AN ABSTRACT OF THE DISSERTATION OF

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Robert B. Stone

Biological organisms, phenomena and strategies, herein referred to as biological systems, provide a rich set of analogies that can be used to inspire engineering innovation. Biologically-inspired, or biomimetic, designs are publicly viewed as creative and novel solutions to human problems. Moreover, some biomimetic designs have become so commonplace that it is hard to image life without them (e.g. velcro, airplanes). Although the biologically-inspired solutions are innovative and useful, the majority of inspiration taken from nature has happened by chance observation, dedicated study of a specific biological entity (e.g., gecko), or asking a biologist to explain the biology in simple terms. This reveals a fundamental problem of working across the engineering and biological domains. The effort and time required to become a competent engineering designer creates significant obstacles to becoming sufficiently knowledgeable about biological systems (the converse can also be said). This research aims to remove the element of chance, reduce the amount of time and effort required to developing biologically-inspired solutions, and

bridge the seemingly immense disconnect between the engineering and biological domains.

To facilitate systematic biologically-inspired design, a design methodology that relies on a framework of tools and techniques that bridge the two domains is established. The design tools and techniques that comprise the framework achieve: Identification of relevant biological solutions based on function; translation of identified biological systems of interest; functional representation of biological information such that it can be used for engineering design activities; and conceptualization of biomimetic engineering designs. Using functional representation and abstraction to describe biological systems presents the natural designs in an engineering context and allows designers to make connections between biological and engineered systems. Thus, the biological information is accessible to engineering designers with varying biological knowledge, but a common understanding of engineering design methodologies. This work has demonstrated the feasibility of using systematic design for the discovery of innovative engineering designs without requiring expert-level knowledge, but rather broad knowledge of many fields.

Systematic Design of Biologically-Inspired Engineering Solutions

by
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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Jacquelyn Kay Nagel, Author

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CHAPTER 1 - INTRODUCTION

1.1 Motivation

The natural world provides numerous cases for inspiration in engineering design. Biological organisms, phenomena and strategies, which can be grouped and referred to as biological systems, are exemplary systems that provide insight into sustainable and adaptable design. Biological systems offer engineers billions of years of valuable experience, which can be used to inspire engineering designers. Studying biological systems to inspire a technical solution to a human problem is termed Biomimicry. Biomimetic design "offers enormous potential for inspiring new capabilities for exciting future technologies" (Bar-Cohen 2006a) and encourages engineering innovation (Lindemann and Gramann 2004; Bar-Cohen 2006b). Furthermore, engineers can not only mimic what is found in the natural world, but also learn from those natural systems to create reliable, smart and sustainable designs.

A handful of engineering innovations resulting from studying and mimicking nature have become so integrated into our society that they have become commonplace. Velcro©, aircraft, and pace makers, all based on biological inspiration, and are engineering breakthroughs for materials, aeronautics and medicine, respectfully. Within the last thirty years several breakthroughs in fluid dynamics, sensors, materials, computational algorithms, alternative energy, and sustainable architecture have had the commonality of taking inspiration from nature (Nachtigall 2000; Brebbia et al. 2002; Brebbia and Collins 2004; Cerman et al. 2005; Bar-Cohen 2006b; Brebbia 2006; Forbes 2006). A few examples of biomimicry, showing the biological system next to the biomimetic system, are provided in Figure 1.1.

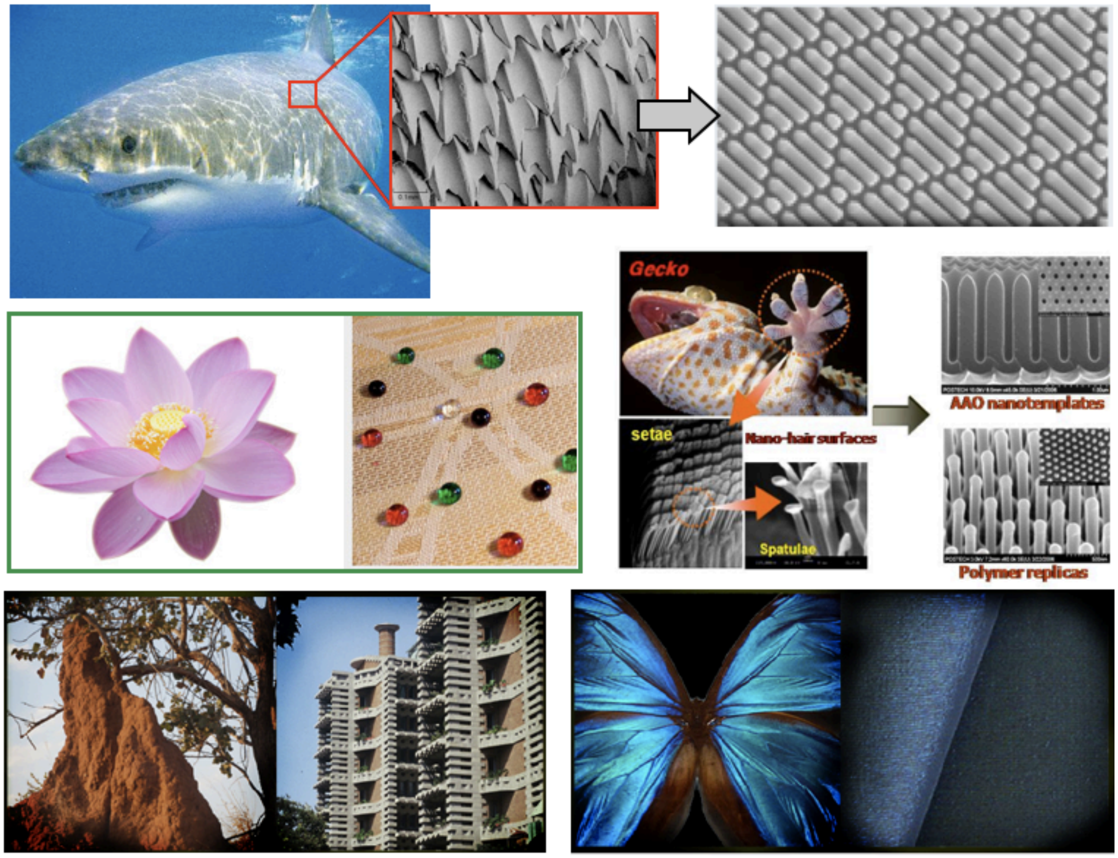

Figure 1.1. Engineering Innovations Inspired by Nature (CW from top: adapted from (Sharklet Technologies Inc. 2010); (Cho Research Group 2008); (Biomimicry Institute 2009)).

Anti-bacterial films were inspired by shark skin, adhesive materials that employ the Van der Waals principle were inspired by the gecko foot, color changing fabrics without dyes or chemicals were inspired by the morpho-butterfly, buildings that have passive heating/cooling were inspired by the termite mounds and self-cleaning surfaces were inspired by the lotus. A lesser known commonality between biomimetic products is that the inspiration for these breakthroughs occurred though chance observations, experiences or conversations. Although there is great potential for engineers to learn and take inspiration from nature, there is a disconnect between the domains, thus making biologically-inspired designs more of a novelty than established practice. Furthermore, transferring the valuable biological knowledge to the engineering domain is currently a disorganized process. While there have been several studies on the success of biomimetic design in the classroom (Chiu and Shu 2007b; Mak and Shu 2008; Lenau 2009; Vattam et al. 2009), few reliable mechanisms exist for working between the two domains. This dissertation builds a bridge between the engineering and biological domains to support systematic biologically-inspired design.

1.1.1 Theoretical Motivations

Engineering design is considered both an art and a science, which encourages the use of engineering principles, imagination, prior knowledge, stored knowledge and a designer's intuition to create engineering solutions. The resulting solution may or may not be innovative, novel or what some would call creative; however, the design should fulfill a purpose or answer a need (Hyman 1998; Otto and Wood 2001; Dym and Little 2004; Ulrich and Eppinger 2004; Voland 2004; Ullman 2009). To arrive at a solution, it is not uncommon for engineers to make analogies amongst different engineering disciplines (i.e. an electrical resistor and mechanical damper are mathematically analogous) during ideation to find solutions or use metaphors to frame or assist with defining the design problem (Hey et al. 2008). The leap made between engineering disciplines using analogies is to be expected as one gains more experience; however, making a leap between domains is less likely to occur without an impetus. Take for instance Velcro©, if it weren't for the curiosity of George de Mestral that caused him to investigate how the tiny burrs he and his dog accumulated from walking through wooded areas, modern day hook and loop may never have been invented or it may not be as effective. George de Mestral's chance observation of a biological system resulted in a very simple, reusable material (Mestral 1955) that has been used for securing everyday items such as shoes to mission critical items needed for exploring space. The morphological similarities can be seen in Figure 1.2.

Cocklebur Velcro©

Figure 1.2. Comparison of Cocklebur (Aroid 2008) to Velcro© (Mestral 1955).

It is evident that nature can inspire innovative engineering designs. However, for engineering designers to adopt such a practice, design tools, techniques and methods are needed. Utilizing biological information during the engineering design process has taken many forms. Inspiration for solving or finding direct solutions to engineering problems has been obtained through functional keyword searches, reverse engineering, use of function-structure-behavior models, use of databases, analogical and case-based reasoning, and bioTRIZ among others (more details are given in Chapter 2). These inspiration facilitators are meant to reduce the time and effort required to learn from and mimic nature. Although each facilitator has a different procedure and focuses on a specific step in the overall design process, they all share one thing in common; the promising biological system must be abstracted to capture some fundamental principle. What is lacking is one comprehensive set of tools and methods, a framework, that approaches biologically-inspired design from a single design perspective that can guide a designer from initial problem definition to complete concept.

Due to the seemingly immense disconnect between the engineering and biological domains, biologically-inspired designs often seem exotic or unachievable unless a significant amount of time and effort is devoted to the task. This reveals the knowledge requirement problem of working across domains. A fundamental problem to effectively execute biomimetic designs is that the effort and time required to become a competent engineering designer creates significant obstacles to becoming sufficiently knowledgeable about biological systems (the converse can also be said). Knowledge requirements, however, can be alleviated with (1) the development of design tools that use a perspective common to engineers to interface with the biological information and (2) integration of those design tools with existing engineering design methods.

An internationally accepted and well-known design methodology is the systematic approach to engineering design developed by the German professors Pahl and Beitz. Their pioneering work was published in German in 1977 and translated into English in 1984 (Malmqvist et al. 1996), and is now in its third edition (Pahl et al. 2007). The systematic approach is summarized in

Figure 1.3. The overall design of a product is broken down into distinct design activities, each consisting of multiple steps. The hallmark of this method is the use of separate functional modules that when aggregated create a functional model. The major advantage of this approach is the simplification of the subsequent design process for the individual module. Overall, this function-based design method offers several advantages for biologically-inspired design:

- archival and transmittal of design information;
- reduces fixation on aesthetic features;
- reduces fixation on some particular physical solution;
- allows one to define the scope or boundary of the design problem as broad or narrow as necessary; and
- encourages one to draw upon experience, knowledge stored in a database or through creative methods during concept generation.

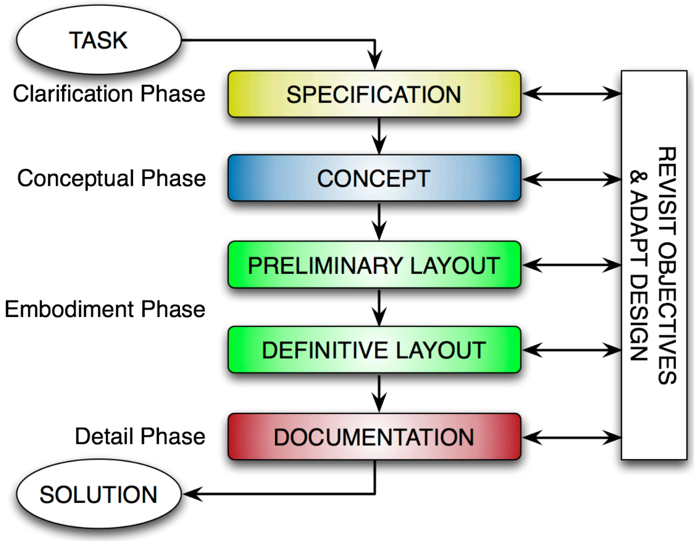

Figure 1.3. Systematic Design Process (Adapted from (Pahl et al. 2007)).

Functional abstraction and representation, as used in systematic design, is recognized as a way to connect nature and engineering through a commonality. This dissertation answers the knowledge requirement problem of working across the biological and engineering domains and, through functional modeling, offers the advantages listed above. Multiple supplementary design tools for existing function-based engineering design methods are developed to enable systematic biologically-inspired design. Together they comprise a framework, which offers guidance for engineering designers in the pursuit of biological inspiration. Such design techniques and tools include a search tool for finding biological inspiration, a thesaurus of biological terms that correspond to engineering terms, a method for developing biological functional models, and two approaches to interacting with biological information for the purpose of concept generation.

In summary, the proposed research approach will provide the necessary support for designers to more quickly access and understand biological information for use with function-based, engineering design methodologies and, thus, eliminate the pre-conceived notions that biomimetic design is unachievable and requires a degree in biology. By creating a bridge between the two domains through the perspective of function, engineers can leverage the simplistic designs found in the world around them.

