

Exploring Natural Strategies for Bio-Inspired Fault Adaptive Systems Design

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ABSTRACT

Fault adaptive design seeks to find the principles and properties that enable robustness, reliability and resilience to implement those features into engineering products. In nature, this characteristic of adaptability is the fundamental trait that enables survival. Utilizing adaption strategy is a new area of research exploration for bio-inspired design. In this paper we introduce a tool for bio-inspired design for fault adaption. Further we discuss insights from using this tool in a undergraduate design experiment. The goal of the tool is to assist designers to develop fault adaptive behaviors in engineering systems using nature as inspiration. This tool is organized as a binary tree where branches that represent the specific details of how an organism achieves an adaptive behavior or characteristic. Results from an initial study indicate, for the specific challenge of designing fault adaption into a system, a strategy based method can provide designers with innovative analogies and help provide the details needed to bridge the gap between analogy and engineering implementation.

1 Introduction

In most biologically inspired design methods and tools, the objective is to identify natural functions, structures, or principles and discover analogies to implement those in engineered systems and products. Research in this field demonstrates that nature can be a useful library for engineering design. However, existing methods are not focused on the specific challenge of adapting to an internal fault or an external disturbance. Specifically, adaption in nature requires a series of behaviors that are not easily captured by formalisms that focus on structure, function, or underlying principles. In this paper we present a novel approach to characterizing adaptive strategies observed in nature and utilize those strategies as inspiration for adaptive system design.

We define an adaptive engineered system as a system that exhibits some set of behaviors or properties that reduce the impact of adverse events such that the system continues to provide value to stakeholders after an adverse event. This

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definition is used so that strategies such as building in reliability, designing reconfigurable options, and enabling resiliency can be compared as design alternatives. Often times, complex systems implement multiple strategies to reduce the impact of adverse events. By characterizing these approaches as strategies, we identify numerous analogous behaviors and properties in natural organisms.

We classify these observed natural strategies as a series of alternatives, enabling the creation of a binary tree structure. We call this binary tree the Strategy Mapping Tool. When the adaptive strategies in nature are structured in this way, it enables engineers to think of novel ways to mitigate the impact of failures in engineered systems. Because this type of biologically inspired design focuses on strategy and is applied to avoiding failure (or the consequence of failure) it results in different types of inspiration in the designers who use it. In order to understand how this approach differs, we conducted a case study where a fault-adaptive design is required. The results of this case study are qualitative. They illustrate that designers using strategy-based analogies have unique insights beyond what is gained by function-based analogy searches.

2 Background

2.1 Biologically-Inspired Design

Bio-inspired design (BID) is an emerging research area in engineering design, computing, and biology that seeks to systematically mine biological knowledge to solve existing design problems. Design researchers have identified successful ways to implement biologically inspired design in terms of the design process [1, 2, 3], analogs storage and representation [4, 5], and recording successful implementation [6, 7, 8, 9]. BID research is active across many areas and has achieved important and meaningful results. Further, in materials design and research, biomimicry has led to novel materials and products [10, 11].

Existing BID tools can be broadly divided into two categories, functional and principle. Functional design tools search the functions (actions which transform energy, material and information flows) of natural analogs to try and match those to problems in the design world. These methods may modify the analog or the problem via abstraction to try and bridge the gap between the different mechanisms used in nature and in mechanical design. Examples include the 4-Box method [12] and Biocards [13]. The second group searches principles seen in those analogs. For example Bio-Triz [14] and AskNature [15] record underlying principles seen in nature and offer these as analogies to inspire problem solving.

2.2 Engineering Strategies for Handling Adverse Events

It is common practice to implement strategies of reliability, resiliency, and occasionally reconfigurability in the design of systems. To do this, a variety of support tools have been developed to assess the impact of adverse events. For example, a function failure modes and effects analysis is useful to guide detailed subsystem and control system design [16, 17]. In some industries, quantitative analysis methods such as event and fault trees and probabilistic risk analysis are used to assess the system performance [18]. In the research community, methods based on systems theory [19] and functional modeling [20] have been used to explore and validate design concepts with respect to potential hazards.

In general, guidance on *how* to design systems that continue to provide value in spite of adverse events is found in

manuals of best practices for reliability and safety engineering [21]. As the objective of this work is to provide potential strategies observed in nature as analogs for designing adaptive systems, it is important to classify common engineering strategies. As in most fields, there is some disagreement in terms and definitions. However, we have chosen to classify the following engineering strategies based on how each addresses the potentiality or impact of adverse events. This perspective is useful as it is similar to the perspective we used to classify natural adaption strategies. In this work, we will use the following classification and definitions for engineering strategies:

1. **Over-Specification:** This general approach modifies component or system parameters (such as dimensions) to reduce the likelihood of experiencing a failure mode or mitigating its impact. The specific strategies that fall under this category focus on faults as a potentiality.

1.1. **Design Envelops:** This strategy includes using margins or factors of safety to cope with potentially fault causing variations. Margins and factors of safety are rough ways to manage uncertainty by making a component or system more resistant towards its most likely failure modes [22]. Though computational support systems exist for analyzing these margins, typically it is left to human designers to define them [23].

1.2. **Robustness:** This strategy utilizes methods which reduce the overall variation of system performance that results from variations on input parameters. Ideally, robustness guarantees the maintenance of certain desired characteristics despite fluctuations in the behavior of constituent components or environment [24, 25]. The Taguchi Method is one of the most well recognized approaches for assessing the variability of the system. The objective is to select the best combination of control parameters so that the product or process is most robust with respect to noise factors [26].

1.3. **Reliability:** This strategy focuses on controlling the probabilities of faults or other adverse events. Reliability is the ability of a system to function under designated operating conditions for a set period of time or number of cycles. Reliability engineering focuses on probabilistic assurance of performance of a system under certain circumstances [27].

1.4. **Resiliency:** This strategy expands on the concept of reliability but adds to the analysis an assessment of the systems ability to recover should the fault or adverse event occur. Resilience is the ability of a system to return to its original (or desired) state after being disturbed [28, 29, 30, 31].

2. **Redundancy:** This general classification of strategies uses multiple components, subsystems, or methods to achieve a particular functionality. It is similar to the over-specification approach but from a system-level perspective. Redundancy involves the strategic and selective use of resources and generally includes a strong focus on the control schema needed to achieve it. Redundancy increases the flexibility of a system usually with a cost of carrying more resources [32, 33]. However, redundant systems are inherently more complex and can occasionally reduce over-all system reliability [34].

2.1. **Reconfigurable:** This strategy includes building in capability to a system to handle new objectives and customer requirements [35, 36, 37, 38]. This can also be considered a type of flexibility.

