# Beetles, Chains And Radar Plots

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This case study is inspired by recent work reported in Professional Engineering (Reference 1). The report describes the use of ideas evolved by the bombardier beetle to help solve the problem of engine re-light in gas-turbines. While interesting as a case of biomimetics in action, the story of the Bombardier beetle (Figure 1) turns out to be much more interesting from several perspectives.

**Figure 1: Bombardier Beetle**

It seems the beetle has been at the centre of a protracted argument between the creationist and evolutionist communities. The root of the disagreement concerns the remarkable predator repelling strategies employed by the beetle.

Reference 2 provides a fascinating description not just of the beetle's defence mechanism, but also a compelling hypothesis of how the beetle could possibly have evolved such a sophisticated design solution naturally. It is that article that forms much of the basis for this one.

Rather than getting into the dangerous waters of creation-versus-evolution argument, and whether Reference 2 is in any event correct or not, the case study makes an excellent example of several phenomena that help in the wider understanding of a number of TRIZ ideas. Specifically, the themes of this article, then, are as follows:-

1) To illustrate how the evolution of systems occurs through a cyclical process in which contradictions successively emerge and then become eliminated, so that over time a chain of contradictions emerges.
2) To illustrate the progressive exhaustion of evolutionary potential in systems as they evolve over time.
3) To illustrate the importance of external tensions as the primary driver of evolution – with in this case the 'external tension' taking the form of an evolutionary 'arms-race'

We begin the discussion with a brief description of the amazing defence strategy used by the beetle.

## The Bombardier Beetle

Although there are over 500 species of Bombardier beetle, the main four tribes of interest here are the Brachinini, Paussini, Ozaenini, and Metriini ground beetles (Reference 3).

The beetles earn their name from their ability to defend themselves against predators by firing a mixture of boiling-hot toxic chemicals from special glands in their posterior. In at least one of the species, this chemical spray takes the form of a pulsed jet. This is the solution currently being investigated in the Reference 1 research (see also Reference 4).

The mechanism of their spray works something like this: Secretory cells produce hydroquinones and hydrogen peroxide (and perhaps other chemicals, depending on the species), which collect in a reservoir. The reservoir opens through a muscle-controlled valve onto a thick-walled reaction chamber. This chamber is lined with cells that secrete catalases and peroxidases. When the contents of the reservoir are forced into the reaction chamber, the catalases and peroxidases rapidly break down the hydrogen peroxide and catalyze the oxidation of the hydroquinones into p-quinones. These reactions release free oxygen and generate enough heat to bring the mixture to the boiling point and vaporize about a fifth of it. Under pressure of the released gasses, the valve is forced closed, and the chemicals are expelled explosively through openings at the tip of the abdomen (Reference 3, 5 and 6). Figure 2 (from Reference 7) illustrates a sequence of photographs showing the process in action.