1.1.2 Practical Motivations

Biomimicry and biologically-inspired design are not widely used in industrial settings currently, which is most likely due to the learning curve. Yet those that keep abreast with the news are likely well aware of the incredible breakthroughs that nature has inspired or have at least heard of the

Biomimicry Institute[1]. It seems, however, in this particular field that small businesses are more likely to form once a biologically-inspired scientific breakthrough has been made; rather that whole-heartily adopt biomimicry as a new practice. Such as the case with BigSky Technologies LLC[2]. BigSky produces a nanotechnology coating named GreenShield® that offers water and oil repellency, and resistance to stains, microbes, bacteria and fire. The technology was inspired by the lotus flower, which also exhibits repellency. On the microscopic scale, a waxy layer of crevasses cover the lotus which minimizes the contact area of particles such as water and dirt. What makes this revolutionary material really stand out is that by learning from the "lotus effect" researchers were able to develop a material finish using eight times less harmful chemicals which improves material recyclability and overall sustainability. This is just one of many examples where a biologically-inspired design has made an impact. As is evident from the case studies on the Biomimicry Institute website (Biomimicry Institute 2009) and a recent article on the Fast Company website (Walker 2010), there is an industrial interest in learning from biology. Interest from the medical, materials science, sensors, defense, alternative energy, manufacturing and sustainability fields have been shown in the media. What are engineers with a limited background in biology to do? Do they rely on chance? Do they make an attempt to learn the biology as a biologist would know it? How do they begin the discussion with biologists whom they may not be able to communicate very well with? These questions are answered by the framework and methodology.

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[1] www.biomimicryinstitute.org

[2] www.greenshieldfinish.com

By developing a systematic approach to biologically-inspired design, that approaches biomimicry from an engineer's point-of-view, more discoveries and perhaps those of greater significance can be made. Furthermore, integration of biological information with existing design tools will enable designers with a limited background in biology to perform biologically-inspired design. As time progresses we will see what inspired solutions will also make an impact in our everyday lives, society and culture.

1.2 Hypothesis and Objectives

Biomimicry research's potential benefits, applications and current problems have been listed in brief. Having motivated this research in biologically-inspired design, a formal statement of the work that follows in this dissertation is presented. First, the hypothesis concerning biologically-inspired design is posed. The hypothesis is followed by a list of practical objectives of the work.

1.2.1 Hypothesis

The overarching hypothesis of this research is that a systematic approach may be prescribed that makes biological inspiration and solutions accessible to every design problem. Direct benefits from following a methodical, biologically-inspired engineering design approach are the ability for engineers with a limited background in biology to interface with biological information, transform the biological information into an engineering context and perform biologically-inspired design.

1.2.2 Objectives

The objectives of this dissertation are:

1. Identify relevant biological systems that solve a desired function.
2. Translate relevant biological information from a biological context into an engineering context.
3. Formalize a functional representation method that captures the biological functionality such that it can best be exploited by designers.
4. Investigate approaches to function-based concept generation utilizing biological information.
5. Formalize an overall methodology for systematic biologically-inspired, engineering design.
6. Apply the systematic method to demonstrate the design of an innovative product.

1.3 Scope

This work is an attempt to establish a methodology that will identify opportunities for biologically-inspired design based on functional representations of biological systems. Functional representations are abstractions in the form of functional language (Stone and Wood 2000) and functional models (or function structures) (Pahl et al. 2007). These abstractions provide the designer with insight into what is happening without focusing on a particular solution (e.g., engineering or biological) and facilitates connections to be made between the biological and engineering domains. It is the connections in the form of analogies, metaphors, first principles and direct imitation that a designer must utilize to develop biologically-inspired solutions to a problem.

The methodology relies on a framework of design techniques and tools, as shown in Figure 1.4, that assist with interfacing engineering designers with biological information. Such design techniques and tools include a search tool for finding biological inspiration, a thesaurus of biological terms that correspond to engineering terms, a method for developing biological functional models, and multiple approaches to concept generation with biological information. Connections through terminology are possible with the engineering-to-biology thesaurus, as it maps synonymous engineering function and flow (material, signal, energy) type terms to their biological counterpart. For the search tool, connections are possible through keyword searching with engineering keywords or thesaurus biological correspondents. The returned biological corpus excerpts contain keywords of interest that correspond to the engineering domain, which a designer can use to establish relationships. Biological functional models allow connections to be made directly with engineering components that also solve the same functions. The concept generation approaches provide opportunities for multiple levels (e.g., system, module) of connections to be formed. A single biological system can provide multiple connections when considered from different viewpoints.

It is evident that mimicking biological systems or using them for inspiration has led to successful innovations and will continue to do so. Mimicking nature offers more than just the observable aspects that conjure up engineering solutions performing similar functions, but also less obvious strategic and sustainable aspects. It is the less obvious aspects that this dissertation aims to facilitate as they hold the greatest potential impact for engineering as a whole.

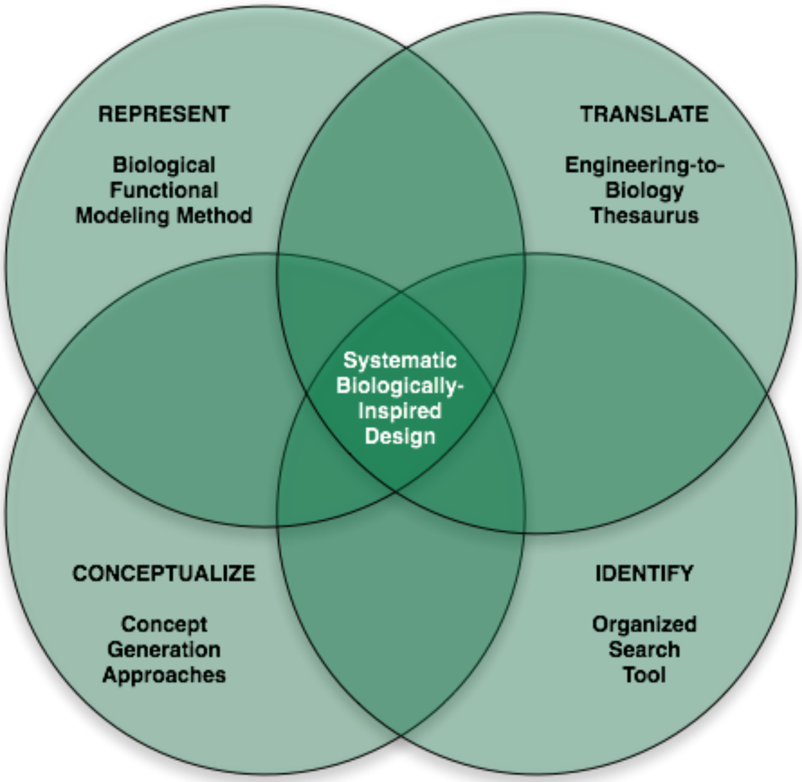


Figure 1.4. Framework Supporting Systematic Biologically-Inspired Design.

An overall methodology for biologically-inspired design ties all the pieces together. It gives a set of steps from problem definition to concept generation. Validation of the method is explored though reproduction of existing biomimetic products, comparison of biologically-inspired designs to existing designs and the creation of innovative designs. Case studies are used to show the application of the methodology. A problem-driven and a solution-driven case are presented.

On a final note, this research has also been driven by an interest in sensor design and biomimetic sensors. To focus solely on researching and developing a methodology for designing biologically-inspired sensors would not be a great service to the field of engineering design. However, biomimetic sensor design provides a wonderful challenge and test of the methodology developed in this dissertation and will be a recurring theme throughout.

1.4 Contributions of this Work

This research contributes to the field of engineering and more specifically the discipline of engineering design by assisting designers with formulating connections between biological information and engineering systems to drive an innovative design process. Systematic design of biologically-inspired engineering solutions arises from using the framework established in this research to identify, translate and represent biological information for the conceptualization of innovative solutions. Overall, this research aims to eliminate the element of chance, facilitate discovery of creative concepts and reduce the time and effort required for biologically-inspired design.

This dissertation makes multiple contributions to biologically-inspired design in particular and to engineering design in general. The contributions are summarized as the following:

- Development of design tools and techniques that integrate with existing function-based design methods.
  - A software tool for searching a biological corpus that allows identification of relevant biological solutions based on function.
  - An engineering-to-biology thesaurus that assists with translation of identified biological systems of interest from a biological context into an engineering context.
  - A method for representing biological information in a functional model such that it can be used for engineering design activities.

  - Multiple approaches to the conceptualization of biologically-inspired engineering designs.
- A systematic design methodology that will identify opportunities for biologically-inspired design based on functional representations of biological systems.
- Archival of functionally decomposed biological systems in a design repository for future design reuse.
- Immediate integration of archived biological design information with undergraduate and graduate design courses. Students will be exposed to biology as a source of ideas for engineered solutions.
- This research challenges traditional engineering design theory and methodology which has been reserved for mechanical and electro-mechanical designs to also include purely electrical designs (e.g., sensors).

1.5 How to Use this Document

Throughout this document, each chapter will begin with an overview containing a synopsis of the chapter and what can be expected within the chapter. A quick read of this first section will tell you specifically what is in store for that chapter. If you are new to biologically-inspired design and functional abstractions, Chapter 2 will provide an introduction to the topics along with example applications. Chapters 3-6 provide a detailed view of the research that comprises the framework needed to bridge the biological and engineering domains for design. The "big picture" inclined will appreciate Chapter 7, which explains how all the pieces of the framework fit together.

Finally, for the applied folks, Chapter 8 and 9 will provide two case studies of biologically-inspired design.

Chapter subject matter in brief:

Chapter 2 outlines many of the contributions to biologically-inspired design, abstractions in design and biomimetic sensors. Those unfamiliar with biologically-inspired design and its many approaches should review the first section. The following section describes the role of functional abstractions in engineering design and sensor design, along with their many forms. A focus on functional modeling is provided as this research is from the perspective of function. Also, the chapter introduces the concept of biological sensing, their classification and multiple biomimetic sensors that have been documented in literature.

Chapter 3 presents the work to achieve identification of relevant biological inspiration. The organized verb-noun search strategy is introduced along with the algorithm and two iterations of the search software. A set of search heuristics are also offered, which are intended to the increase the likelihood of a successful search for biological inspiration based on a functional model. Finally, an example of smart flooring is presented used to verify the search tool and its application to biologically-inspired design.

Chapter 4 presents the work to achieve translation of biological information into engineering speak. The structure, population method, particulars and terms of the engineering-to-biology thesaurus are reviewed. It also presents the integration effort taken to compile a well-rounded set of biological function correspondent terms. Examples that verify two of the many applications of the thesaurus are provided along with discussion.

Chapter 5 presents the work on representation of biological information for function-based engineering design activities. A method for creating biological functional models is given along with an in-depth look at the concepts of biological category and scale. An example of insect chemoreception to verify the biological modeling methodology is given.

Chapter 6 presents the work on conceptualizing engineering solutions with a mixture of engineering and biological information. Two approaches that integrate with existing function-based engineering design tools and methods are presented and discussed. Additional considerations for the two approaches, such as combining inspirational systems into a single concept, are given along with the advantages to each approach.

Chapter 7 discusses the framework for function-based biologically-inspired design and presents the systematic design methodology. Along with the individual steps, the problem-driven and solution-driven approaches of the method are reviewed. Method validation through reproduction of existing biomimetic technology and generation of biologically-inspired concepts that have nearly identical functionality, morphology and components to existing technology is presented. Finding a closely related developed version of the biologically-inspired conceptual design indicates that the concept is feasible.

Chapter 8 contains a case study applying the systematic design method of Chapter 7. A chemical sensor design is developed following the traditional needs based flow chart of the problem-driven approach. Several interesting biological systems are identified, analyzed, reflected upon and utilized to inspire multiple concept variants. The reader is walked through thought processes, model iterations and connections formed that facilitate leaps from biology to engineering.

Chapter 9 contains a second case study applying the systematic design method of Chapter 7. This chapter demonstrates how a designer can follow a curiosity and turn it into a worthwhile design. Lichen is the biological system of curiosity used to inspire a solar thermal collection device following the solution-driven approach. The Design Repository housed at Oregon State University and a broad knowledge of many disciplines are key to a successful design following this approach. The reader is walked through thought processes, model iterations and connections formed that facilitate leaps from biology to engineering.

1.6 Summary

This chapter introduced the biologically-inspired design problem under consideration in this dissertation. In this chapter, several terms were used that may seem unfamiliar. Those that were introduced and several others that form the vocabulary for this research are summarized here.

Biomimicry is a design discipline devoted to the study and imitation of nature's methods, mechanisms, and processes to solve human problems.

Biologically-Inspired Design is an approach to solving human problems that requires taking inspiration from nature. The inspired solution can be completely new or encourage consideration of current components, materials, etc. in a new way to develop a novel solution.

Biological organism is a biological life form that is observed to exist.

Biological phenomenon is a biological event or occurrence that can be observed.

Biological strategy is a biological action that is observed to exist.

Biological system is any biological organism, organism sub-system, portion of an organism, phenomenon or strategy (i.e., Bacteria, sensing, grasshopper, insect compound vision, DNA, human heart, abscission, pore exposure).

Physiology refers to the function or functions of a biological system.

Morphology refers to the structure of a biological system.

Behavior refers to the reaction of a biological system to a stimulus.

Corpus is a collection of written material in machine-readable form, assembled for the purpose of studying linguistic structures.