2.2. **Parallel:** This strategy refers to having two or more system elements performing the same function, such that a loss of one (or a few) does not result in a loss at the system level. This strategy is distinct from the following strategy in that systems operate multiple alternatives at the same time [39]. **Stand-By:** This strategy refers to having some system components or resources available should a fault or adverse event occur in the primary system. Data-backups and spare

tires are common examples of included stand-by redundancy.

2.2.1. **Maintenance:** This general approach of strategies is focused on handling faults after they occur or are about to occur. It is the process of maintaining equipment in its operational state either by preventing its transition to a failed state or by restoring it to an operational state following a failure [40].

2.3. **Scheduled:** This strategy is sometimes called preventive maintenance or planned maintenance. Scheduled maintenance's timing and scope are both known and planned in advance. Furthermore, all parts and equipment are subjected to regular inspection scheduled to detect performance or safety problems and to ensure that all items receive necessary maintenance [40].

2.4. **Condition-Based:** This is a type of corrective maintenance. It includes aspects of monitoring, warning, and providing planned actions in response to conditions [40]. An extension of this is the use of prognostics health management systems. That is, the use of models and heuristics that predict the remaining useful life of a component or subsystem such that maintenance can be optimally implemented [41, 42].

These engineering strategy classifications are broad and occasionally overlap. However, they provide a broad lens to interpret the strategies observed in nature. In section 5.1 we will discuss the effect of viewing natural strategies through this reliability and safety engineering perspective.

2.3 Challenge to Implementing Bio-Inspired Design

Several challenges of implementing bio-inspired design relate to the underlying differences between natural and engineered systems [2]. First, is the difference between the scale of nature and engineering problems. Often the mechanisms that produce potentially inspirational behaviors in nature work on a microscopic level while engineering problems are generally at a macroscopic level. A second major challenge is that nature uses a fundamentally different set of mechanisms than engineering. Nature uses biochemical cellular mechanisms while engineers typically use electro-mechanical mechanisms to solve problems. The work presented here attempts to address these two challenges by taking the specific circumstances out of the problem, allowing the designer to use principles seen at the microscopic level for macroscopic applications. For example, the specific solution of using white blood cells to find and eliminate pathogens may not be directly applicable. However, there may be analogs in how those cells are created, search, and operate that engineers can use.

Finally, research in BID related to representing, searching and using analogs typically focuses on finding a set of natural organisms that are associated with specific search terms. This situates them in the design stage after some functional decisions have been made and specific solutions are developed. Thus the focus is often on improving creativity through BID [43]. However, adaptation strategies in nature are complex interactions of events that form a path that moves an organism from one state to another. Further, we propose it is the options along this path that are useful for strategy-based BID. Therefore, the Strategy Mapping Tool presented in this work is intended to show not just the final analogs in nature but utilize the path and options as a means for the designer to explore various potential strategies.

3 Theoretical Foundation

Before describing the theoretical foundation, three terms of importance need to be addressed: adaption, strategy, and analog. For the purposes of this research we define these as:

Adaption: Response to an internal or external event, allowing for a modification of the system or organism's goals.

Strategy: The properties and sets of behaviors that mitigate the impact of adverse events.

Analog: A particular example of the execution of a strategy observed in natural organisms.

The rationale for these definitions will be further described in the following section.

3.1 Differences with the Biological Sciences Study of Adaption

In this work, we propose that we can look at existing natural systems and categorize the adaption strategy seen as a path made from selecting between alternatives. However, this is not consistent with our current understanding of how organisms actually achieve those adaptive behaviors. The mechanisms of adaption are evolutionary and a particular organism does not *choose* to execute a particular adaption strategy. Rather, in a population, context-specific and dynamic natural selection processes eliminate unsuccessful behaviors.

In this work we look at the current adaption behaviors (analog) observed in nature and apply a classification schema to those behaviors. This classification approach is focused on grouping or distinguishing analogs using binary alternatives. The specific points of difference are based on the observation of differences between analogs. This leads to a schema of alternatives that is represented in the Strategy Mapping tool discussed below. It is a useful fiction to describe these as strategies an organism uses because, while the organism makes no choices with respect to adaption, designers using their behavior for inspiration can make choices between alternatives.

Further, in this work we focus on the attribute of *adaption*. From an engineering perspective, we define it as: *the characteristic of a system or product to continue to provide value after experiencing internal or external undesired events*. This distinguishes this property from the similar term *resilient*. Resilient systems or products have a means of recovery from adverse events back to original operating behavior. However, this term does not account for the system changing operational goals, which is a behavior observed in natural organisms.

3.2 Structuring Adaptive Strategies as a Decision Tree

Decision tree analysis is a convenient way to analyze project decisions when having more than one uncertainty [44]. By classifying adaption strategies in a binary tree structure, we intend to reflect the alternatives available to a designer in the conceptual stage. This decision tree structure provides an intuitive means of developing strategies and identifying analogs that offer flexibility and enables the evaluation of various strategies.

The Strategy Mapping tool presented in this work is a binary decision tree with different paths or set of nodes that lead to a solution. The set of decisions that constitutes a single route through the tree represent the strategy, and the solution or last node at the end of each path represents the analog. Essentially, a strategy is a set of nodes or path that leads to a solution.

This results in an important feature of the Strategy Mapping tool. Namely, that both the realization of the strategy in Nature (the analog node at the end of the path) and the path through the tree support the inspiration of design solutions.

3.2.1 Characterizing the Adaption Strategy Binary Tree

In order to understand the structure of the Strategy Mapping tool, is necessary to establish the formalism for describing and navigating the tool itself. The following terms are use to describe the structure and detail of binary trees as it relates to the tool presented in this paper.

1. Depth: the depth of a binary tree is the number of edges that need to be traversed when traveling from the root of the tree to node n .
2. Height: the height of a binary tree is one more than the depth of the deepest node.
3. Level: a node with depth d is said to be at level d of the tree.
4. Complete Binary Tree: a binary tree is said to be complete if all levels except the last have two child nodes.

The process for constructing the Strategy Mapping tool is discussed below. However, it is important to point out that the strategy mapping tree is complete because a node is only created if there are differences in the observed adaption strategies. Further, because the tree is created based on categorizing strategies, there are no paths that can be traversed through the tree such that an analog cannot be reached.

3.2.2 Defining a Strategy as the Path through the Tree

Huffman Coding [45] can be used to represent a path down the tree. The path through the tree to an analog (leaves of the tree) is described by the answer to the binary questions. Using Hoffman's Code, the code for a given analogue is the sequence of 0's and 1's encountered on the path from the root to the node. For consistency, 0 is the negative answer and 1 is the positive answer. Every node in the tree has a code based on the one and only path to reach that node. A code of [0.1.1] is reached by answering the questions in the tree as [No, Yes, Yes].

