has the same number of teeth that we have, but separated in time. This solution therefore includes elements of *Discarding* and *Prior action* or *Segmentation*.

Discarding and recovering - also used in molluscs (snails, slugs, octopus, etc) where the teeth are produced in a long ribbon (the radula). As the teeth at the front are worn away they are replaced by new ones from behind. Another strategy, used by the rabbit, is to eat the partly digested faeces and subject them to the action of the gut enzymes for a second time. Functionally this doubles the length of the gut, but increases the time taken for digestion.

Prior action - many animals (especially insects) void enzymes on to their food so that it is partly, or totally, digested when they eat it or suck it in. Perhaps an enzyme (which could be quite severe in action) could be voided over the plant to disrupt the silica.

Shape vs Volume suggests:

Asymmetry - already apparent in teeth of herbivores, where the teeth have complementary shaped surfaces which are ridged to provide severe shearing forces.

Blessing in disguise - already touched upon. The silica can increase the ease with which the cells are broken open and their contents released. The silica could also be embedded in a soft surface of the tooth, giving a hard abrasive surface. A similar mechanism occurs with aluminium pistons in steel liners. Metal swarf is embedded in the aluminium and wears down the harder material. The animal could also adapt to the silica, metabolise it and incorporate it into the growing teeth.

Comments

After two hours the students wrote their reports from which this selective summary has been prepared. For the first time in the course I had to turn them out of the laboratory, so it was an immensely popular approach to biology. The students also made comments on the approach, pointing out that many of their solutions appeared to be available in nature already (though this may indicate that the students were not able to escape their biological environs). One of the students reported she was disbelieving of TRIZ when she started the exercise, as it appeared that if she thought hard enough she could apply all the Inventive Principles to any particular problem. But this, she thought, is probably because biological problems can have numerous solutions, whereas other areas of science have more defined solutions. TRIZ is an excellent was to promote thinking. It definitely broadens the picture and suggests novel solutions. Another student complained that there were too many solutions! Some students pointed out that there are gaps in the contradiction matrix for some of the contradictions which they had identified. We said that this shows that engineering hadn't thought of ways of overcoming these problems, and showed the need for integrating biology into TRIZ!

The 40 Inventive Principles were used to good effect during the experiment as a systematic brainstorming tool. Several groups started the exercise in fact as a conventional brainstorming exercise, and then subsequently found that when they started using the Principles not only did the process become much more systematic, but a significant number of additional solution possibilities were generated.

At no time in the experiment did it emerge that nature knew any solutions that did not fit into the structure provided by the 40 Principles. On the other hand the problems *were* carefully chosen to illustrate rather than test the workings of TRIZ!