Design methodology is an orderly arrangement of steps concerned with the application of engineering principles to solve a real problem. While design methodology is commonly associated with the creation or modification of devices, it is not limited to devices. A design methodology is said to be systematic when the steps are structured and ordered in a specific way.

Original design is the process of gathering customer needs, abstracting the problem, decomposing the overall function, generating concept variants, selecting a concept variant and embodying that variant for a new problem.

Conceptual design refers to the part of either original design or reverse engineering where the overall function is decomposed and concept variants (for an entire device or only a part of a device) are generated and selected.

Decomposition is the process of decomposing an overall problem or function into smaller parts or sub-functions. A functional model or function structure is a graphical method of decomposition.

Functional Basis is a well-defined modeling language comprised of function and flow sets at the class, secondary, tertiary levels and correspondent terms.

Functional model is a visual description of a product or process in terms of the elementary functions and flows that are required to achieve its overall function or purpose.

Function is an action being carried out on a flow to transform it from an input state to a desired output state.

Flow is the material, signal or energy that travels through the sub-functions of a system.

In the chapters that follow, the individual parts of the framework for supporting systematic design of biologically-inspired engineering solutions will be explored along with validation cases and case studies applying the methodology in efforts to make a convincing case for the relevance of biologically-inspired design.

CHAPTER 2 - BACKGROUND

2.1 Overview

This chapter provides the majority of the background information relevant to the research in this dissertation. Four major topics are reviewed here, biological inspiration methods for design, functional abstractions, sensor design and biomimetic sensors. Engineering solutions inspired by biology have been arrived at through a multitude of perspectives and schools of thought. A brief introduction to several research efforts in the areas of inspiration facilitators, representation methods, information transfer methods, concept generation techniques and two holistic design approaches are provided. Next, functional abstractions used within the fields of engineering design and electronic design are reviewed. With my interest in sensor design and development of biologically-inspired sensors, a short introduction to sensor design followed by an overview of current biomimetic sensor research is also presented. Related research that applies to only one specific chapter has been reserved for introduction in the respective chapter.

2.2 Biology in Engineering Design

The name *biomimetics* was coined by the biophysicist Otto Schmitt during the 1950s (Schmitt 1969). During that same time period U.S. Air Force flight surgeon and psychiatrist Major Jack Steele coined the term *bionics* (Steele 1960), which is widely used in Europe. It was not until the 1990s that the term *biomimicry* was popularized by Janine Benyus (Benyus 1997) who founded the Biomimicry Institute. However, biologically-inspired or bio-inspired are more preferred in engineering design to avoid confusion between cybernetics and medical bionics, but also to include solutions that were inspired by biology and do not directly copy a specific feature.

Biologically-inspired solutions are often novel and innovative, but generally, the inspiration happens by chance or through dedicated study. With biologically-inspired design emerging as its own field, engineering design research has begun to investigate methods and techniques to systematically transfer biological knowledge to the engineering domain. The main goal of these research efforts is to create methods, knowledge, and tools to facilitate design activities. Prominent research in biologically-inspired design theory has led to focused investigation of and searching for inspiration facilitators, representation methods, information transfer methods, and concept generation techniques.

2.2.1 Inspiration Facilitators

Inspiration facilitators for biologically-inspired design include keyword searching and the development of analogies between biological and engineering principles, components and systems. Focused searching for biological inspiration has been achieved through keyword searches of a biological corpus. Hacco and Shu devised a search process that uses natural language processing to identify relevant non-technical keywords for searching a biological corpus (Hacco and Shu 2002). Inspiration for a remanufacture problem was generated at different levels of biological organization using the search process. Later, Chiu and Shu refined the method for identifying relevant biological analogies by searching a biological corpus using functional keywords (Chiu and Shu 2007a; Chiu and Shu 2007c). The engineering domain keywords are expanded using WordNet to create a set of natural-language keywords to yield better search results.

Although keywords can lead to analogies drawn between biology and engineering there are several efforts devoted to formulating those types of analogies. Nachtigall has spent many years identifying analogous systems in nature and produced several books that catalog his findings (Nachtigall 2002; Nachtigall 2003; Nachtigall 2005). The books are intended to provide a designer or manufacturer with a large pool of creative implementations to spur more applications. Mak & Shu examined the processes involved with the selection and use of relevant biological phenomena (Mak and Shu 2004). It was found that analogies based on strategies, rather than those based on descriptions of phenomena that focus on forms and behaviors are more likely to lead to a suitable design. Research by Linsey et al. explores a method of breaking down products into a vocabulary that can then be easily transferred to an analogous system (Linsey et al. 2008). Their findings show that representing systems of interest in a semantic form increases the probability of innovation of novel, analogous systems. Hey et al. provides a thorough overview of the relationship between metaphor and analogy use in the design process and offers biomimetic examples (Hey et al. 2008). In a similar vein, Vattam et al. provides a thorough analysis of creative analogies in biologically inspired design and their theoretical foundations (Vattam et al. 2009). Tsujimoto et al. have researched deriving inspiration from the behavioral aspects of natural phenomena rather than simply mimicking it, with applications to robots and computer graphics (Tsujimoto et al. 2008).

2.2.2 Representation Methods

Representation of biological systems for engineering design has taken many avenues. Chakrabarti, et al. developed a software package entitled Idea-Inspire that interfaces with a database of natural and complex artificial mechanical systems categorized by a verb-noun-adjective set that captures the principle of the system (Chakrabarti et al. 2005; Sarkar et al. 2008). Each database entry is further classified under seven behavioral constructs. These comprise the SAPPhiRE model of causality (Srinivasan and Chakrabarti 2009a; Srinivasan and Chakrabarti 2009b). Vincent et al. uses TRIZ (Theory of Inventive Problem Solving) to abstract and categorize biological systems by the generalized engineering problems that can be solved by biology (Vincent and Mann 2002). The result was a BioTRIZ matrix that can be used simultaneously with the standard TRIZ matrix. Wilson and Rosen explored reverse engineering of biological systems for knowledge transfer (Wilson and Rosen 2007). Their method results in a behavioral model and truth table depicting system functionality. Vattam et al. investigated the use of compound analogical design models to convey function, sub-function, adaptation and analogous solution information (Vattam et al. 2008). The compound analogy is derived from a combination of biological systems that solve the same design problem. Nagel et al. explored how to apply functional modeling with the Functional Basis to biological systems to discover analogous engineered systems; however, only engineered designs with more obvious biological counterparts were considered (Nagel et al. 2008b). Their research was merely an exploration on the feasibility of modeling biological organisms with functional models, and as such, it stops short of providing a methodology or approach that may be used for repeatable functional model generation. However, it sparked additional efforts in researching functional modeling for biologically-inspired design (Shu et al. 2007; Vakili and Shu 2007). Some of the resultant models were entered into a design repository for archival and for use with existing automated concept generation techniques.

2.2.3 Information Transfer Methods

Conveying biological information in an engineering context has led to methods of aesthetic design, material design, determination of biologically meaningful terms and transferring biological principles. Wen et al. have developed the Product Design from Nature method that assists designers with inspiration based on biological geometric features (Wen et al. 2008). Vincent has performed extensive research in the area of biologically-inspired materials and has identified the major categories of natural materials and explains how engineers can potentially benefit from each (Vincent 2004). Cheong et al. have worked to provide designers with biologically meaningful words that correspond to Functional Basis functions based on semantic relationships (Cheong et al. 2008). Synonyms, troponyms and hypernyms of functions were identified. Hill recognized that multiple disciplines could benefit from studying the natural world and that it leads to innovation (Hill 1995). However, he suggests that ways "of thinking and acting which overcome the gap between models in nature and the technological solution" should be integrating into pedagogy. Also recognizing that biological principles offer inspiration for innovation were Lindemann & Gramann whom developed a procedural model for knowledge transfer (Lindemann and Gramann 2004). The procedural model prescribes one to make analogies, abstractions and correlate biological principles to technical systems, but loosely defines the steps and tasks needed.

2.2.4 Concept Generation Techniques

Concept generation techniques for biologically-inspired design include diagrammatic and textual descriptions of biological organisms, strategies or phenomena. The work of Chakrabarti et al. and Vattam et al. use images and models to develop concepts (Chakrabarti et al. 2005; Sarkar et al. 2008; Vattam et al. 2008). Vincent uses the engineering contradictions of TRIZ to develop complete concepts. Another database driven approach is the work by Wilson et al. (Wilson et al. 2009). They present a design repository for storing and retrieving biological and engineering design knowledge through the use of description logics, which aims to reduce the number of irrelevant results. Research by Vakili and Shu explored a biomimetic concept generation process for finding suitable analogies for engineering problems (Vakili and Shu 2001). A checklist was developed to assist with the method. Mak and Shu studied the use of biological phenomena descriptions for idea generation (Mak and Shu 2008). Participants were provided with support for analogical mapping and a variety of concepts were developed.

2.2.5 Holistic Design Approaches

Very few holistic design approaches to biologically-inspired design exist to date. The two most notable are the design spiral of the Biomimicry Institute and the problem-driven and solution-based methods of the Design Intelligence Laboratory. Steps within the design spiral address, "physical design, ... manufacturing process, the packaging, and all the way through to shipping, distribution, and take-back decisions" (Biomimicry Institute 2010). There are six phases within this process: identify, interpret, discover, abstract, emulate and evaluate. Each phase is comprised of multiple steps, similar to the systematic process of Pahl and Beitz. The two processes for biologically-inspired design developed by Helms et al. involve defining the biological solution, extraction of the biological principle and application of the biological principle (Helms et al. 2009). Specifically, the problem-driven approach follows a set of steps that define the problem, reframe the problem, search for biological solutions, define biological solutions, extract the biological principle and apply the biological principle. It was found through a study that designers tend to fixate on a biological system that they think will solve the problem without thorough investigation. The observed actions were analyzed and named the solution-based approach. The solution-based approach follows the order of identify a biological solution, define biological solution, extract the biological principle, reframe solution and search for a problem that the solution might solve. Both diagrammatic and textual descriptions are used in the design processes. Neither holistic design approach provides or suggests design tools to carry out the steps, thus, it is at the discretion of the designer.

2.3 Functional Abstractions

This section introduces the multiple forms of functional abstractions that are related to this dissertation. The two major subject areas covered in the following sections are functional abstractions for engineering design and sensor design. Functional abstractions for engineering design utilize conceptual ideas and high level representations disregarding actual operation, where as for sensor design they are typically mathematically defined.

2.3.1 Functional Abstractions for Engineering Design

Abstractions perform a fundamental role in the problem solving process. Without appropriate abstractions, many complex problems could not be solved. An abstraction, by definition, allows a problem to be extracted from its foundations in reality, separate from actual instances and reformulated in such a way as to provide a means for problem solvers to solve complex problems (McKean 2005). In science and engineering, abstractions take various forms from Computer Aided Drafting (CAD) models to free-body diagrams or circuit diagrams. To use biology both systematically and repeatedly as a source of inspiration in engineering design, finding an appropriate abstraction is a fundamental issue. This research proposes using functional modeling to represent biological organisms in a repeatable and systematic manner. Functional modeling is often considered a fundamental step in the engineering design process (Miles 1961; Dieter 1991; Cutherell 1996; Otto and Wood 2001; Ulrich and Eppinger 2004; Pahl et al. 2007; Erden et al. 2008; Ullman 2009) allowing a design problem to be quickly abstracted from customer needs and design requirements without requiring the design team to consider potential components, solution principles or potential feasibility.

Numerous parallel functional modeling approaches have been developed. For example, Umeda and Tomiyama's Function-Behavior-State (termed Function-Behavior-Structure in (Umeda et al. 1990)), state is the physical description of an entity in a design, behavior is the change in the state and function is the realization of the behavior through the use of the design (Umeda et al. 1990). Structure-Behavior-Function similarly uses structure to represent a physical description for components, function is the pre- and post- conditions for the behavior of the system, and behavior is the transition between states (Goel and Chandrasekaran 1992; Goel et al. 2009). Welch and Dixon use behavior as representation of how the system will meet the required functionality. Function, in their approach, defines what a system is going to do, and the conceptual design process is the transition from function-to-behavior-to-structure (Welch and Dixon 1992). Function-Behavior-Structure, developed by Gero, similarly follows the evolution as a conceptual design moves from function variables to behavior variables to structure variables (Gero 1990). Function variables represent requirements for the design; behavior variables represent the intended or anticipated actions of the final system, and structure variables represent the physical form of the system. To capture environmental interactions, Gero's approach is expanded in situated Function-Behavior-Structure (Gero and Kannengiesser 2002). The Behavior-driven Function-Environment-Structure (B-FES) modeling framework similarly includes representation for environmental interactions of the system and proposes a direct mapping from function to behavior to physical structure (Tor et al. 2002; Zhang et al. 2002).