Equation 1 helps quantify the number of paths from the root node to every leaf of a decision tree. Since $Path_G^{(n)}$ represents a path followed from the root node to a leaf (head-to-tail path), the number of leaf nodes will determine how many paths a graph has, where $i = 1, 2, \dots, N$ and represents the number of leaves on the tree. In the case of the Strategy Mapping tool, this is the set how many differentiating question nodes it takes to reach an analog.

$$p = \sum_{i=0}^N Path_G^{(n_i)} \quad (1)$$

What these questions are and how they are formulated is discussed below. But first, it is important to note that the binary tree is a representation of information. It is possible to use the tree in multiple ways. These ways are described as traversing the tree.

When searching a decision tree, the path followed from the root node to one of the leaves is classified as different types of traversing categories. Traversing a binary tree refers to the order in which each node is analyzed. Depending on what the goal, a certain order might be more beneficial over others.

1. Preorder Traversal: visiting a given node before visiting either of the node's children and their subtrees.
2. Inorder Traversal: in this order, one visits a given node's left child (and the left child's subtree), then the node itself, and then that node's right child (and the right child's subtree).
3. Postorder Traversal: in this case, one visits a given node's two subtrees before visiting the node itself.

These traversal options in our tool correspond to a designer asking "Is there a specific analogue in the tree I am looking for?", "Can I compare certain adaptive strategies?" or "What is the impact of answering only yes or no to each binary question?"

If a designer were to focus on a subsection of the tree based on the context of the question on a node, then he or she could prune the right side of that subtree saving effort on analyzing a few nodes and focus on the rest of the tree. In the strategy mapping tool, this occurs when one of the questions eliminates a large set of strategies. For example, selecting the *No* path to the question "Are there external recourses available to support the repair?" eliminates searching many branches of the repair strategy tree.

4 Developing the Strategy Mapping Tool For Biologically-Inspired Adaptive Design

Existing biologically inspired design tools such as BioTRIZ [46] facilitates the identification of problems at a functional level and then provides compelling indicators to innovative solutions. Similarly, repository tools like AskNature [15] help designers, biologists, and engineers generate ideas for their own designs by writing questions such as: "How does nature conserve water?" or "How does nature prevent fracture?" This tool provides the designer with examples of organisms in nature that possess these abilities and describes how they work.

The specific focus of this work is on identifying, classifying, and using adaptive strategies observed in Nature as a way to support designers to develop innovative adaption strategies in their own systems. There are several potential ways this type of design support tool could be used. It seems the most benefit is from use at the later conceptual design and system architecting stage. Often a function failure modes and effects analysis or similar exploration of potential hazard states occurs before detailed subsystem design. At this stage, designers can explore natural strategies to minimize the impact of adverse events in Nature and use that information to generate solutions based on one or more strategies. However, the tool could also be used at the initial stages or a system redesign as illustrated in the case study discussed in this paper.

The following sections describe the systematic process we used to develop the Strategy Mapping tool. We iteratively developed the classification questions which define the observed strategies as we classified the strategies. The classification schema described below is based on our interpretation of biological literature. Thus, as we identified novel strategy distinctions the schema took shape. As we classified more natural examples, overall changes to the classification decreased.

4.1 Meta-Classification of Questions in a Decision Tree

Inspired by BioTRIZ [46], we begin with identifying the underlying principles which differentiate strategies. This is different than trying to identify the principles in the analogs themselves (as in BioTRIZ). Rather, we are seeking to identify the cross-cutting relationships in the classification system itself. We identified six different categories of strategy differentiation based on substance, structure, space, time, energy, and information differences in the observed adaptations. These are:

1. Energy Usage
2. Downtime
3. Material Removal
4. System Change
5. Foreign Assistance
6. Resource Usage

The binary questions that define the decision tree are classified into these categories. Most questions fall under more than one category.

4.1.1 Energy Usage

All organisms require some type of energy to do work necessary for survival and reproduction. Within this category are sub-questions that further differentiate the observed strategies. Some examples include:

1. Is there a trigger event to begin the repair?
2. Can the control system be used to rectify the problem?
3. Is the intent to mimic the lost part directly?

In all these questions, an energy source is imperative for the answer to be *yes* in a decision tree.

4.1.2 Downtime

Downtime of a machine or a system is defined as the period in which the machine cannot perform any work. Systems may experience downtime or waiting time for many reasons such as maintenance, failure, machine modification or when the system is just not available. In our case, designing for adaptability, failure is going to be the main reason our system is going to experience downtime. Some of the questions designers may encounter in this category are:

1. Is the fault due to changes in the environment?
2. Does this adaptation inhibits any other functions or components?
3. Is the faulty component in the fuel system?

In this category, either the whole system or the damaged components will be down for strategies that follow the *Yes* path to these questions.

4.1.3 Material Removal

A system can discard materials that the system is no longer using to either dispose of faulty parts that have been already replaced or parts that will trigger certain reactions if not detached. In manufacturing, machining can result in the need to remove unwanted material from the system. There are special machines to dispose of these unwanted materials. Biological systems must use other mechanisms. The following list shows examples of potentials questions under this category.

1. Is the foreign material removable?
2. Can the foreign material be destroyed?

4.1.4 System Change

The system is changing by adding, removing or regrouping parts, or properties of parts or a material [46]. Example questions that can be drawn from this category are listed below.

1. Does the healing change the characteristics of the system?
2. Can the mechanism include both original and new role at time of deployment?
3. Can a new function be programmed to restore full functionality?

Even though the name of the category is *System Change*, the whole system does not have to experience a change in order for a question to fall under this category. A small part of the system can change with the rest of the system remaining intact.

4.1.5 Foreign Assistance

Some adaptable engineering systems are autonomous, meaning they do not require any external agents or other systems to assist them in their task. Our meaning of foreign assistance, however, implies that there is an agent helping the system through the process of returning to full functionality. Foreign material refers to any material (alive or inert) that does not belong to the original system. Examples of foreign materials can include water (in the form of rain, snow, ice, etc.), air and any chemical reactions (such as oxidation) that the system can use to its advantage. Some of the questions that can be drawn for this category are as follows:

1. Is there any foreign material present?
2. Can the surrounding environment be changed to adapt to the fault?
3. Can the undesirable environmental effects be removed by changing the coating?

Most foreign materials are going to be present due to the environment. In the case of environmental effects being detrimental to the system, the system can adapt to protect itself or to use these effects as resources if necessary, which brings us to the last category *Resource Usage*.

4.1.6 Resource Usage

External resources refer to materials in the surroundings that are a result of environmental effects or are manufactured parts that are attached or stored in the system and designed to start functioning to replace faulty parts when the system is

down. Some questions that can be drawn for this category are listed below.

1. Are there any external resources that can be used by the damaged component?
2. Are any of these external resources manufactured?
3. Does the external resource belong to the original mechanism?