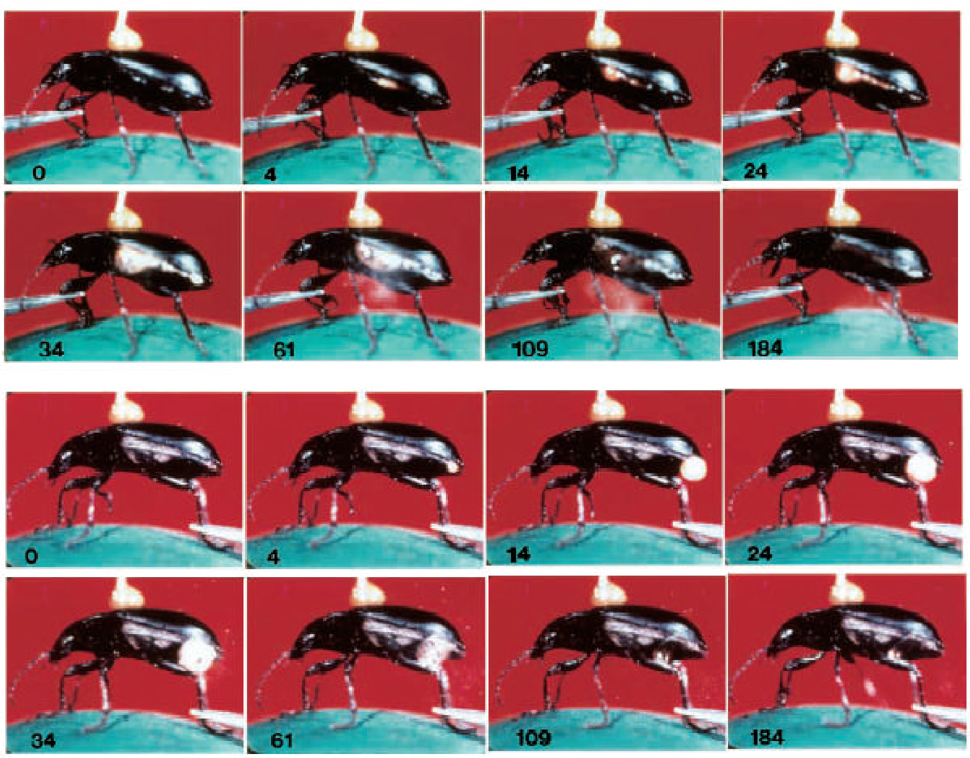



**Figure 2: Bombardier Beetle – Defence Mechanism**

The main thrust of the creationist argument regarding the Bombardier is that it could not be possible for natural evolution processes to produce such a complex and sophisticated solution. The main thesis of Reference 2, on the other hand, is that evolution of such a system is in fact highly possible. The Reference 2 makes the case for evolution by highlighting a chain of 15 stages of incremental evolution steps that could have lead to the solution now used by the beetle.

Whether or not the proposed sequence of evolution turns out to be actually correct or not, it serves as a wonderful example of evolution as a process of contradiction emergence and resolution. What we shall do in the next section is explore the proposed evolution stages through the lens of contradictions and use of Inventive Principles. The format we shall use is to first take each stage proposed by Isaak, identify how that stage jump might have occurred, and then see how the strategy used by the beetle compares to what the TRIZ methodology would have recommended.

Isaak's text is in italics. All other text is the 'TRIZ perspective' on the story.

*1) Quinones are produced by epidermal cells for tanning the cuticle. This exists commonly in arthropods (Reference 8).*

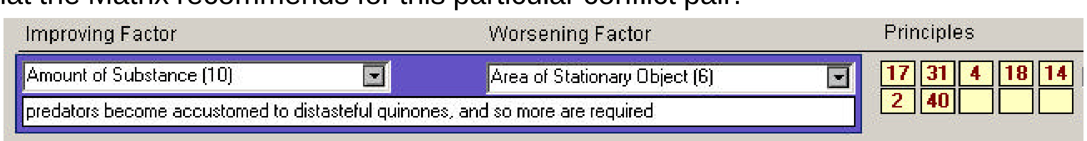
During this early evolution phase, a new functional requirement 'tanning' emerges. The beetle evolves an ability to deliver that function. No contradiction present at this stage in the evolution. We might see this as a stage in which **function** first emerges.

*2) Some of the quinones don't get used up, but sit on the epidermis, making the arthropod distasteful. (Quinones are used as defensive secretions in a variety of modern arthropods, from beetles to millipedes (Reference 9).*

Still no real contradiction; the functional solution to the cuticle tanning process also serves an additional defensive function and hence the beetle begins to deliver increasing amounts of the quinine. This represents a phase of function increase.