In this research, flow-based functional modeling (Pahl et al. 2007) based on the Functional Basis (Hirtz et al. 2002) has been chosen to represent biological systems. This form of functional modeling can trace its roots back to Value Analysis with the work of Miles (Miles 1961) and Rodenacker (Rodenacker, W., 1971). Miles develops a functional representation on the basis that a product's usefulness stems from its functionality (Miles, L., 1961). Rodenacker develops models based on the functional transformation of energy, material and information to describe a product functionality, and defines the functions for conceptual design based on Value Analysis (Rodenacker 1971). This early work in Value Analysis is expanded through the proposal of additional functions by Roth (Roth 1982), which is further formalized through Koller's proposal of twelve basic functions (Koller 1985). At a high level of abstraction, Pahl and Beitz develop a list of five generally accepted functions and three flow types (Pahl and Beitz 1984). Hundal then proposes a set of six function classes in (Hundal 1990), but excludes the flow of information, which are re-added to the structure by Little et al., with the functional basis set (Little et al. 1997). Standardized sets of function and flow terms are then proposed separately by Szykman (Szykman et al. 1999) and Stone (Stone and Wood 2000); these function and flow terms are reconciled by Hirtz et al. into the Functional Basis (Hirtz et al. 2002) to form a standard lexicon consisting of two sets of morphemes—one for functions and another for flows. Each set of morphemes is comprised of three levels of detail: primary, secondary, and tertiary and is provided at the primary and secondary levels of detail (classes) in Tables 2.1 and 2.2.

Table 2.1. Primary and secondary function classes (Hirtz et al. 2002).

(Class) **Primary**	**Branch**	**Channel**	**Connect**	**Control Magnitude**	**Convert**	**Provision**	**Signal**	**Support**
Secondary	Separate	Import	Couple	Actuate	Convert	Store	Sense	Stabilize
	Distribute	Export	Mix	Regulate		Supply	Indicate	Secure
		Transfer		Change			Process	Position
		Guide		Stop				

Creating models, as detailed in (Pahl et al. 2007), begins with the overall functionality (often termed a black box) of the product. This black box model, the top model in Figure 2.1, defines the transformation of all required input flows into the desired output flows for a design. The high-level function may be decomposed into sub-functions repeatedly, the bottom model of Figure 2.1, until all of the desired functionality for a product has been identified. Each level of detail is based on transformation of flows available at the highest level of detail.

Table 2.2. Primary and secondary flow classes (Hirtz et al. 2002).

(Class) **Primary**	**Material**	**Signal**	**Energy**		
Secondary	Human	Status	Human	Electrical	Mechanical
	Gas	Control	Acoustic	Electromagnetic	Pneumatic
	Liquid		Biological	Hydraulic	Radioactive
	Solid		Chemical	Magnetic	Thermal
	Plasma				
	Mixture				

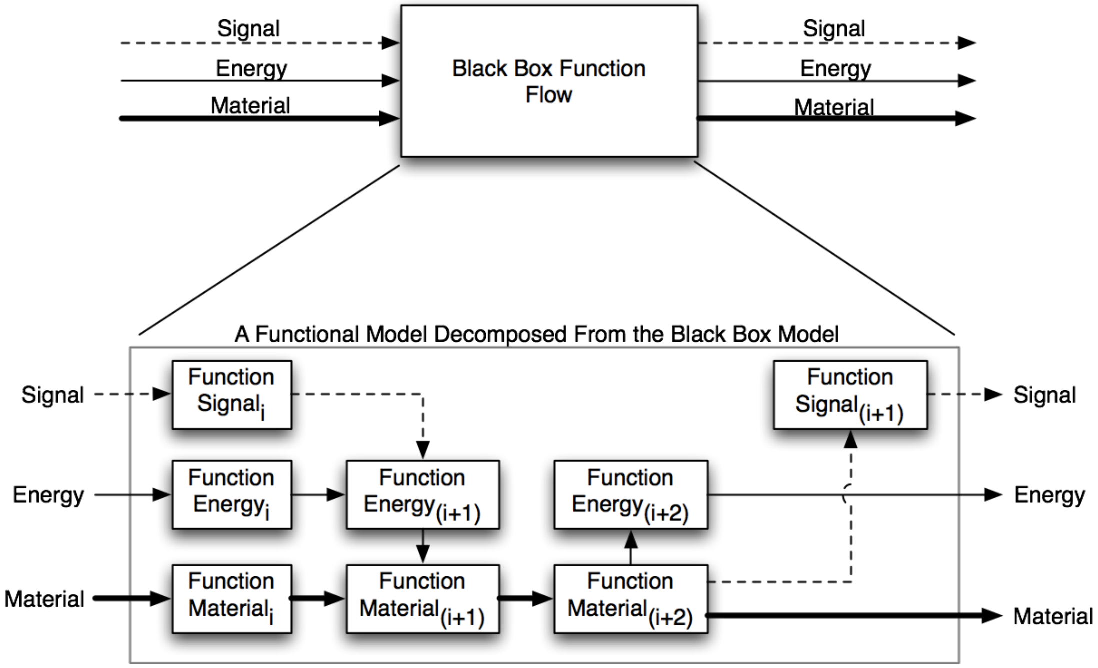


Figure 2.1. Concept of Black Box and Functional Models.

2.3.2 Functional Abstractions for Sensor Design

Functional abstractions used in the design of electrical systems have taken on many forms, from schematic diagrams to behavioral diagrams to integrated functional blocks. The form that is closely related to the functional abstractions used in engineering design are the integrated functional block diagrams. Electronic circuit and system design is largely governed by standards set for individual components, which are manufactured outside the workplace concerned with the design of complete circuits and systems (Novák 1980). In the case of integrated circuit design at the microelectronic level, the realization of individual components is identical with that of a complete circuit (Novák 1980), thus leading to a more complex problem. To address design complexity Novák offers, "comprehensive information mainly in the field of methodology" through modeling elements of microelectronic circuits using integrated functional blocks (Novák 1980). The methodology suggests treating groups of common individual components as modules, and integrating those modules together to complete the circuit. Integrated functional blocks are abstractions of multiple components that when put together form a useful module. A designer can sketch out a circuit concept using these functional blocks, much like the functional model of systematic design, and then choose suitable modules that achieve the design needs and constraints. This practice allows one to utilize previous design knowledge during circuit synthesis, spend less time re-inventing a circuit and capitalize on pre-determined reliability and cost information. When choosing a solution for a function block a designer needs to consider the modules' classification (i.e., analog, discrete, linear, nonlinear, passive, active), surface area, cost, power consumption, weight, reliability and number of components. Examples of integrated functional blocks are: logic elements, amplifiers, analog-to-digital converters, and shift registers. Although the concept of integrated functional blocks was formulated before computers were a necessary tool for engineers, they are an integral part of circuit simulation software packages (e.g., PSpice, Multisim, Mentor Graphics).

A similar method to integrated functional blocks is analog behavioral modeling for integrated circuit design, which recognizes an abstraction hierarchy. The hierarchy consists of conceptual, system, functional and device levels of abstraction, in that order (Duran 1998). Within this format, functional blocks comprise the system, but can be individually verified. Once defined they are "modeled and verified through behavioral modeling, macro-modeling, and simulation" (Duran 1998). These functional models are abstractions of physical components that will be implemented within a signal "chip" or integrated circuit and aim to define the physical behavior mathematically. In the area of VHSIC (very-high-speed integrated circuit) hardware description language-analog and mixed-signal extensions (VHDL-AMS) functional abstractions are also just one level in the abstraction hierarchy: functional, behavioral, macro, and circuit level (Huss 2001). Just as with the previously described method, the functional abstractions are realized through mathematical functions. The resulting representation yields a block diagram, a wide spread specification means used in automation and control engineering as well as in digital signal processing (Huss 2001). What these two methods have in common with the functional models of systematic design is the mapping of input to output signals. The difference is the signal flow is transformed quantitatively by algebraic and differential equations rather than qualitatively by an abstract concept of function.

In the area of digital system development an extensive model taxonomy and format has evolved over the years (Bailey 2005). Within digital system design there exist four primary model classes, two specialized model classes and two computational model classes. Of the primary classes, functional models are “timeless algorithmic models” while behavioral models “add time to function” (Bailey 2005). Structural models “build up models from other models” (i.e., represent interconnections) and interface models “separate the specification of internal function in a model from the specification of its externally visible part, such as the communications protocol it uses” (Bailey 2005). Although specific implementation is not given in a functional model, it accurately depicts the physics that govern operation of a system or component. These mathematically based functional models are abstractions of components, algorithms, and modules that may be implemented in a digital system, but also verified via computer simulation. Digital system functional models are similar to the performance functional models of systematic design that include physical equations (Pahl et al. 2007). Additional similarity between digital and systematic design is the consideration of multiple levels of abstraction.

2.4 Sensor Design

Sensors are an integral part of many engineered products, systems, and manufacturing processes as they provide feedback, monitoring, safety, and a number of other benefits. Development of sensor technology is an exciting area of research as it spans engineering, science and technology. As products become increasingly autonomous and technology ubiquitous in our daily lives, sensors provide the necessary input to make these ideas a reality. Sensors come in a number of scales from prepackaged, calibrated and ready for use for industrial operations down to an individual IC style component that will be integrated into a future product. No matter the application, the first question the designer must address is “what is the measurand?”, meaning, what is the parameter to measure (Fraden 2004). From there, a series of questions about the resolution, environment, accuracy, calibration, span, mounting, etc. derived from empirical knowledge are posed (Wilson 2005) and some may go unanswered. As Wilson explains, “all environmental, mechanical and measurement conditions must be considered” (Wilson 2005). However, sensor technology handbooks focus on providing reference material for several types of sensors and do not prescribe a methodology for design. Rather, information on standards and combined practical information on diversified subjects related to the most important physical principles, design and use of various sensors are presented (Frank 1996; Webster 1999; Fraden 2004). Frequently, industrial white papers, resource guides, original equipment manufacturer application notes and empirical design guides are suggested for further reference (Frank 1996; Fraden 2004; Wilson 2005). Electronic product design books are available, however, they assume the designer is above the novice level and focus on providing check lists for specific types of designs (Stillwell 1989; Ward and Angus 1996; Haskell 2009).

Even with the wealth of information available to a sensor designer, depending on the focus and knowledge of the designer (e.g., electron transport, transducer, packaging, complete device) the design can quickly become overwhelming and follow a disorganized process. Having a set of guiding steps or a design methodology could assist with streamlining the sensor design process. It is clear that a systematic design process is lacking for the development of sensor technology. Fraden states that his book is merely, “to stimulate a creative reader to choose alternative ways of design and to apply nontrivial solutions to trivial problems” (Fraden 2004). The sensor design process can benefit from high level, generalizations of function as used in the design of consumer and electro-mechanical products (Otto and Wood 2001; Ulrich and Eppinger 2004; Pahl et al. 2007; Ullman 2009). By considering what must be done, without focusing on how it is actually accomplished, a designer can take advantage of analogies drawn from other disciplines (e.g., biology). Doebelin confirms this viewpoint, “[o]nce the general functional concepts have been clarified, the details of operation may be considered fruitfully” (Doebelin 2004). Functional abstractions, disregarding specific mathematical behavior, as used in engineering design theory are the key to achieving innovative sensor designs. The formalized method for biologically-inspired design established in this dissertation offers a systematic design process for the development of biomimetic sensor technology, which can assist with system and component level design. Example sensor designs are given in Chapters 7 and 8.

2.5 Biomimetic Sensors

This section provides an overview of the wide range of biomimetic sensor technology being developed, including details about inspiration and innovation. Sensing unusual parameters can require out-of-the-box thinking or borrowing ideas from another discipline. This sort of motivation has allowed nature to impact the field of sensor design. Biomimetic sensor technology is an emerging branch of sensor research (Barth et al. 2003) and offers several advantages over traditional sensor technology. Sensors and sensing systems are an integral part of natural systems as they provide a means for interacting with the environment and support the instinctual actions of sustaining and protecting life. Not only is nature rich with sensing methods, but also it provides strategies associated with the use of those sensing methods. Nature has developed and optimized an incredible variety of sensors for navigation, spatial orientation, prey and object detection, etc., which afford engineers ideas for improvements to current technology, new sensor technology and potential sensor miniaturization (Nachtigall 2002; Barth et al. 2003; Bleckmann et al. 2004).

Studying nature to gain design inspiration or to understand how sensory information is handled by biological systems has resulted in remarkable innovations. Nature has been developing biological sensors for billions of years; therefore the lasting solutions have evolved to fulfill unique ecological niches, which make them ideal for study and imitation. Biological sensors typically exhibit low energy requirements, high sensitivity and redundancy. Although small, having tens or even hundreds of receptor organs in parallel, each containing dozens of receptor cells, promotes parallel sampling and processing of sensory information, which improves the signal-to-noise ratio through averaging (Bleckmann et al. 2004). This also reduces the likelihood of error due to loss of or failure of a receptor organ. A great lesson from nature is redundancy; in most biological systems there are many instances of redundancy.

This background review does not include biosensors, devices that use specific biochemical reactions mediated by isolated enzymes, immunosystems, tissues, organelles or whole cells to detect chemical compounds usually by electrical, thermal or optical signals (Nic et al. 2006). Biomimetic is synonymous with biology- or biologically-inspired, therefore the scope of the sensor technology covered in this review is broadened to include mimicry of biological physiology, morphology, behavior, and strategy.

2.5.1 Biological Sensory Systems

To claim that a biomimetic sensor is one that simply transduces a stimulus, as explained in this section, would designate all sensors on today's market biomimetic. Instead, there must be a unique feature or method of interpreting the stimulus, which mimics a biological sensing solution to classify the sensor as biomimetic. Thus, for biomimetic sensor conceptualization, it is imperative to understand the biology behind natural sensing to leverage the elegance in engineering design. This section covers fundamental knowledge of the biological processes involved during natural sensing and specifically how natural sensing occurs in the Animalia and Plantea Biological Kingdoms.