These six categories help differentiate the adaption strategies observed in Nature and structure the Strategy Mapping tool. Further, the classifications are important for defining the important aspects of an adaption strategy. We do not yet know if every category of the strategy is equally useful for inspiring design solutions. This is one area of continuing research.

4.2 The Resulting Tool

The Strategy Mapping tool was built with a collection of over 150 biological examples of fault adaptation [47]. The were collected from a literature search in the field of biology and are not necessarily all relevant examples. This collection was then organized by the strategies being implemented in each analog which yielded over 100 different strategies (some organisms implement the same strategy). The tool takes a similar form to a flow chart, with the designer beginning at an initial location on the tool. The tool then presents the designer with a group of paths that lead to examples with fundamentally different strategies. The designer begins a path that starts with a binary question. The binary questions are answered with respect to the problem the designer is working on or the desired way of solving the problem if the designer already has a solution in mind. This then begins a series of similar tasks where at each point the designer is presented with binary questions and the designer must answer the question. That answer will advance the designer to the next question node. This continues until the designer reaches the conclusion of the path and is presented with one or more biological examples. The questions and their answers each form a component of the strategy for that set of analogs. A diagram showing an overview of the structure of the tool is seen in Figure 1. The observed analog titles is presented in Tables 1 through 7. Due to the size of some of the trees, there is no way to represent their complete structure in a readable, standard printed size. However, Figure 3 describes the repair strategy. The complete and most updated tool can be accessed online at <https://goo.gl/TBg8h7>. All four strategy maps and resulting analogs can be viewed in their entirety using the web-based tool.

The Strategy Mapping tool has 4 separate roots: replace, repair, reconfigure, and reprogram. These correspond to different end goals of the various strategies observed in Nature.

1. Replace: An adaptation where a faulty component is completely or partially replaced by a new one.
2. Repair: An adaptation where a faulty component is brought back to full functionality.
3. Reconfigure: Adaptations which uses other components and characteristics of the system to mimic the function of the faulty component in that system.
4. Reprogram: Adaptations which adjust the programming or behavior of the system to work around the fault without fixing it. That is, changing its goals.

A binary tree follows from each of these four roots with yes/no questions that are answered with respect to the system being designed.

The process by which a designer comes to this analog is as follows. The designer begins by deciding on a particular strategy category from the four available. The designer then answers the initial question for that category. Selecting yes or no leads to a new binary question until the end is reached at one or more biological analogs. The tree structure for paths not taken is intentionally not hidden because it is expected that the designer may be indifferent to two alternatives and consider both paths simultaneously. Figure 2, gives an example of an analog description that can be reached following a particular path.

5 How the Strategy Mapping Tool Can Be Used

One area where having an adaptive system would be highly valuable is space manufacturing and other similar robotic applications. We will use this application area as a way to demonstrate how we expect the Strategy Mapping tool to be used. Having robots operating reliably in space where humans cannot be present represents a big challenge for engineering. Consider the design challenge of how to avoid or mitigate the impact of a joint failure on a robotic arm manipulator.

To begin using the Strategy mapping tool, we begin with deciding which overall strategy to pursue. A *repair* strategy would involve excepting the risk of failure and mitigating that risk by fixing the broken joint. A *replace* strategy would mitigate the risk of failure by using a different component or replacing the broken joint component with an alternative. A *reconfigure* strategy will focus on using other aspects of the robot to mimic the functionality achieved through the joint. Finally, using the *reprogram* strategy will accept the broken joint and modify future missions to meet different objectives that don't require the joint functionality. From an engineering design perspective, these strategies are not mutually exclusive. Designers may consider implementing several strategies to mitigate the risk of faults. While the Strategy Mapping tool directs the designer towards specific strategies, it is assumed that in the early design stage, multiple competing design alternatives will be considered.

Consider exploring the *repair* strategy first. Figure 3 shows the overall layout of the tree. The questions and resulting analogs can be found online at <https://goo.gl/TBg8h7>. The root question of the repair tree is "Are any factors, that are external to the mechanism usable?" This means, are there resources available that could be used to implement the repair strategy that are not currently part of the machine. If the designer decides there could be (perhaps using space junk), then the next question in the strategy mapping tool is "Are any of those factors (resources) manufactured before the instigating event?" This narrows down whether the repair resources are readily available or must be created. Working with the concept of utilizing space junk, assume the designer selects the *No* path. Note, since the tree is a static representation, designers can follow more than one path simultaneously if they are not sure about an answer. The *No* answer leads to the final question in this path, "Is the faulty component used directly?" This questions addresses whether we will be using the same broken component completely or if part of the external resources will be replacing a part of the effected component. Complete replacement would be found in the *replace* strategy tree. The *Yes* path leads to analog 14 "Sewing a Finger/Toe Back On." From here the designer may choose to use this analogy or save it for later and continue searching. Assume the designer chooses to find more analogs and starts over and begins at the root question answering *No*. Following the same procedure as above the designer may end up at the set of analogs 16, 17, and 18 that all implement a similar strategy. Analog 16 is "North American Opossum," in the

associated information with the analog the designer reads that the opossum has an adaption strategy that allows it to absorb the venom of most snakes and turn that venom into a digestible compound.

The designer discussed above now has two very different analogs to use as a basis for design inspiration. There are numerous methods to support the creative ideation process once analogs are identified. This work is focused on identification of analogs and not the best approach for creative ideation. The designer may consider way in which the broken arm joint could be sewn or patched. Alternatively, there may be a way for the joint to have some absorbance and changing properties towards whatever may cause the failure in the first place. From here it is up to the designer to develop inspired solutions.

The Strategy Mapping tool can also be transversed in an upward direction. Meaning, the designer may go through the catalog and select a few interesting strategies. Then, using the pruning rules and path descriptions, the designer is provided with the limited set of strategy steps (as described by the question nodes). This approach to transversing the tree helps provide information on how the strategy addressed the six categories (energy usage, downtime, etc.) listed above. This can help the designer come up with the details necessary to develop an inspired engineered adaptive strategy.

The above description details how the Strategy Mapping tool is envisioned. However, there are many interesting questions on how to use the tool, what stage of design it is most effective, and how the strategy-based approach is different with respect to the designers thinking about analogies. These questions, will be pursued in future research. However, to implement a proof-of-concept, the Strategy Mapping tool was used in a design class and the outcomes of that preliminary experiment are described below.