*3) Small invaginations develop in the epidermis between sclerites (plates of cuticle). By wiggling, the insect can squeeze more quinones onto its surface when they're needed.*

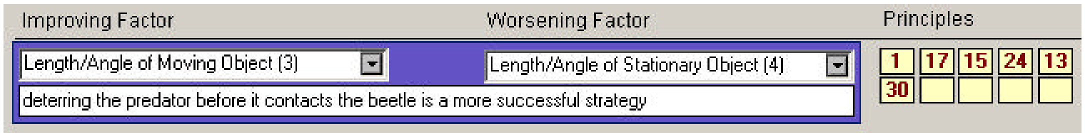
Now a contradiction begins to emerge – predators become accustomed to distasteful quinones, and so more are required. An evolutionary 'arms race' begins between predator and prey. The CONTRADICTION - amount of substance versus available surface area, strategy used by beetle: 17, another dimension)
What the Matrix recommends for this particular conflict pair:




*4) The invaginations deepen. Muscles are moved around slightly, allowing them to help expel the quinones from some of them. (Many ants have glands similar to this near the end of their abdomen (Reference 10).*

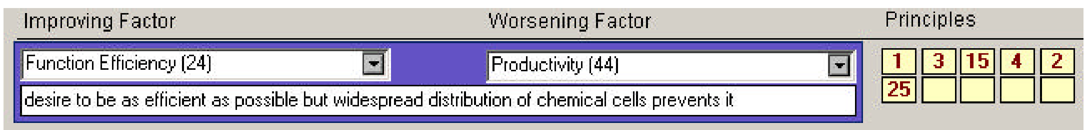
The arms race moves to another phase. Beetles capable of deterring the predator before it contacts the beetle are more successful than those that cannot. The CONTRADICTION

- distance from prey versus distance that quinine is from the beetle, strategies used: 17, Another Dimension, 30, Thin & Flexible, 15, Dynamics)
What the Matrix recommends for this particular conflict pair:



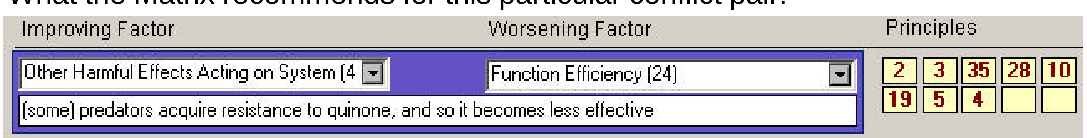

*5) A pair of the invaginations (now reservoirs) become so deep that the others are inconsequential by comparison. Those gradually revert to the original epidermis.*

In this stage of the evolution, it seems that beetles that store their quinones in special regions rather than in many are conferred some form of evolutionary advantage. Possible CONTRADICTION (although it is not immediately obvious from Isaak's description) – function efficiency versus productivity; strategy used: Principle 2, Taking Out.
What the Matrix recommends for this particular conflict pair:



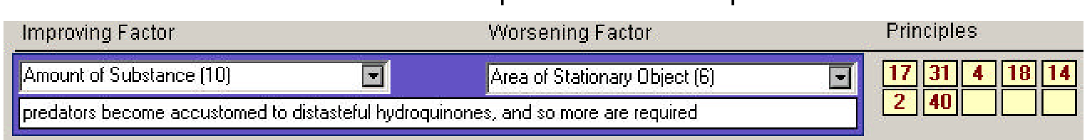

*6) In various insects, different defensive chemicals besides quinones appear. (See Reference 9 for a review.) This helps those insects defend against predators which have evolved resistance to quinones. One of the new defensive chemicals is hydroquinone.*

Another phase in the arms-race begins as (some) predators acquire resistance to quinone, so making it less effective as a defence agent. The CONTRADICTION - harmful factors acting on system versus function efficiency, strategies used: 35, Parameter Change, 5, Merging.
What the Matrix recommends for this particular conflict pair:



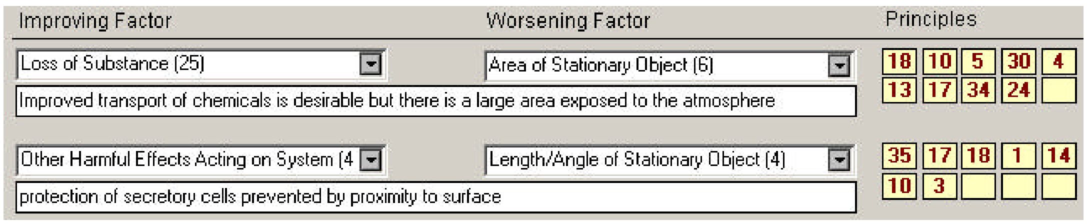

*7) Cells that secrete the hydroquinones develop in multiple layers over part of the reservoir, allowing more hydroquinones to be produced. Channels between cells allow hydroquinones from all layers to reach the reservoir.*

Arms race – predators become accustomed to distasteful hydroquinones, and so more are required: CONTRADICTION - amount of substance versus available area, strategy used: 17, Another Dimension – one already used in an earlier evolutionary phase.
What the Matrix recommends for this particular conflict pair:



*8) The channels become a duct, specialized for transporting the chemicals. The secretory cells withdraw from the reservoir surface, ultimately becoming a separate organ.*
*This stage -- secretory glands connected by ducts to reservoirs -- exists in many beetles. The particular configuration of glands and reservoirs that bombardier beetles have is common to the other beetles in their suborder (Reference 11).*

Beetles capable of transporting the chemicals more efficiently and by moving the secretory cells together and to a more protected position have an advantage over ones that don't, and so are more likely to survive. CONTRADICTIONS: loss of substance versus area (exposed to the atmosphere) and harmful factors acting on system versus proximity to surface (length), strategy used: 31, Holes, 17 Another Dimension, 5 Merging.
What the Matrix recommends for these particular conflict pairs:

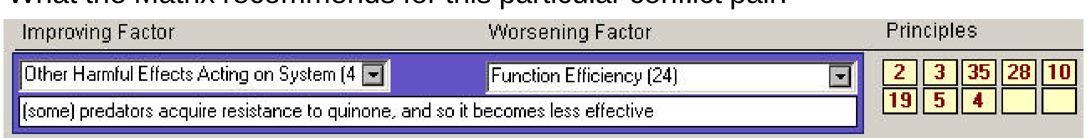



*9) Muscles adapt which close off the reservoir, thus preventing the chemicals from leaking out when they're not needed.*

Beetles capable of preserving chemicals better than others are more likely to survive and hence eventually come to dominate. CONTRADICTION – the reservoir needs to be open and closed. Strategy used by the beetle: Principles 15, Dynamics, and 35, Parameter Changes (35C; change the degree of flexibility)
TRIZ recommendation – separate the contradiction in time and on condition – two most commonly used strategies to realize these two effects are Principles 35 and 15.

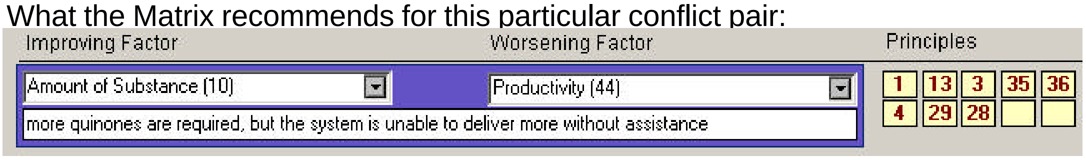
*10) Hydrogen peroxide, which is a common by-product of cellular metabolism, becomes mixed with the hydroquinones. The two react slowly, so a mixture of quinones and hydroquinones get used for defense.*

No obvious contradiction in this desciption, but a clear jump along the Mono-Bi-Poly(Various) trend of evolution. We may hypothesise that there is a similar jump as happened in evolutionary Stage 6 – where, as predators become accustomed to existing defence mechanisms, those beetles that are able to produce alternative chemical formulations have an evolutionary advantage. Contradiction - harmful factors acting on system versus function efficiency; strategies used: 35, Parameter Change, 5, Merging.
What the Matrix recommends for this particular conflict pair:



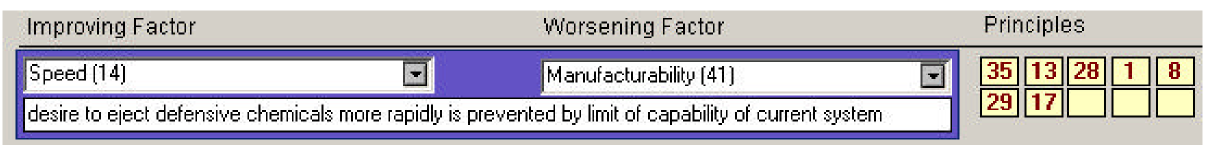

*11) Cells secreting a small amount of catalases and peroxidases appear along the output passage of the reservoir, outside the valve which closes it off from the outside. These ensure that more quinones appear in the defensive secretions. Catalases exist in almost* *all cells, and peroxidases are also common in plants, animals, and bacteria, so those chemicals needn't be developed from scratch but merely concentrated in one location.*

Beetles that are able to produce and focus chemicals that enable the production of more quinones are conferred an evolutionary advantage over those that don't.
CONTRADICTION – amount of substance (quinone) versus productivity (limit); strategy used: 3, Local Quality.
What the Matrix recommends for this particular conflict pair:



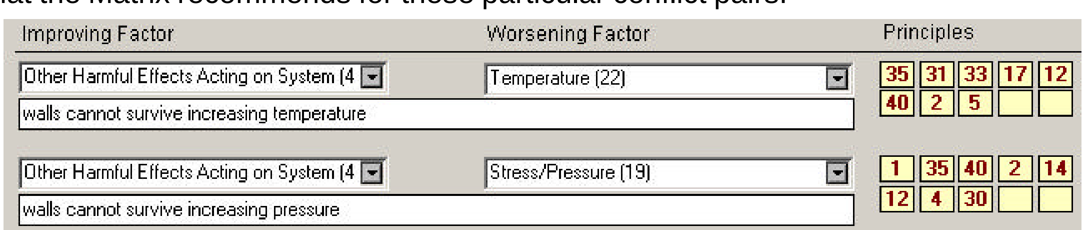

*12) More catalases and peroxidases are produced, so the discharge is warmer and is expelled faster by the oxygen generated by the reaction. The beetle Metrius contractus provides an example of a bombardier beetle which produces a foamy discharge, not jets, from its reaction chambers. The bubbling of the foam produces a fine mist (Reference 7).*

Again, beetles that are able to deploy their defensive chemicals more effectively have an evolutionary advantage over others. The predator-prey arms-race shifts to another level as the beetle becomes able to eject its chemical discharge more rapidly. CONTRADICTION – speed versus the limited capability of the current system; strategy used: 35 Parameter Changes (35B, 'change in concentration or consistency', 35A, 'change physical state').
What the Matrix recommends for these particular conflict pairs:




*13) The walls of that part of the output passage become firmer, allowing them to better withstand the heat and pressure generated by the reaction.*

A mini-chain of conflicts are resolved at this stage; beetles that are able to withstand higher temperatures and pressures can in turn generate chemicals at higher temperatures and pressures, which in turn enable greater defensive capability. Specific CONTRADICTION: Harmful factors acting on system versus temperature and pressure. Strategy used – 35C, 'change the degree of flexibility'.
What the Matrix recommends for these particular conflict pairs:




*14) Still more catalases and peroxidases are produced, and the walls toughen and shape into a reaction chamber. Gradually they become the mechanism of today's bombardier beetles.*

Beetles that are capable of delivering more defensive chemicals, at higher temperatures and in a more powerful jet have a stronger chance of survival, and so an evolutionary advantage develops. CONTRADICTION – function efficiency versus speed and temperature; strategies used: 35, Parameter Change, 31, Holes.
What the Matrix recommends for these particular conflict pairs:

| Improving Factor | Worsening Factor | Principles |
|---|---|---|
| Function Efficiency (24) | Temperature (22) | 19, 35, 3, 31, 28, 21, 37, 24 |
| stronger jets are beneficial but are limited by ability to withstand temperature | | |
| Function Efficiency (24) | Speed (14) | 3, 4, 15, 30, 29, 28, 13 |
| stronger jets are required but are limited by limitations in jet expulsion speed | | |