Natural sensing occurs by stimuli interacting with a biological organism, which elicits a positive or negative response. All organisms possess sensory receptor cells that respond to different types of stimuli. The receptors that are essential to an organism understanding its environment and surroundings, and of most interest to the engineering community, for mimicry are grouped into the class known as extroreceptors. The three classes of receptors are (Aidley 1998; Sperelakis 1998):

- Extroreceptors – External – Light, heat, force, etc.

- Proprioceptors – Internal – vestibular, muscular, etc.
- Interoceptors – Internal without conscious perception – blood pressure, oxygen tension, etc.

Proprioceptors and interoceptors are excellent biological sensing areas to study for developing medical assistive technologies, however, they are not the focus of this research. The receptors of interest are the six families under the class of extroreceptors. Extroreceptors take in stimuli and transduce the signal, which generates a response from the system (Sperelakis 1998). All external stimuli can be recognized by the six different extroreceptors (Sperelakis 1998):

- Chemoreceptors,
- Electroreceptors,
- Magnetoreceptors,
- Mechanorecpetors,
- Photoreceptors, and
- Thermoreceptors.

Once a stimulus excites the biological organism, a series of chemical reactions occur converting the stimulus into a cellular signal the organism recognizes. Converting or transforming a stimulus into a cellular signal is termed transduction. Although all biological organisms share the same sensing sequence of perceive, transduce, and respond, they do not transduce in the same manner. Biological organisms that are capable of cognition have the highest transduction complexity and all stimuli result in electrical cellular signals (Sperelakis 1998). Other organisms have varying levels of simpler transduction, but result in chemical cellular signals (Spudich and Satir 1991). The Kingdom level sensing sequence is summarized in Table 2.3 (Stroble et al. 2009a).

Table 2.3. Comparison of Sensing Sequence for Two Biological Kingdoms.

Biological Term		**Functional Basis Term**	
		Animalia Kingdom	**Plantae Kingdom**
Perceive		Sense	
Transduce	Detect	Detect	Detect
	Amplify	Change	Change
	Discriminate	Process	
	Adapt	Condition	Condition
Respond		Actuate	

Animalia Kingdom:

The Animalia Kingdom simply refers to multi-cellular, eukaryotic organisms capable of cognitive tasks (Purves et al. 2001; Campbell and Reece 2003). Within this set of organisms, transduction occurs in one of two ways (Aidley 1998; Sperelakis 1998):

- Direct coupling of external stimuli energy to ion channels, allowing direct gating, or
- Activation of 2nd messengers - external stimuli energy or signal triggers a cascade of messengers which control ion channels.

Transduction in this Kingdom is a quick process that happens within 10µm - 200ms per stimulus (Aidley 1998). During transduction, a sequence of four events occur, which are uniform across the six receptor families (Sperelakis 1998):

1. Detection (protein binding, signal propagation about receptor cell),
2. Amplification (cascade of intracellular chemical signals),
3. Discrimination (modulation of chemical reactions into an electrical code sent to the nervous system), and

4. Adaptation (over time, a prolonged stimulus has less of an effect).

Recognition of a stimulus happens within the nervous system, as denoted by discrimination in the transduction sequence. Mechano, chemo, thermo and photoreceptors are the dominant receptors in organisms of the Animalia Kingdom, however fish and birds utilize electro and magnetoreceptors, respectively, for important tasks as shown in Table 2.4.

Plantae Kingdom:

The Plantae Kingdom simply refers to multi-cellular, eukaryotic organisms that obtain nutrition by photosynthesis (Purves et al. 2001; Campbell and Reece 2003). Transduction converts external stimuli into internal chemical responses and occurs by either (Mauseth 1997; Sperelakis 1998):

- Direct coupling of external stimuli energy to ion channels, allowing direct gating, or
- Activation of 2nd messengers - external stimuli energy triggers a cascade of messengers which control ion channel gates (most common).

Transduction within plants is a slow process, often taking hours to complete. Cross talk between signaling pathways permits more finely tuned regulation of cell activity than would the action of individual independent pathways (Berg et al. 2007). However, inappropriate cross talk can cause second messengers to be misinterpreted (Berg et al. 2007), much like high frequency circuits that couple to other electronic devices causing an undesired effect. During transduction a sequence of three events occur, which are uniform across the six receptor families (Sperelakis 1998):

1. Detect (protein binding and signal propagation about receptor cell),

2. Amplify (cascade of intracellular chemical signals), and
3. Adaptation (change in turgor pressure or chloroplast orientation).

Photo, mechano, chemo, magneto and thermoreceptors, in that order, are the dominant receptors in organisms of the Plantae Kingdom as shown in Table 2.5. Particular stimuli result in particular reactions, which are known as tropisms in this Kingdom. Electroreceptors are the least understood in Plantae Kingdom organisms and experiments do not provide consistent results, however, it has been suggested that electrical signals can traumatize organisms of this Kingdom (Spudich and Satir 1991).

Table 2.4. Example Animalia Kingdom Sensations Resulting from Stimuli.

Receptor Family	**Sensations that are Detected**
Chemo	Taste, Smell
Electro	Electrolocation, Impedance changes, Conductivity changes
Magneto	Flight navigation
Mechano	Vibration, Pressure, Stretch/strain, Force, Muscle/joint position, Hearing (sound pressure), Water flow (fish), Orientation (lateral line in fish), Angular velocity (halteres), Echo-location (dolphins ,bats)
Photo	Light (vision), Polarized light detection, IR
Thermo	Heat/IR, Cold

Table 2.5. Example Plantae Kingdom Sensations Resulting from Stimuli.

Receptor Family	**Sensations that are Detected**
Chemo	Starvation, Growth
Electro	Possible trauma
Magneto	Gravity
Mechano	Pressure/force, Stretch/strain, Wounding, Wrapping around an object
Photo	Light (solar energy), Growth, Chloroplast movement, Turgor changes (water)
Thermo	Heat, Cold

2.5.2 Classification

Adapting many of the features and characteristics of biological systems can significantly improve sensor technology. The basic concepts behind sensory physiology, the fundamental ideas of how biological systems relate to their environment, can be adopted as a working model to construct different types of sensor technology (Martin-Pereda and Gonzalez-Marcos 2002). However, not all biomimetic sensors function identically to the biological sensory system being mimicked. Once the biological system is fully understood, the engineer can decide if direct or analogous mimicry is the best course of action. Direct being copy one for one and analogous being comparable in only some aspects. Both types of design have been successful and have led to sensor technology innovations. Directly copying the functionality, principal, morphology behavior or strategy of the biological system is the easiest form of biomimicry. This procedure is much like reverse engineering a biological system (Wilson and Rosen 2007). However, abstracting the biological system using analogical reasoning, allows an engineering designer to look for a specific solution through mimicry (Mak and Shu 2004). This background aims to provide a glimpse of what biological sensing systems have fascinated engineers to the point of mimicking them.

There are a number of specific sensor types, however, to present the various biomimetic sensors in this review, the classification scheme by (White 1987) and later updated by (Fraden 2004), is utilized. Through this scheme, sensors can be grouped into ten categories:

- Acoustic,
- Biological,
- Chemical,
- Electric,

- Optical,
- Magnetic,
- Mechanical,
- Radiation,
- Thermal, and
- Other,

with over 40 types of measureands in nine categories. The sensor type categories of biological and other do not apply to biomimetic sensors and will be left out of this review. Extensive research of published biomimetic sensors has resulted in 33 different documented sensors, which are categorized in Table 2.6. A majority of the sensors have inherent mechanical qualities measuring strain, force, deformation, position etc., typically with voltage.

Table 2.6. Sensor Breakdown by Type Classification.

Type	Acoustic	Chemical	Electric	Optical	Magnetic	Mechanical	Radiation	Thermal
Number	6	5	7	2	0	12	0	2

To understand where engineers are focusing their research in sensors from a biological perspective, further refinement of the sensor classification is needed. The refinement is achieved by using the biological classifications for sensing, which are the six families of extroreceptors, proprioceptors and interoreceptors. Table 2.7 shows that the majority of biomimetic sensors mimic the mechanorecptor with chemoreceptors and photoreceptors as the second highest of interest. As previously mentioned biological systems have diverse function and form; this can be further identified by the groupings of sensor types under receptor types. The majority of the electric type sensors of Table 2.6 fall under the photoreceptor type of Table 2.7 because those sensors mimic vision or the way light is interpreted in nature. Electric and optical type sensors are extremely versatile with the ability to measure a variety of parameters, which allows them to span many receptor types.

Table 2.7. Sensor Breakdown by Mimicked Sensory Physiology.

Receptor Type	Mechano	Photo	Chemo	Thermo	Electro	Magneto	Proprio
Sensor Type	Acoustic, Mechanical, Electric	Optical, Electric	Chemical, Electric	Thermal, Radiation	Electric, Optical	Magnetic, Optical	Mechanical, Electric
Number of Sensors	16	6	6	2	1	1	2

2.5.2 Biomimetic Sensors by Classification

The following sub-sections provide insight into the technique chosen for mimicry, what portion of the biological system was imitated, the innovation afforded and what extroreceptor type the biomimetic sensor technology falls under. A short description for each sensor type is also provided. All of the sensors reviewed are captured in Figure 2.2.

Acoustic Sensors:

Acoustic type sensors are excited by longitudinal mechanical (sound) waves with certain frequencies created by alternate physical compression and expansion (oscillation or vibration) of a medium such as gas, liquid or solid, which are a function of temperature. To date, principles from the human inner ear cochlea, and dolphin and bat echolocation have been utilized for inspiration. All acoustic sensors described in this sub-section are of the mechanoreceptor type. A cochlear amplifier design has been shown to outperform typical surface acoustic wave resonators by narrow-band frequency analysis over a broad range through active dampening (Bell 2006). The structural parallels suggest direct mimicry of cochlear morphology. An analog auditory sensing

Acoustic
- Cochlear amplifier
- Cochlear speech recognition system
- Dolphin based sonar receiver
- Binaural dolphin echolocation system
- Micro echolocation system
- Binaural bat echolocation system

Chemical
- Artificial human tongue
- Artificial chemical recognition sites
- Piezoelectric artificial human nose
- Conducting polymer artificial human nose
- Chemo-fluorescent artificial human nose

Electric
- Artificial electrolocation device
- Fly based vision system
- Fly based, hexagonal oriented vision system
- Fly based, non-camera motion detection system
- Artificial bilayer lipid membrane
- Primate eye based vision system
- Human eye based vision system
- Artificial muscle monitoring

Optical
- Artificial ommatidia array
- Vision-based magnetic compass

Mechanical
- Artificial halters
- Artificial muscle spindle
- Artificial meissner corpuscles
- Artificial lateral line system
- Artificial arthropod hair cell
- Artificial cricket filiform hair array
- Campaniform sensillum strain sensor
- Carbon microcoil tactile sensors
- Electroactive polymer muscle
- Micromachined campaniform sensillum strain sensor
- Artificial posture monitoring
- Artificial crustacean antenna

Thermal
- Photo-mechanical IR Sensor
- ThermalSkin

Figure 2.2. Summary of Biomimetic Sensors.

system suppresses background noise during speech recognition in much the same way humans can by directly mimicking the functional principle behind front-end signal processing of the cochlea (Hasler et al. 2002). A new concept for a sonar receiver has been developed based on the morphology and functional principle of the dolphin lower jaw (Dobbins 2007). Direct mimicry leads to the innovation of using endfire arrays in monopulse mode for angular localization, which provides high-resolution output in shallow water (Dobbins 2007). This is of the mechanoreceptor type. Two very similar sensors, that additionally mimic the dolphin's behavior directly, replicate echolocation through strategic movements to maximize binaural information; one used for object localization and identification (Kuc 1997; Kuc 2007) and the other for passive/active remote sensing, homing and communication in unmanned underwater vehicles (Olivieri 2002). A binaural sonar system which directly imitates the physiology and morphology of bat echolocation can reconstruct a complex environment (Reijniers and Peremans 2007). Time-frequency representations are compared with predefined templates to recognize objects (Reijniers and Peremans 2007).

Chemical Sensors:

Chemical type sensors identify and quantify specific substances or chemical reactions in a medium such as gas, liquid or mixture and exhibit selectivity to the desired target substance with little or no interference from surrounding substances. Sensitivity, the minimal concentration or change needed for successful sensing, is synonymous with resolution for chemical sensors. The human senses of taste and smell are currently the focus of research, which aims to replace human taste and smell testers; these sensors can also double as a method for drug "sniffing" and other pharmaceutical applications. All chemical sensors described in this sub-section are of the chemoreceptor type. A microchip with electrode recognition sites or "taste buds" has been developed to measure taste and map the selected compound to the five primary tastes of salty, sweet, sour, bitter and umami (Toko 2000; Toko 2004). The artificial recognition sites directly mimic the physiology of the human tongue. Directly mimicking a human taste bud is a piezoelectric quartz crystal with a molecularly imprinted polymer coating with an enhanced "memory effect," which is inherently stable, long-lasting, can be washed and has high reproducibility (Tan et al. 2001). The bulk acoustic wave sensor demonstrates a shift in the frequency response to indicate the sensed analyte molecules (Tan et al. 2001).