5.1 Natural Strategies through the Lens of Reliability and Safety Engineering

As discussed in Section 2.2, there are a variety of strategies commonly implemented by engineers to reduce the likelihood or impact of faults and adverse events. Using the earlier classification it can be observed that most system designers implement multiple strategies. However, these high-level classifications provide general guidelines. How to achieve a particular engineering strategy is design and domain dependent. The objective of the search tool presented in this paper is to identify the mechanisms and sequences of natural adaption such that it can serve as inspiration in system design. We can look at the specific natural adaption strategies classified in the tool from the reliability and safety engineering perspective. Doing so provides high-level classification and grouping into these familiar forms. However, because these strategies overlap, a particular natural analog can be viewed as implementing more than one type of engineering strategy. Table 1 lists the reliability and safety engineering strategy classification for each natural analog in the search tool using the definitions presented in Section 2.2.

6 An Exploratory Study

In order to explore the impact of using biological adaption strategy for design inspiration, we conducted a preliminary experiment with 33 students in 11 groups who were participating in a combined undergraduate/graduate mechanical engineering design course. This course was not specifically about biologically inspired design, however, it was an included topic. The purpose of this study was to illicit how designers use the tool presented in this work. The results of this experiment help

identify the important research questions with respect to cognition and efficacy for future studies. However, it is presented here to qualitatively describe results of using the tool and to establish how strategy-based biologically inspired design differs from other approaches.

6.1 Preliminary Study Approach

In this preliminary experiment, 11 groups of students were presented with the same design problem and constraints and asked to generate and submit as many solution concepts as possible and select one final concept as their preferred solution. The students were required to use Bio-Inspired Design to address the design problem and had some exposure to the field. In order to explore some differences, three groups were asked to use their own experience to come up with solutions. Four groups were required to use AskNature as a search platform to begin their ideation process. Finally, four groups were presented with an electronic version of the Strategy Mapping tool. No specific ideation method or organizational structure was imposed on the students. Further, they performed these activities in the same room. There are many potentially confounding variables in this initial study. Therefore, the impact of this preliminary experiment is focused on the type of solutions students reached.

In this study, students used an earlier version of the tool that was implemented through a very large spreadsheet. Students traversed through the spreadsheet to find the analogs and then opened a large text file and looked for the analog number. This searching approach was not optimal and may have resulted in students searching through the strategies and not using the graphs to arrive at an analog. In future work, we will evaluate using the decision trees versus using just the analog descriptions by themselves. The current version of the tool is now web accessible at: <https://goo.gl/TBg8h7>.

6.2 The Adaptive System Design Problem

The design problem given to the 11 groups was to address the potential for a crack in the lens of a satellite telescope. The satellite was expected to exhibit fault adaptive behavior to address the crack. The students were asked to come up with several concepts and to present one of them as a solution. The final design was expected to be detailed enough that the mechanisms and biological principles are evident. It was not necessary for the design to be fully specified in terms of material and dimensions unless it is necessary to illustrate the principles in use. The handout provided to the students is provided in Appendix 1.

6.3 Qualitative Analysis of the Concepts Generated

Three groups' concepts are presented here reflecting the three tested approaches. These groups were selected because they spent similar amounts of time and submitted the same number of concepts. It was also noted that these groups seemed to be representative of other groups using the same methods. All three groups submitted relatively detailed concepts and summaries of how the analogs they chose were used in the concepts.

The first set of concepts to be discussed were developed by a group using their own experiences and knowledge to search for analogies. This group will be referred to as Group A and its concepts as 1, 2 and 3. This group submitted three concepts

that used stem cells in the human eye, the ability of humans to heal from a cut and the regenerative process of a newt as analogs. Concept 1 was to provide the lens with a liquid repair mechanism that would harden to fill in a crack whenever a crack occurred. This concept was generated by using the idea that undifferentiated cells in the eye later differentiate to fill in lost or damaged sections and that a liquid would mimic that effect in a mechanical system. Concept 2 was to use a similar method to concept 1 but enclose the lens in a case and pump the liquid in from outside the lens. This is based on the fact that the human body forms a scab and then cells are sent to the damaged area to repair it. Concept 3 used a newt as an analog and that concept was very similar to the group's first concept. The key difference being that an active mechanism would be used to repair the lens instead of the passive mechanism used in the first concept. This group chose their second concept as their preferred concept.

The second group used AskNature to locate analogs. This group also reported three concepts using nurse shark teeth, human skin and crocodile eye lenses as analogs. This group will be referred to as Group B and its concepts as 1, 2 and 3. Concept 1 was to have multiple lenses on-board the satellite in case of one cracking. The inspiration for this was based on how nurse sharks have multiple rows of teeth so that if one breaks there is another to replace it. Concept 2 uses human skin and involves lacing the lens with hollow fibers filled with a liquid. The liquid would be exposed to the low temperatures in orbit and when a crack occurs, it would freeze in the cracked area and fill it. This concept used human skin forming a scab as its analog. It should be noted that the Group A had a similar concept 2 but the difference is that Group B used the scab forming process as the analog whereas Group A used the formation of new tissue under the scab as their analog. Group B's concept 3 used the secondary lens on a crocodile as an analog to create a concept where a disposable and removable cover was used to prevent the fault from happening.

Group C used the Strategy Mapping tool and also generated three concepts which will again be numbered 1, 2 and 3. This group used the Alaskan Wood Frog, American Shad and the Achatinoidea Snail as analogs. Concept 1 used the Alaskan Wood Frogs ability to shut off organs due to temperature fluctuations. The concept involves placing two clear plastic plates around the lens which is made of a polymer that has a low melting temperature. Between the plates and the lens will be liquid nitrogen which keeps the lens below its melting point. The plastic plates will then be polarized to generate an electric field through the lens and any cracks in the lens will disrupt the electric field. A voltmeter will register this change and pump the liquid nitrogen out of the cracked area causing the lens to melt in just that area and once the electric field returns to normal the liquid nitrogen will be pumped back in to refreeze the lens. Concept 2 uses the kidneys of the American Shad as an analog. The American Shad regulates the amount of salt in its body and can over time change between salt and fresh water environments. Using this as an analog, Group C suggested a concept of a spring-mass damper system that would cause the lens to float, allowing it to adjust to sudden shocks and vibrations that may occur during launch and transport. The group noted that the lens is mission critical so damage is not acceptable as is the case with the American Shad's salt level. The final concept, uses the Achatinoidea Snail's ability to regenerate its shell if it cracks. It does this through a series of layers that combined, give the shell its properties and whenever a crack occurs the snail secretes a plasma corresponding to the damaged layers which repairs the crack. This was applied to the telescope by making the lens out of three layers (or more) and using a vibration sensor to determine if a crack occurred and how deep it was. This would then lead to the system releasing a

gel, corresponding to the damaged layer, which would then harden in the crack surface and fill it in. These solutions are summarized for comparison in Table 8.

When these groups are compared, several interesting trends emerge. First is that Group C had far more developed concepts than the other two. This group went into great detail about specific mechanisms and techniques that would be used where the other groups provided less refined ideas. This also led to Group C's concepts being the most complicated.