*15) The tip of the beetle's abdomen becomes somewhat elongated and more flexible, allowing the beetle to aim its discharge in various directions.*

The arms race again moves on a stage when beetles develop a capability to direct the jet of defensive chemicals. This is important since predators can appear from many different directions and the beetle cannot always turn its body quickly enough: CONTRADICTION - length (direction) of moving object versus speed, strategy used: 15 Dynamics, 17, Another Dimension)
What the Matrix recommends for these particular conflict pairs:

| Improving Factor | Worsening Factor | Principles |
|---|---|---|
| Length/Angle of Moving Object (3) | Speed (14) | 14, 1, 13, 4, 17, 12, 4, 3 |
| predators can appear from different directions and the beetle cannot always turn its body quickly enough | | |

*16) Some species of the Bombardier Beetle develop an ability to pulse the flow of defensive chemicals ejected from the tip of the abdomen (Reference 4). (NB this 16$^{th}$ stage added to the 15$^{th}$ described by Isaak in his paper)*

The A possible hypothesis at this stage, based on the reasons why other systems shift from a continuous to a pulsed system is that fluids can be projected further and perform their function more effectively when they reach their destination. Possible CONTRADICTION – distance versus function efficiency; strategy used: 19 Periodic Action.
What the Matrix recommends for these particular conflict pairs:

| Improving Factor | Worsening Factor | Principles |
|---|---|---|
| Length/Angle of Moving Object (3) | Function Efficiency (24) | 17, 35, 19, 3, 4, 1, 13, 28 |
| desire to project greater distances conflicts with effective use of chemicals when they reach target | | |

We will discuss some of the effects and implications of this analysis in the discussion section at the end of the article. Before we do that, it is also useful to examine the evolution of the beetle from the evolutionary potential perspective:

## Evolution Potential Analysis

Another of the things we can do with Isaak's proposed evolutionary sequence for the Bombardier Beetle is view the story through the lens of the trends of evolution and the evolutionary potential plotting method (Reference 12). Figure 3 illustrates an evolutionary potential radar plot showing the evolutionary progress of the Beetle's defence mechanism from its early stages (orange) – Step 2 in Isaak's sequence – to its current state (blue). As is common to human-made systems, the Figure shows how evolutionary potential gradually becomes used up as systems evolve.