Three approaches to replicating the human nose have been successful at detecting and identifying an odorant. A metal oxide or conductive polymer that changes resistance in the presence of an odorant, atop electrodes, is the most common method which directly mimics the physiology and morphology of the olfactory epithelium thin mucus layer (Nagle et al. 1998; Toko 2000). A less direct method, yet analogous to the olfactory epithelium physiology, is a sensor utilizing a quartz crystal microbalance comprised of a polymer-coated resonating disk that changes mass in the presence of an odorant, thereby changing the resonant frequency of the sensor (Nagle et al. 1998). Also analogous to the olfactory epithelium physiology is a fiber optic sensor coated with a chemically active fluorescent dye that changes polarity in the presence of an odorant (Nagle et al. 1998; Bar-Cohen 2006b). A shift in the fluorescent spectrum indicates an odorant is present through a wavelength change, making this sensor ideal for applications in electrically noisy environments.

Electric Sensors:

Electric type sensors detect analog or discrete electric parameters (electric field, voltage, current, capacitance, etc.) and transform the input into another electric parameter that is output or processed by circuitry. Electric fish, common fly, primate eye, human eye and human muscle system have all provided biological inspiration for the sensors in this category. Directly mimicking the function and morphology of active electrolocation in Mormyriformes, a sensor with dual-purpose electrodes detects, localizes, measures the distance of and analyzes objects (Schwarz and von der Emde 2001; Bleckmann et al.

2004; von der Emde 2004; von der Emde 2007). Electrolocation functions in unfavorable conditions where other sensors fail and falls under the electroreceptor type. A small, low-power analog VLSI implementation of a fly neuronal model provides a remarkably accurate response for small-target tracking (Higgins and Pant 2004; Brinkworth and O'Carroll 2007). This photoreceptor type sensor directly mimics the behavior or strategy of the fly. Analog circuitry inspired by the fly has been developed to imitate the parallel "miniretinal" processing that occurs in hexagonally oriented photoreceptors, directly mimicking the fly's morphology (Wright et al. 2004). Extremely fast throughput, sub-pixel resolution (hyperacuity), and six-fold photon capture (Wright et al. 2004) make this photoreceptor type an improvement over traditional photometric sensors. Also inspired by the fly is a visual sensor that combines motion detection with variable speed scanning, which mitigates the concern of distance and light levels (Viollet and Franceschini 1999). This non-camera approach to motion detection and tracking using local motion detection photodiodes (Viollet and Franceschini 1999) is analogous to the physiology of the fly visual system and puts this sensor under the photoreceptor type.

A neuromorphic vision sensor that directly mimics the morphology of the primate eye foveal region of the retina and neurological behavior of primate visual processing has been developed (Van der Spiegel et al. 2002; Van der Spiegel and Nishimura 2003). This sophisticated vision system reduces the amount of data without losing information for fast processing (Van der Spiegel et al. 2002; Van der Spiegel and Nishimura 2003) and is of the photoreceptor type. A theoretical approach to improving machine vision was proposed by directly modeling the functional architecture of the human vision system (Harvey and Heinemann 1992). Neural networks and vision sensors mimic the location and classification channels to increase object recognition in busy environments (Harvey and Heinemann 1992) and make this of the photoreceptor type. An electronic, implantable sensor, directly imitating the internal proprioceptor physiology of humans, has been created to monitor muscle movements for feedback control of medical prostheses (Loeb and Tan 2005). This is of the mechanoreceptor type.

Optical Sensors:

Optical type sensors are stimulated by light, natural and artificial in the ultraviolet to mid-infrared spectral range, and require a light source, light guidance devices and a photodetector. Changes in the desired parameter (light) can be measured directly, or changes in a light guidance device serving as an intermediary between the desired parameter and detector allows for non-contact measurement of diverse parameter types. Principles from the insect compound eye and magnetically sensitive chemical processes within migrating birds have been utilized for mimicry. The self-aligned microlenses for omni-directional detection, or wide field-of-view, directly imitate the physiology, morphology and manufacture of a compound eye ommatidia array (Jeong et al. 2005). This photoreceptor type sensor is an effort toward true 3D artificial compound eyes (Jeong et al. 2005). A theoretical concept for a vision-based magnetic compass that relies on radical-pair processes directly mimics the sensitivity modulation of the light receptors in the eye (Ritz et al. 2000). This concept is of the magnetoreceptor type.

Magnetic Sensors:

Magnetic type sensors directly measure geo-magnetic or artificial magnetic fields if they are the desired parameter, or detect changes in an artificial magnetic field created as an intermediary between the desired parameter and detector, which allows for non-contact measurement of diverse parameter types. We are unaware of any biomimetic sensor research that fits into this classification.

Mechanical Sensors:

Mechanical type sensors detect parameters associated with mechanical energy (movement, force, strain, flow, etc.) or material properties and transform the parameters into suitable outputs or processed by circuitry. Biological systems that provided inspiration for mechanical type sensors were: insects, mammalian muscles, human skin, arthropods with flexible shells, crustaceans and fish of the chordata phylum. All mechanical sensors described in this subsection are of the mechanoreceptor type. Directly imitating the physiology and morphology of winged insects is an artificial haltare that measures the Coriolis force for use in mechanical flying insects (Wu et al. 2002; Wu et al. 2003). This design provides a significant improvement over microelectromechanical system (MEMS) gyroscopes. A detailed length and velocity sensor directly mimics the physiology, behavior and morphology of the human muscle spindle, which is useful for motion control systems, as well as, medical prosthetics (Jaxx et al. 2000; Jaxx and Hannaford 2004). An artificial muscle constructed of electroactive polymers, analogous to human muscle physiology and behavior, can withstand high torque and requires little voltage to activate (Bar-Cohen 2006b).

The skin and sensitivity of human fingers has been mimicked as a tactile sensor for biorobotic applications. Measuring fractional conditions and the stretch of the skin via a silicone finger with molded bellows and coils provides feedback for adapting grip force and directly mimics the meissner corpuscles physiology (Sano et al. 2006). Also mimicking the meissner corpuscles physiology is a tactile sensor with embedded carbon microcoils floating in polysilicone, which compress and extend freely, yielding a quick and accurate response (Yang. et al. 2005). A strain sensor based on the campaniform sensillum of arthropods directly imitates the behavior of global strain amplification through composite materials, mitigating the need for multiple strain gauges (Skordos et al. 2002). Similarly, a micro strain sensor was fabricated via MEMS techniques to create a SiO2/SiN thin film over a membrane-in-recess (Wicaksono et al. 2004). Both of these designs improve upon current strain gauge sensor technology.

A micro flow detection sensor, which directly mimics the physiology and morphology of chordata hair cells that make up the lateral line system, transfers the bending moment to a horizontal cantilever beam and provides high integration density (Fan et al. 2002; Motamed and Yan 2005). The piezoresistive sensor is coated with parylene to add strength making it robust, lightweight and suitable for distributed arrays. Similarly, an artificial hair cell directly based on the arthropod filiform hair cell has the same characteristics as above, but improves upon sensitivity, which allows for underwater use and provides dipole field measurements (Engel et al. 2006; Yang et al. 2007). An analogous imitation of cricket filiform hair morphology via MEMS technology has resulted in SiRN suspended membranes with SU8 polymer hairs for capacitive flow measurement, electrostatic actuation, effective spring stiffness tuning, and sensitivity to acoustic stimuli (Krijnen et al. 2007; Wiegerink et al. 2007). A complex MEMS fabricated cantilever beam structure with integrated electrical switches is analogous to the antennae physiology of crustaceans (i.e. lobsters), which are evolved hair cells (Ayers et al. 1998; McGruer et al. 2002; Motamed and Yan 2005). These sensors provide a quick response to minute force. The mechanical sensor created to measure transient linear acceleration, direction and magnitude of gravity and angular velocity of a system in 3D space is direct mimicry of the human vestibular system physiology (Dario et al. 2005). This sensor is the only proprioceptor type of this category.

Radiation Sensors:

Radiation type sensors are excited by the emission of charged (α and β particles and protons) or uncharged (neutrons) particles from atomic nuclei, or nuclear electromagnetic γ and x rays. These types of sensors either detect the presence of radioactivity or measure the radiative energy. Biomimetic sensor research that fits into this classification was not found at the time of the literature search.

Thermal Sensors:

Thermal type sensors absorb radiation from the mid- and far infrared spectral range, monitor temperature over a specified range or measure the specific heat of a material. Thermal sensing occurs through contact and non-contact methods. The Infrared (IR) sensing beetles of the genus Melanophila and cutaneous receptors found in human skin has been utilized for inspiration. A novel photo-mechanical IR detector directly mimics the physiology and morphology of the Melanophila pit organs and provides a highly sensitive, cost effective IR sensor (Bleckmann et al. 2004). This technology is an improvement over the popular bolometer design and is of the thermoreceptor type. A robotic navigation device monitors the heat transfer coefficient change from a heated surface to its surrounding environment via fluctuation in the surrounding fluid velocity (Marques and Almeida 2006). ThermalSkin (Marques and Almeida 2006) directly imitates the thermal anemometer principle of human skin and is of the thermoreceptor type.

Nature offers a model and serves as a guide for engineering designers whom are looking outside of the engineering domain for inspiration. Designs that emphasize redundancy, low power, high sensitivity and multi-purposes are lessons to be learned from nature. Majority of biomimetic sensor research has directly emulated the morphology and physiology of biological sensors; what could be easily observed or understood was chosen for further examination. While fascinating and significant, in order to maintain the innovation momentum engineers need to consider analogical reasoning, in addition to direct mimicry, in future designs.

This background review uncovered that little attention was placed on thermal, optical, acoustic, radiation and magnetic type sensors. These gaps indicate that nature does not provide novel approaches to those sensing areas or those areas are simply untapped, just waiting to be discovered. Only time will tell. Furthermore, most of the biomimetic sensors regard technologies that are applicable to many situations. Investigating sensing phenomena that have specific applications provides an alternative motive for research in this branch of sensor research. From the biological standpoint, the thermo, electro and magnetoreceptor, and proprioceptor type sensors are largely unresearched by the engineering community. This finding also provides further direction for research.

As cooperation and collaboration between biologists and engineers continues to increase, the phenomenological view of the natural world will increasingly influence the engineering perspective (Stroble et al. 2009e; Stroble et al. 2009d). Leading to further advancements in biomimetic technologies and potentially result in solutions to unsolved engineering problems.

2.6 Summary

Four major related topics were reviewed here. Biological inspiration methods for engineering design, from multiple perspectives, were presented. Abstracting or framing the biological information for use with engineering design activities can clearly take many avenues. Research in the areas of inspiration facilitators, representation methods, information transfer methods, and concept generation techniques have all shown to be successful at inspiring engineering solutions. However, there is not a comprehensive method that can guide the designer from initial problem definition to complete concept from a single design perspective. The second topic reviewed was functional abstractions, in both engineering design and sensors and electrical systems design. Function-based design representations, traditionally reserved for electro-mechanical or purely mechanical designs, are compared to the design representations of sensors. The third topic reviewed was sensor design practices. Although there is a wealth of documentation on the concepts, principles and use of sensors, established design methods or schemes beyond empirical are basically non-existent. This means that there is room for research examining a systematic approach to sensor design, which could lead to faster discovery of novel sensor designs. Functional abstraction promotes creativity and removes the component boundaries that engineers all too often impose upon themselves.

Finally, an overview of current biomimetic sensor research was presented. The majority of biomimetic sensors have directly emulated the morphology and physiology of biological sensors and are of the type mechanical, electrical or chemical. Regardless of the problem being solved or innovative design being researched, nature offers a model and serves as a guide for engineering designers whom are looking outside of the engineering domain for inspiration. It will be interesting to see if Bar-Cohen's assessment of the future of biomimetic technology holds true, "The inspiration from nature is expected to continue leading to technological improvements and the impact is expected to be felt in every aspect of our lives" (Bar-Cohen 2006).

CHAPTER 3 - IDENTIFY: FINDING BIOLOGICAL INSPIRATION

3.1 Overview

Searching for and retrieving solution information as part of function-based design has several methods. Each method contains unique properties that provide successful results. However, they fall short when accessing biological information. A search strategy designed specifically to work with non-engineering subject domain specific information has been developed to alleviate this problem. In this chapter, the strategy behind the organized search tool is explained, followed by the algorithm. The organized search tool software is then presented. First as the existing version and, second, as the next iteration. A set of heuristics (not related to modern heuristics such as genetic algorithms, tabu search, ant colony optimization, simulated annealing or immune systems) are then introduced that assist engineering designers with mining data for biological inspiration or direct solutions. To illustrate the organized search an example design problem of smart flooring is presented. The example demonstrates the advantages of the second version of the search software by eliminating irrelevant results and increasing the number of relevant results.

3.2 Related Work

Work in the area of information retrieval in design related to this research involves the design of a hierarchal thesaurus, software and search methods. A general approach to design information retrieval was undertaken by Wood et al., which created a hierarchical thesaurus of component and system functional decompositions to capture design context (Wood et al. 1998). Strategies for retrieval, similar to search heuristics, of issue based and component/function information were presented. Bouchard et al. developed a content-based information retrieval system named TRENDS (Bouchard et al. 2008). This software aims at improving designers' access to web-based resources by helping them to find appropriate materials, to structure these materials in way that supports their design activities and identify design trends. The TRENDS system integrates flexible content-based image retrieval based on ontological referencing and clustering components through Conjoint Trends Analysis (CTA). Previous research in retrieval of biological inspiration (Stroble et al. 2009b; Nagel and Stone 2010) serves as the foundation for this chapter.