The most common concept was refreezing liquids or gels to repair the crack and Group A's concepts were all related to this. Group B had two concepts (1 and 2) and so did Group 3 (1 and 3). However, Group C had a much more detailed and unique approach in both cases. Groups B and A used a crack to expose the gel/liquid to low temperatures while Group C used the crack to warm the gel and Group C used a layered approach instead of a single layer as seen in Groups A and B.

It is also interesting that Group B, and in the AskNature groups in general, students tended to focus on crystalline gels/liquids and eyelids and lenses. This is an interesting pattern since those groups all consistently came up with the same analog sources. There are occasional deviations from this norm such as Group B's shark teeth concept but more groups stayed in the gel/liquid and eye concept area than those that moved out of that area. This may be due to directly searching for component analogs (lenses in this case). Groups using the Strategy Mapping tool found surprising solutions from unexpected areas. For example, one group used the honey badger as an analog to fix the telescope lens. The honey badger exhibits fault adaptation when it is bitten by a venomous animal, thus introducing a harmful compound into the badger. The honey badger's body collects the venom in sacs which it can then later use in its own defense. The strategy for this analog is based around redirecting a fault into a location where it is less harmful or even beneficial and the students used this to create concept by which the lens broke in a specific location. The concept was based around manipulating the situation to ensure the fault occurred in a part where its effect was limited as is consistent with the strategy of the honey badger adaptation. This seems to indicate a relationship between Strategy Mapping and diversity of analogs selected. This result seems to indicate that groups using the Strategy Mapping tool identified analogs with completely different characteristics, function and situations than the design problem they were provided.

For the Strategy Mapping Tool groups, some analogs were used multiple times such as the African Clawed Frog which Group C did not use but 3 other groups did. However, the majority of analogs were unique. These groups also showed a greater tendency to change the way they solved the problem. Group C presented a concept that prevented damage while other groups using Method 3 generated concepts that forced the damage to occur in specific areas and some groups made the lens readjust to the crack instead of repairing it. One group suggested making the lens a combination of several lenses and then just changing which one was in use. An interesting thing to note is that many groups using Strategy Mapping generated at least one preventative concept and specifically mentioned that it was because the design tool differentiated between strategies relating to mission critical components and non-critical components. As a final note, nearly every analog found by the AskNature groups and the groups using a generic search engine were also present in the Strategy Mapping tool's analog pool at the time of the experiment.

7 Conclusions

In this work we present a new design tool for bio-inspired fault adaptive systems. We envision this tool to be useful in the later conceptual design of new systems to avoid known hazards or in the early stages of redesigning existing systems. To evaluate the potential effectiveness of this tool, we conducted a small preliminary study comparing this tool with a directed and undirected search for biological analogs.

The underlying motivation for this work is that organisms in nature have special traits that help them avoid and recover from internal and external negative factors. As engineered systems have similar objectives, it is logical to look to Nature as a source for inspiration for designing adaptive systems.

Using the examples found in Nature, this work identified four strategy categories for dealing with faults. These are: *repair* a part, *replace* a part, *reconfigure* another part to fulfill the original objective, and *reprogram* to ignore previous and meet new objective. The specific strategies exhibited in nature were collected as analogs for designers. However, it was also useful to develop a series of binary questions to distinguish sets of strategies. By presenting both the alternatives that lead to a particular natural analog and the analog, designers can both find inspiration as well as develop the translations necessary to move from the natural analogy to the engineering context.

The experiment discussed in this paper illustrates the usefulness and effectiveness of the Strategy Mapping tool. Because the designer is focused on developing a strategy to avoid faults, simple analogs of components or functions are more difficult to translate to the engineering domain. The benefits shown by this study do not address the usefulness of the search tools in general but are restricted to the fault impact avoidance context presented. That is, the Strategy Mapping tool would not be effective for addressing attribute capability functions such as “how to fly”.

There are large differences in the size of the trees and number of analogs for the four different strategy types. This is both a product of human effort in building the tool and the prevalence in Nature of these different strategies. Determining how complete and representative a tree is for describing a set of strategies will be explored in future work. Further, the binary tree structure was created by the research team and the organization of the questions was designed to minimize the number of strategies. However, no formal optimization effort was made to achieve the current structure. Further, we observe that there are multiple ways to connect the information content of each analog, including viewing them through the lens of reliability and safety engineering practices. This indicates that a more complex information representation is likely needed. In future work we will use an ontological representation to capture this complex information relationship.

Because bio-inspired fault adaptation strategy involves more than mimicking structures, functions, or general principles, a novel approach is needed to make use of these natural analogs. The Strategy Mapping tool focuses on the analog and the categorization schema which classifies that analog. Using this type of approach, designers can be presented with analogs for inspiring solution ideas that are creative and extend beyond copying functions and forms.

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Appendix A: Design Challenge Prompt for the Case Study

Biologically Inspired Design Project

Project Summary: Each group will be asked to solve a design problem using Biologically Inspired Design (BID). Each group will be assigned a BID method to use in the design process and for selecting an analog. Groups will also fill out a feedback sheet to provide some other information about the design process for analysis. After 1 week each group will submit a design concept and filled out feedback sheet.

Design Problem: You are working on a new orbital telescope satellite and one of the major concerns with the design is the lens fracturing during loading and/or launch. Use BID to come up with a concept design to address this problem after the rocket transporting the satellite has lifted off (Use the Hubble Space Telescope as a model for the satellite if necessary and you are free to define how the rocket/launch mechanism and satellite behave after launch).

You can solve this problem however you want, so long as there is a biological analog corresponding to the design. Your design can function at any stage of the products life (Immediately after liftoff, after achieving orbit etc.).

The Analog: Each group must identify a biological analog corresponding to their final design. Groups may only search for this analog via the method assigned to them although additional resources may be used to find more information about the analog. How the analog is reported depends on the method being used.

Final Product: Each group will turn in a summary of their design concept. Turn in sufficient material (summaries, drawings, critical calculations) so that someone who is not familiar with the concept can understand it. In addition, a feedback sheet will be provided on blackboard by Monday, September 28 and a completed feedback sheet is to be included with the concept. Concepts and feedback sheets can be turned in via email to the test coordinator or in his mailbox in the MEEG office.