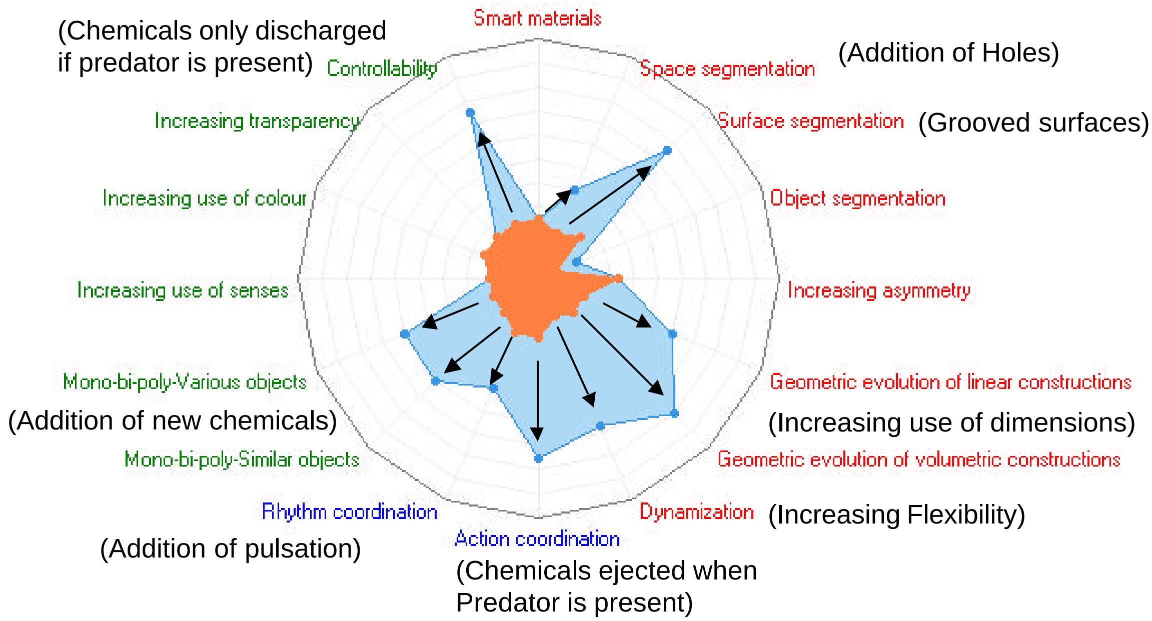



**Figure 3: Evolution of the Bombardier Beetle Defence Mechanism In Evolutionary Potential Terms**

Without wishing to suggest that there is any kind of drive towards some kind of 'Ideal Final Result' in the beetle, it does seem clear that the general rule that successful innovations occur when things travel in the direction towards the perimeter of the p lot is also relevant in this biological instance too.

## Discussion

Biological evolution contains at least some elements of random mutation. We might think of such a mechanism as the 'creativity' engine that enables biological systems to solve problems. In all likelihood the vast majority of such mutations will be unsuccessful in evolutionary survivability terms. Some, on the other hand will lead to success, and it is those that we can observe in the chain of contradictions that may have lead to today's Bombardier Beetle. As suggested by Figure 4 below, it seems plausible that the Bombardier Beetle has evolved as just one path out of many millions of possible alternative paths. It is not our intention here to get into discussions about the details of such mechanisms, but rather to focus on the idea of contradictions emerging and being resolved throughout the evolution of the Beetle, and the further idea of Inventive Principles being used to achieve the resolution.

Each stage along the evolution path projected in Figure 4 represents a successful mutation, while all of the other arrows represent some of the many mutations that failed to deliver a more successful design (note: not all of Isaak's evolution steps have been included in the picture in order to maintain clarity of the mutation/advance idea).

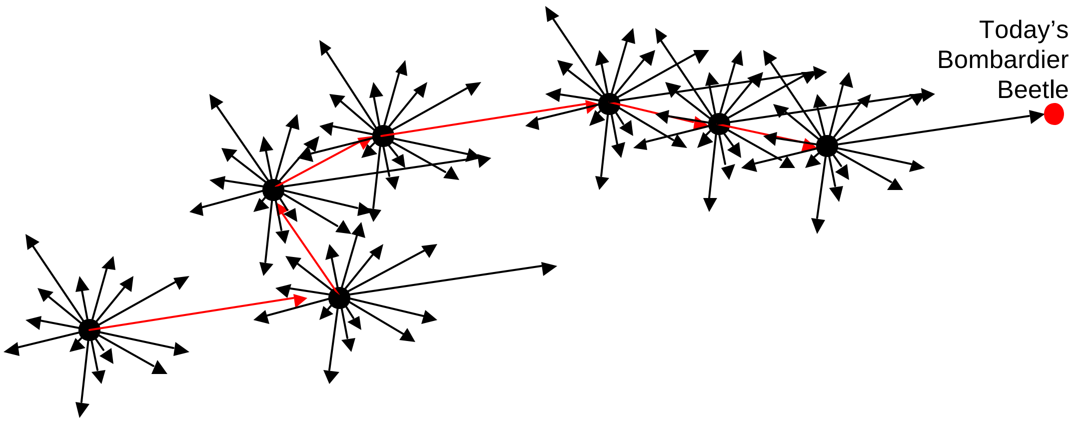



**Figure 4: Bombardier Beetle – One Path Of Many Possible Evolution Paths**

Looking at all of the evolutionary 'jumps' made by the Beetle it appears clear that only a relatively few of the Inventive Principles have been utilized. A closer examination of the suggested evolutionary history reveals a sequence of Principles as follows:-