3.3 Search Strategy

Engineers have struggled with utilizing the vast amount of biological information available from the natural world around them. Often it is because there is a knowledge gap due to difficult to grasp terminology, and the time needed to learn and understand the biology represents an infeasible burden. Therefore, software that can assist with identifying and presenting valuable biological knowledge, indexed by engineering terms, to an engineering designer looking for inspiration would significantly increase the likelihood of biologically-inspired designs.

Function-based design, aims to represent a system or product in it's most abstract form using functionally descriptive words. Using familiar functionally descriptive keywords to search for solutions or inspiration for solutions to the desired function is an obvious corollary. Therefore, the search strategy presented here is formulated in the manner stated by Abbass: “we need somehow to choose the problem solving approach before representing the problem” (Abbass 2002).

The search strategy presented here is designed specifically to work with non-engineering subject domain specific information to address the problem of engineers searching for inspiration in a domain that is unfamiliar to them. The majority of non-engineering domain texts are written in natural-language format, which prompted the investigation of using both a Functional Basis function and flow term when searching for solutions. Realizing how the topic of the text is treated increases the extensibility of the organized verb-noun search algorithm. The organized verb-noun combination search strategy presented here provides two levels of results: (1) broad results associated with verb only, of which the user can choose to utilize or ignore, and (2) narrowed results associated with verb-noun. This search strategy requires the designer to first form an abstraction of the unsolved problem using the Functional Basis terms, typically through a functional model. The verbs (functions) used in the functional model are used as keywords in the organized search to generate a list of matches in sentence form, and subsequently a list of words that occur in proximity to the searched verb in those text excerpts. The generated list contains mostly nouns, which can be thought of as flows (materials, energies and signals), analogous to the correspondent words already provided in the Functional Basis flow set. The noun listing is then used in combination with the verb for a second search to locate specific text excerpts that describe how the non-engineering domain systems perform the verb (function) used in the organized searches. If the designer does not want to search by verb-noun, then the noun listing should be ignored to focus on the function only results. To increase the accuracy and decrease ambiguity of the results, the terms of the engineering-to-biology thesaurus (presented in Chapter 4) may be utilized during searching. The goal achieved by the search strategy is an effective and efficient way of identifying suitable non-engineering domain solutions for function-based design inspiration.

This search strategy is embodied in software that allows an engineering designer to selectively choose which corpora to search and to upload additional searchable information as it is made available. For this research, the non-engineering domain chosen for solutions is biology and the searchable corpus chosen is an introductory college level biology textbook. By selecting an introductory text that covers a broad spectrum of topics, a wide range of solutions are afforded, which are presented at a level that is understandable for engineering designers. The biological corpus is Life, The Science of Biology by (Purves et al. 2001). The corpus is comprised of 58 chapters, divided into four sections: animals, heredity, plants and the cell. With the corpus being over a 1000 pages, the information was initially divided into 58 documents, one for each chapter. However, collecting detailed information across multiple chapters was tedious and the information was compiled into four documents according to the corpus sections. This also allows comparison of results amongst the major subjects within a non-engineering corpus. The results are separated by each file of the corpus and each result references the paragraph and sentence within the searched file. The search typically yields multiple biological systems. Thus, the designer will need to examine the text excerpts and decide which biological system is best suited for solving the problem. This software will promote biologically-inspired, engineering designs that partially (i.e., one or two components) to completely (i.e., entire design) mimic a biological system. Consequently, using the search software lends itself more toward innovative design problems where novel solutions tend to dominate.

The designer utilizing this organized search technique does not need an extensive background in the non-engineering domain but, rather, the designer must have sufficient engineering background to abstract the unsolved problem to its most basic level utilizing the Functional Basis lexicon.

3.4 Organized Search Algorithm

This section describes the algorithm of the organized verb-noun search. Figure 3.1 shows the algorithm in flow chart form. The designer initiates the search using a function word, choosing how the search word is treated and presses the search button. Search results are then presented to the designer whom must decide which biological systems are best suited for solving the problem. The designer can then choose to jump straight to the function results or manually parse through the nouns to find a specific instance that might solve a function/flow pair. Search heuristics for optimizing use of the search tool are provided in Section 3.6. Multiple scenarios an engineering designer might encounter when searching for design inspiration or solutions are given.

3.4.1 Step 1: Initial Verb Search

Functional Basis functions are the foundation for the organized verb-noun search. In context, the “verb” is any secondary or tertiary level function from the Functional Basis. To produce additional search results, the class or primary level Functional Basis words can also be used. However, those words are generally discouraged as the resulting text excerpts are often repeated and offer limited insight. Thus, the designer should choose the correct verb from the Functional Basis, based on the definitions and examples provided in appendix of (Stone and Wood 2000) for the problem that needs to be solved. For example, to find out how biological systems measure various parameters, the word measure (tertiary level under Signal in the Functional Basis) should be the chosen search verb. In the event that the search does not yield results using a Functional Basis term, a term from the next level up within the same class or a corresponding biological term should be tried. For example, if *measure*, under the class *signal* does not produce useful results, the secondary term *detect* or one of the biological correspondent terms of *observe, monitor, gauge or watch* should be the next search term to try. The results of the verb search are used to generate the list of collocated subject domain specific nouns in Step 2.

3.4.2 Step 2: Generate a List of Collocated Nouns

The "nouns" generated in this step can be likened to Functional Basis flows, as they are often representations of material, energy and signals within the chosen subject domain. Using a verb (function) as the search keyword yields many results, however, a poor choice of keyword can yield ambiguous or unhelpful results. By generating the set of subject domain specific nouns, a complementary set of search keywords to the original verb keyword is provided to focus and minimize time spent searching.

Utilizing a similar collocation strategy to (Chiu and Shu 2007a), the results of Step 1 are passed through a script that generates the set of subject domain specific nouns. Only content-bearing words are counted and English language articles, spelled-out forms of numbers, single letters, common adjectives, verb phrase headers and other frequently used verbs are ignored. The result entails a list of words that occur in the Step 1 results with the paragraph and sentence location for each instance of the word. The list is sorted alphabetically. Each of the subject domain specific nouns is used in the second search (Step 4). Occasional adjectives or verbs appearing in the noun list should be dismissed as most, if not all, are abstract in nature. Now the designer has the two pieces that are needed for the complete organized search.

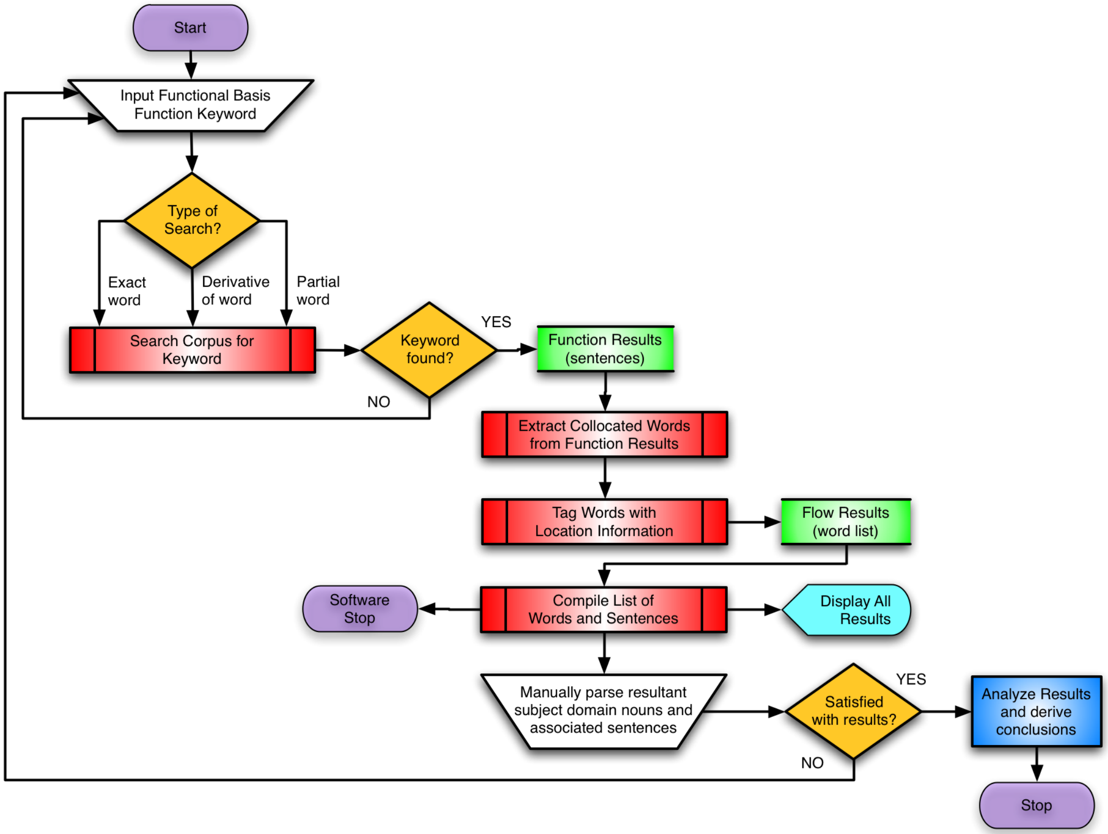


Figure 3.1. Organized Search Algorithm Flow Chart.

3.4.3 Step 3: Display Search Results

The results from the search are complied to form the set of biological nouns and text excepts, in the form of sentences, that contain the verb (function) and are displayed to the designer. The list of subject domain specific nouns is listed first with references to their occurrence in the searched document. The noun listing is preceded by the name of the searched document and the numerical quantity of nouns extracted from the resulting text excepts. Results follow the same format for each search document: name of document, quantity of collocated nouns, list of nouns with references and list of text excerpts. In this case, there are four sets of results form a single corpus. Extra spacing is placed between the results of each searched document and a header including the search verb is placed at the top of the result listing to label the displayed results. Searching multiple documents displays each set of results individually and sequentially to deter confusion. If search documents represent corpora, placing the corpus title in the document file name will assist with determining which set of results are from which corpus. The organized results can be saved for future reference by clicking the save button.

3.4.4 Step 4: Perform Verb-Noun Search

This salient step is the key to eliminating the majority of non-relevant or ambiguous search results. Leading to a quick judgment of the search keyword and its success thus, saving time and effort. With the original search verb and a list of subject domain specific nouns, the designer can search non-engineering knowledge in natural-language format to identify focused results, in this particular case, for relevant biological systems. The nouns used for the verb-noun search are, at this point in time, manually parsed for equivalents to the flow of the function/flow pair of a black box or functional model. Control of the noun list is only through the chosen search documents and the style in which they were written. The engineering-to-biology thesaurus of Chapter 4 can be used to assist with translating engineering flow terms into biological correspondent terms.

To perform the verb-noun search, each period delimited sentence of the chosen documents is scanned for concurrent instances of the verb and noun pair, not necessarily in consecutive order. Recursively scanning the noun list for all instances that align with the desired flow term leads to focused solutions. If the designer chooses to include thesaurus terms the results will lead to focused and more accurate solutions. For example, function/flow search pairs using only the Functional Basis terms might be:

- Detect-chemical energy, solid material, thermal energy
- Regulate-electrical energy, thermal energy, liquid material

Example function/flow search pairs using the terms of the engineering-to-biology thesaurus to translate the above pairs might be:

- Locate-carbohydrates, dirt, heat
- Maintain-potential, temperature, buffer

3.4.5 Step 5: Interpreting Results

The organized verb-noun search algorithm results can suggest direct solutions by examining the resulting compiled excerpts that describe biological systems and mapping them to possible engineering design solutions through formulated connections. Otherwise, the biological information is used for inspiration. Determining whether or not to use a particular biological system is largely up to the designer's discretion.

3.5 Inspiration Search Software

Automated methods promise engineers a faster realization of potential design solutions based upon previously known products and implementations. Search software also provides the added advantage of limitless resources for inspiration. Two versions of the organized search software have been designed. Version one is a proof-of-concept that the organized search strategy results in a useful tool. The second version exists in concept and can be executed manually using the software of the first version. Where version one results in solutions only extracted from a biological knowledge base, the second version aims to provide solutions from both biology and engineering simultaneously. Thereby increasing the chance for connections between the two domains to be formulated. The computational methods described here assist with identifying biological solutions and inspiration for solutions to engineering functions; however, to arrive at the final concept, the designer is required to formulate connections within the engineering domain that support what the biological solution suggests.

3.5.1 Version 1 of the Search Software

Version one of the search software has a simple interface. The user interface initially presents the designer with and entry field, search options a display window and a save button as shown in Figure 3.2. Search options prompt the designer to choose from exact word, derivatives of the word, and partial word. Choosing derivatives changes the tense of the search word. For the word detect, derivatives would be detects, detecting, and detected. Partial allows the word to be included in other words or lead to a correlated word (i.e., detector, detective).