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Table 1: Analogs in the Strategy Mapping Tool- Repair

Analog Number	Title	Engineering Corollary
1	General wound healing	Robustness, Resilience
2	Skin Grafts, same individual	Stand-by
3	Muscles (humans)	Robustness, Resilience
4	Transplants, in vitro	Stand-by, Scheduled
5	Transplants, 3D printing	Stand-by, Scheduled
6	Ear piercing	Robustness, Resilience
7	Tattoos	Robustness, Resilience
8	Common Hippopotamus	Robustness
9	Wood frog	Envelope, Robustness
10	Skin Grafts, allograft	Stand-by, Scheduled
11	Photosynthetic systems	Condition-based
12	Bioengineered skin grafts	Condition-based
13	Sewing finger or toe back on	Condition-based
14	Stents	Envelope, Condition-based
15	North American Opossum	Robustness
16	Vibrio cholerae - immune system	Robustness, Resilience
17	Salmonella - immune system	Robustness, Resilience
18	Scavenging reactive species	Robustness

Table 2: Analogs in the Strategy Mapping Tool- Reconfigure

Analog Number	Title	Engineering Corollary
1	Spider monkey	Robustness
2	Prosthetics	Condition-Based
3	Wheelchairs	Condition-Based
4	Robotics	Condition-Based
5	Self-driving wheelchair	Condition-Based
6	Jellyfish	Robustness
7	Blue shark cleaner wrasse	Robustness, Resilience
8	Cuttlefish	Envelope, Robustness, Parallel
9	Clown fish	Robustness, Resilience
10	Parrotfish	Robustness, Resilience
11	Hawkfish	Robustness, Resilience
12	Scarlet macaw	Envelope, Robustness
13	Spanish shawl	Envelope, Robustness
14	Puffer fish	Envelope, Robustness, Parallel
15	Asian tiger keelback	Envelope, Robustness
16	Great barracuda	Envelope, Robustness, Parallel

Table 3: Analogs in the Strategy Mapping Tool- Reprogram

Analog Number	Title	Engineering Corollary
1	Losing a limb	Robustness
2	Losing a tail	Robustness
3	Vision loss	Robustness
4	Hearing loss	Robustness
5	Losing teeth	Robustness
6	Losing an arm	Robustness
7	Having one kidney	Parallel, Condition-based
8	Bull sharks	Envelope, Robustness
9	Pink salmon	Envelope, Robustness
10	American shad	Envelope, Robustness
11	Red drum	Envelope, Robustness
12	Atlantic striped bass	Envelope, Robustness
13	Rainbow smelt	Envelope, Robustness
14	Qhino checkerspot	Robustness, Resilience
15	Alpine chipmunk	Robustness, Resilience
16	European wasp spider	Robustness, Resilience
17	Nine-banded armadillo	Robustness, Resilience
18	Red-billed gull	Robustness, Resilience
19	Wild salamanders	Robustness, Resilience
20	Tawny owls	Robustness, Resielince
21	Colonies of grass-eating ants	Envelope, Robustness

Table 4: Analogs in the Strategy Mapping Tool- Replace (1)

Analog Number	Title	Engineering Corollary
1	Mexican axolotl	Envelope, Resilience
2	Snapping shrimp or pistol shrimp	Robustness, Resilience
3	Sea cucumbers	Envelope, Resilience
4	Planarian	Envelope, Resilience
5	Zebrafish	Envelope, Resilience
6	Stick insects	Robustness, Scheduled
7	Colonies of temnothorax ants	Robustness
8	American cockroach	Envelope, Resilience
9	Hairy frog	Condition-based
10	Brittle stars	Envelope, Resilience
11	Brown ghost knifefish	Envelope, Resilience
12	Japanese spiky sea cucumber	Robustness, Resilience
13	Common octopus	Design/Operational Envelope/Resilience
14	Deer	Robustness/Scheduled
15	Colonial sea squirt	Envelope, Resilience
16	Painted turtle	Envelope, Robustness
17	Italian crested newt	Envelope, Resilience
18	Human	Envelope, Resilience
19	Human	Envelope, Resilience
20	Immortal jellyfish	Envelope
21	Snail	Envelope, Resilience
22	Zebrafish	Envelope, Resilience
23	Catfish	Envelope, Resilience
24	American alligator	Envelope, Resilience
25	Ciccid	Envelope, Resilience
26	Rat	Envelope, Resilience
27	Brown Hydra	Envelope, Resilience

Table 5: Analogs in the Strategy Mapping Tool- Replace (2)

Analog Number	Title	Engineering Corollary
28	Tropical clawed frog	Robustness, Resilience
29	Mammal	Envelope, Resilience
30	North American Opossum	Envelope, Resilience
31	Sea cucumbers	Envelope, Parallel
32	Chinese mystery snail	Envelope, Resilience
33	Humans	Envelope, Resilience
34	Percival's spiny mouse	Envelope, Resilience
35	Purple sea urchin	Envelope, Resilience
36	Noble feather star	Envelope, Resilience
37	Antartic brittle star	Envelope, Resilience, Parallel
38	Fatty membranes of cells	Envelope, Resilience
39	Eastern (red-spotted) newt	Envelope, Resilience
40	Hermann's tortoise	Envelope, Resilience
41	Human	Envelope, Resilience
42	Zebrafish	Envelope, Resilience
43	Pacific blood star	Envelope, Resilience
44	Underground storage swelling	Robustness, Scheduled
45	Freshwater pearl mussel	Envelope, Robustness
46	Rabbits	Envelope, Robustness, Resilience
47	Killer whale	Envelope, Robustness
48	Long-spined sea urchin	Envelope, Resilience
49	Zebrafish	Envelope, Resilience
50	Japanese sea lily	Envelope, Resilience
51	Human	Envelope, Resilience
52	Cattle	Envelope, Condition-based
53	Senegal (gray) bichir	Envelope, Resilience
54	Hair regrowth	Envelope, Stand-by

Table 6: Analogs in the Strategy Mapping Tool- Replace (3)

Analog Number	Title	Engineering Corollary
55	European lesser spotted dogfish	Envelope, Resilience
56	Rat	Envelope, Resilience
57	Chicken	Envelope, Resilience
58	American bullfrog	Envelope, Robustness
59	House mouse	Envelope, Resilience
60	Mexican axolotl	Envelope, Resilience
61	Mexican axolotl	Envelope, Resilience
62	Little skate	Envelope, Resilience
63	Rabbit	Envelope, Resilience
64	Zebrafish	Envelope, Resilience
65	Zebrafish	Envelope, Resilience
66	Atlantic sand fiddler	Envelope, Resilience
67	Zebrafish	Envelope, Resilience
68	Atlantic tomcod	Envelope, Resilience
69	Japanese spiky sea cucumber	Envelope, Resilience
70	Whitespotted bamboo shark	Envelope, Resilience
71	Goldfish	Envelope, Resilience
72	Green anole	Envelope, Robustness
73	Rat	Envelope, Resilience
74	Laver spire snail	Envelope, Resilience
75	African clawed frog	Envelope, Resilience
76	Deepwater spiny dogfish	Envelope, Resilience
77	Common leopard gecko	Envelope, Robustness
78	Eastern (red-spotted) newt	Envelope, Resilience
79	Japanese rice fish	Envelope, Resilience
80	Megarian banded centipede	Envelope, Resilience
81	American five-lined skink	Envelope, Robustness