1) no contradiction
2) no contradiction
3) Principle 17
4) Principles 15, 17, 30
5) Principle 2
6) Principles 5, 35
7) Principle 17
8) Principles 5, 17, 31
9) Principles 15, 35
10) Principles 5, 35
11) Principle 3
12) Principle 35
13) Principle 35
14) Principle 31, 35
15) Principles 15, 17
16) Principle 19

Thus over the suggested evolutionary history of the beetle, 7 of the 40 Principles have been used. Separation and merging strategies (Principles 2 and 5) are commonly used in biological systems (Reference 13). All of the other Principles used appear to be ones that can occur through a gradual rather than one-giant-leap process. Thus, to take one example, it is possible to imagine the gradual deepening of the invaginations in Evolutionary Step 3, over successive generations of beetle. In the same way, increases in length, flexibility, development of localized geometric features are all things that can occur gradually.

Although it is not the purpose of this article to try and match what the Bombardier Beetle might have done compared to what the new Contradiction Matrix (Reference 14) would suggest, it is interesting to note that 21 of the 23 uses of the Principles are predicted by the Matrix. The original Matrix would have suggested only 8 of the 23.

More important to distill from the case study is the idea of the evolutionary arms-race. The Beetle is unlikely to have evolved in the way that it has without some incentive to do so. That incentive comes in the form of predators; a successful predator may completely wipe-out the Beetle population, and so in this situation the beetle has a real 'incentive' to develop better survival capabilities. Conversely, if the Beetle develops strategies that make it invulnerable, then the predators will be in danger of being wiped out, and thus the arms race swings in the other direction. As suggested by Figure 5, the Beetle is only likely to evolve to other forms at those times in evolutionary history where they have had a disadvantage over the predators, or, in other words, when an evolutionary driving pressure has been present.

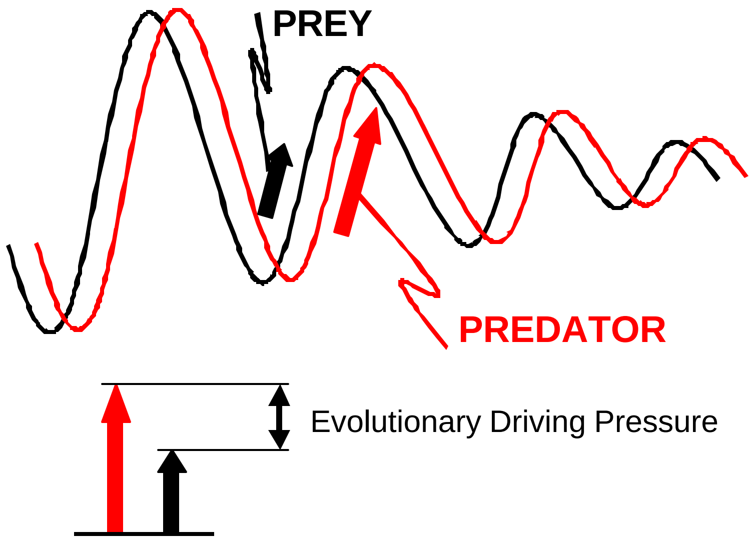



**Figure 5: Evolutionary Driving Pressures Drive Arms-Races**

The evolutionary potential analysis recorded in Figure 4 suggests that there is still a considerable amount of untapped potential in terms of the evolutionary possibilities of the beetle. This may suggest that there is still plenty of opportunity for the Beetle to continue successfully competing against its predators as the arms-race advances into the future.

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