Table 7: Analogs in the Strategy Mapping Tool- Replace (4)

Analog Number	Title	Engineering Corollary
82	Chicken	Envelope, Resilience
83	Common fruit fly	Envelope, Resilience
84	Eastern (red-spotted) newt	Envelope, Resilience
85	Chicken	Envelope, Resilience
86	Oyster toadfish	Envelope, Resilience
87	House mouse	Envelope, Robustness
88	Blackback land crab	Envelope, Resilience
89	Catfish	Envelope, Resilience
90	Rainbow trout	Envelope, Resilience
91	Brown garden snail	Envelope, Robustness
92	Nile tilapia	Envelope, Resilience
93	Pharaoh cuttlefish	Envelope, Resilience
94	Snail fur	Envelope, Resilience
95	Rusty crayfish	Envelope, Robustness
96	Eastern glass lizard	Envelope, Robustness
97	Star ascidian	Envelope, Resilience
98	Himalayan newt	Envelope, Robustness
99	Porcupine	Envelope, Resilience, Parallel
100	Halechiniscus grevini	Envelope, Resilience
101	Vityazicrinus petrachenkoi	Envelope, Resilience
102	Shark	Envelope, Robustness, Parallel
103	Chicken	Envelope, Resilience
104	Eastern (red-spotted) newt	Envelope, Resilience
105	California sea hare	Envelope, Resilience
106	Black-ball sponge	Envelope, Resilience

Table 8: Summary of Concepts from Example Groups A, B, and C

	Undirected (A)	AskNature (B)	Strategy (C)
Concept 1	Analog: Human Retinal Stem Cells	Analog: Nurse Shark Teeth	Analog: Alaskan Wood Frog
	Repair lens by freezing liquid contained in lens	Have redundant lenses	Use localized melting of lens to repair crack
Concept 2	Analog: Human Wound Healing	Analog: Human Wound Healing	Analog: American Shad
	Enclose lens and pump liquid in to fill gaps and then freeze liquid	Repair lens by freezing liquid contained in nanotubes in lens	Spring-Mass damper to prevent crack
Concept 3	Analog: Newt Regenerative Process	Analog: Crocodile Eye Lens	Analog: Achatinoidea Snail
	Repair Lens with active repair system	Replaceable exterior cover	Layered lens with solidifying liquid

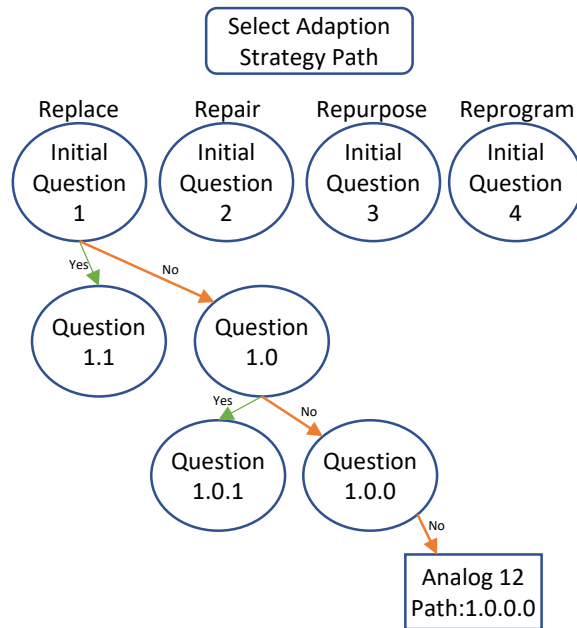


Fig. 1: Overview of the structure of the Strategy Tool. Note only one path is shown for image clarity.

Replace Analogy 1 - Engineering Strategy: Resilience

1) Mexican Axolotl, *Ambystoma Mexicanum*

The Mexican Axolotl is a salamander in the amphibian class. It can live 10 to 15 years in the wild but are considered endangered due to the water pollution, trading business, and being a food delicacy in Mexico ("Mexican Axolotls"). The Axolotl has a great ability of regenerating its limbs as true limbs, muscles, and differentiated cells, not as scar tissues.

After the limb is amputated a plasma clot forms and the epidermal cells from the stump migrate to cover the wound surface and form the obligatory wound epidermis. This layer continues to reproduce and forms the apical ectodermal cap. The cells under the apical ectodermal cap undergo dedifferentiation and genes that express differentiated tissues, such as *MRF4* and *myf5*, are down-regulated and *msx1*, proliferating progress zone, is up-regulated (Gilbert). The undifferentiated cells beneath the apical ectodermal cap are called the regeneration blastema. These cells will multiply and differentiate into the structures of the limb by *PAX7+* cells, which are regulated by *TGF-beta1*. Down-regulation of *p53* is essential to form the blastema, and later on in the healing process up-regulation is needed for re-differentiation of the cells (Yun et al.). A major difference Godwin et al. found in Axolotl regrowth compared to mammalian healing is that the presence of macrophages and pro-inflammatory and anti-inflammatory cytokine signals in the blastema within hours of the amputation are required to stimulate and sustain regeneration. This allows for no tissue scarring and perfect regrowth of the limb.

Fig. 2: An example of an analog strategy reached through the Strategy Mapping Tool. Data from: [48,49]

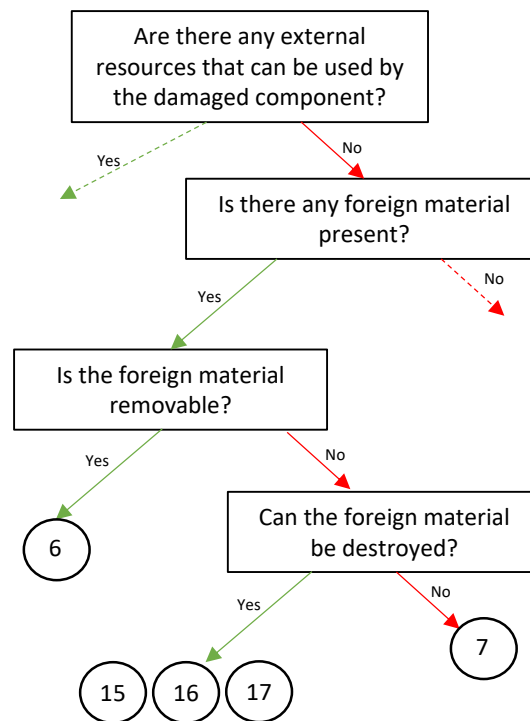


Fig. 3: A portion of the Repair binary tree. Dotted lines indicate portions of the graph not shown due to readability issues for the large graph. The complete tree can be found at: <https://goo.gl/TBg8h7>