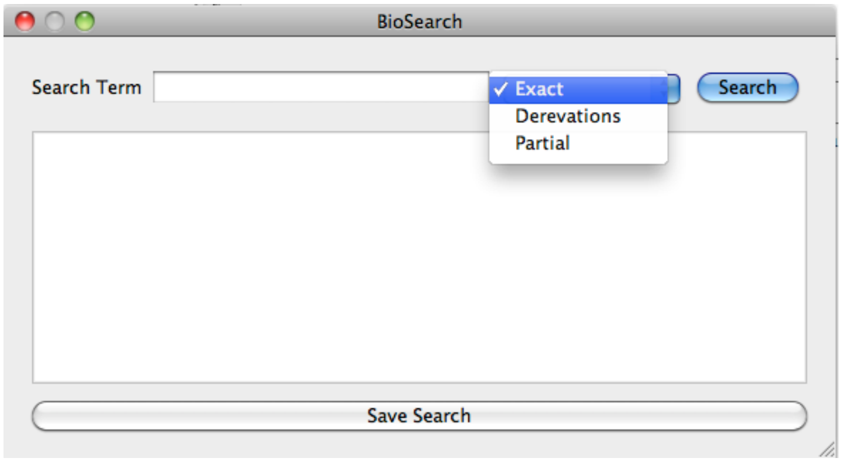
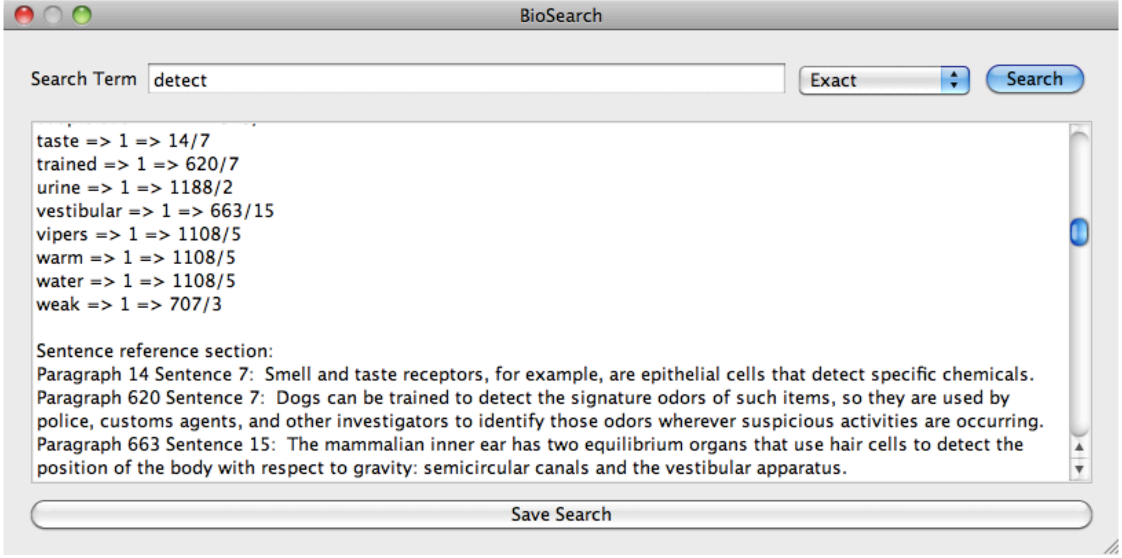


Figure 3.2. Organized Search Software Version 1 Screen and Menu.

The software is comprised of two main files, the search GUI and ignore list, and a folder for search documents. The search GUI is the executable file that provides the interface and the ignore list is a text file containing words that should not be displayed. At any time the ignore file can be modified. The simple file structure allows an engineering designer to selectively choose which documents to search and to upload additional searchable information as it is made available. All documents in the folder are searched by the software each time the software is executed. Saved searches are in the .txt format.

Figure 3.3 provides example results of an exact search of the verb *detect*. The figure shows the generated nouns in alphabetical order, with paragraph and sentence citations, above the collection of resultant text excepts. Notice the noun taste is indexed by paragraph 14, sentence 7, which is the first sentence in the reference section. Taste is contained within the sentence, and in this instance, is not near the search verb of *detect*. However, the receptors that detect taste are described and could be used for inspiration.



```
taste => 1 => 14/7
trained => 1 => 620/7
urine => 1 => 1188/2
vestibular => 1 => 663/15
vipers => 1 => 1108/5
warm => 1 => 1108/5
water => 1 => 1108/5
weak => 1 => 707/3

Sentence reference section:
Paragraph 14 Sentence 7:  Smell and taste receptors, for example, are epithelial cells that detect specific chemicals.
Paragraph 620 Sentence 7:  Dogs can be trained to detect the signature odors of such items, so they are used by
police, customs agents, and other investigators to identify those odors wherever suspicious activities are occurring.
Paragraph 663 Sentence 15:  The mammalian inner ear has two equilibrium organs that use hair cells to detect the
position of the body with respect to gravity: semicircular canals and the vestibular apparatus.
```

Figure 3.3. Organized Search Software Version 1 Results Screen Shot.

3.5.2 Version 2 of the Search Software

The second version of the search software requires the designer to input desired functionality, in the form of a functional model, and based on an algorithm several solutions from engineering and biology are presented to the designer. Each function/flow pair of the model is then searched in a biological knowledge base and an engineering knowledge base. The biological knowledge base is the biological corpus of the organized search tool and the engineering knowledge base is the Design Repository[3] housed at Oregon State University. Searching the engineering knowledge base emulates the concept

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[3] repository.designengineeringlab.org

generator software MEMIC (Bryant et al. 2005a; Bryant et al. 2005b; Bryant et al. 2007; Bryant Arnold et al. 2008). In addition to adding the engineering solutions search, the algorithm would automatically substitute the biological correspondent terms of the engineering-to-biology thesaurus for the function/flow pair terms. The search algorithm parses the repository entries for the exact engineering function/flow pair, where as, the biological corpus is parsed repeatedly with the biological terms corresponding to the engineering terms. Multiple solutions from both domains, to each function/flow pair, are returned and presented to the designer. A sketch of the proposed interface is shown in Figure 3.4. The biological solutions are not indented for physical use, but are intended for spurring creative ideas, connections and designs that could be implemented in an engineered system. Version two of the search software can is extensible through the addition of entries into the Design Repository and corpors into the biological corpus search folder.

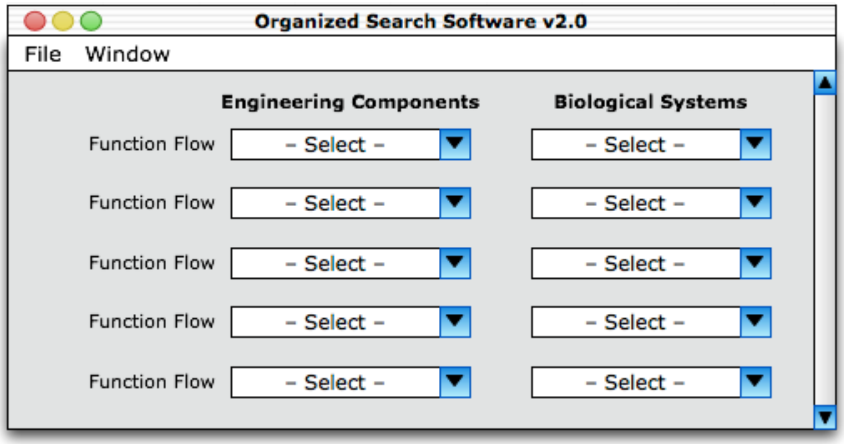


Figure 3.4. Organized Search Software Version 2 Mock Up.

Version two of the search software utilizes the Functional Basis, Design Repository, MEMIC, organized search tool and engineering-to-biology thesaurus to create, filter and inspire concept variants. The algorithm combines the research efforts that developed MEMIC and the organized search tool, but also adds recursive biological text search functionality using the engineering-to-biology thesaurus. There are two threads in this algorithm that execute simultaneously: (1) parse the Design Repository to find engineering solutions, and (2) chosen biological corpora with thesaurus terms to find biological solutions for engineering inspiration.

Thread 1: Parse Design Repository for Engineering Solutions

This thread of the algorithm utilizes function-component relationships established through a Function-Component-Matrix (FCM) to compute a set of engineering components that solve the function/flow pairs of the input functional model. Next, the resultant set is filtered using component-component knowledge through a Design-Structure-Matrix (DSM). Each match is stored for display to the designer. The resultant engineering components found in the Design Repository and that are compatible are displayed to the designer as a textual list of potential solutions that have previously solved that function/ flow pair.

Thread 2: Parse Biological Corpus for Biological Solutions using Thesaurus Terms:

First, this thread of the the algorithm swaps the engineering function and flow terms for corresponding biological function and flow terms based on engineering-to-biology relationships. The biological corpus is then searched for the biological function and all sentences containing the function are extracted for further processing. The thread then searches those sentences for any of the corresponding biological flow terms. Each match is stored for display to the designer. When multiple biological function terms are present, the search is executed recursively until all corresponding biological functions have been searched. The resultant biological information is displayed to the designer as individual sentences containing the desired function/flow pairs, which are indicators of potential solutions from the biological domain.

3.6 Search Heuristics

Strategies for retrieving focused results from a subject domain specific corpus are presented here. Depending on the stage of the design process, search criterion may vary widely, thus a set of heuristics has been complied to promote efficient searching using this technique. The definition of heuristics for information retrieval used here is: A method of extracting useful information from a user defined corpus, empirical in nature, to aid in engineering design. Functional models are used in function-based design and are considered input for these scenarios. Stone et al. (Stone 1997; Stone et al. 1998; Stone et al. 2000) identified three modular heuristics for functional models that identify groups of functions that may be embodied as a single module. Two of those heuristics have been adapted to this research and modified with the concept of primary/carrier flow by Nagel et al. (Nagel et al. 2007). A primary flow is the flow required to meet the input/output requirements of a functional model, while being supported by a carrier flow that aids the primary flow in the completion of its requirements. This designation allows a designer to focus a functional model to specifically represent an individual aspect of a system. The Delta cordless circular saw functional model in Figure 3.5 is provided to demonstrate several of the heuristics. The function-based design heuristics grew out of using the organized search tool. Bullet points summarize the objective and/or requirements of the heuristic followed by usage explanation.

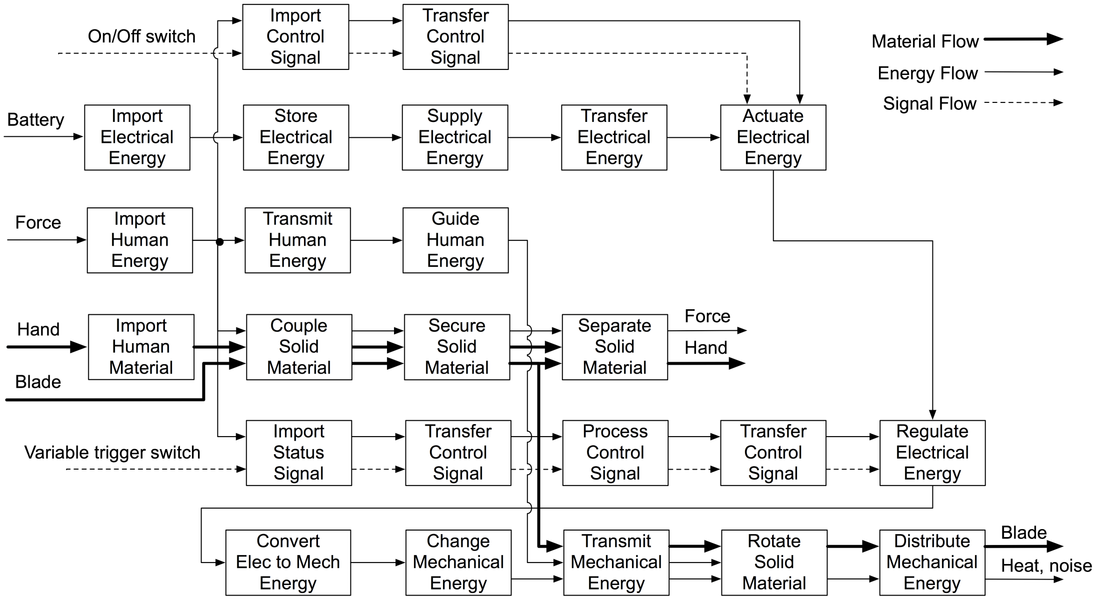


Figure 3.5. Delta Cordless Circular Saw Functional Model.

3.6.1 General Inspiration Search

- Gather a broad set of non-engineering domain solutions
- Provides the largest solution space

To provide the broadest set of biological systems, perform a verb only search with the Functional Basis function that is closest to the desired functionality of a conceptual design. Creating a black box model is a reliable method for narrowing down possible functions when performing the verb only search. For example, in the Delta circular saw of Figure 3.5, the black box function is separate solid and the search would begin with *separate* as the keyword. Opting for the partial word search will return the most matches by generating the most nouns related to the subject of the searched corpus.

3.6.2 Dominant Flow

- Concept has dominant material flow
- Concept has dominant energy flow
- Concept has dominant signal flow
- Provides a narrowed solution space

A dominant flow can be of material, energy or signal type. It must enter or be initiated within the system, pass through until it exits or is converted into another flow and be of importance to the system as a whole. The dominant flows, or primary flows, in Figure 3.5 are: (1) on/off switch control signal, (2) variable trigger switch control signal, (3) electrical energy of the battery, (4) mechanical energy of the rotating blade, and (5) human hand guiding the blade. With a dominant flow, nouns are of great importance and choosing the exact search word option during a verb-noun search yields only the text excerpts for prime nouns; reducing ambiguity in the results.

3.6.3 Branching Flow

- Concept has flows that are transformed in more than one way concurrently
- Provides overlapping solution spaces

A branching flow is a material, energy or signal flow that creates parallel function chains. Human energy as force and the blade in Figure 3.5 are examples of branching flows. From a functional standpoint they are carrier flows as they are necessary to the system but not of primary importance to the user. Thus, a verb-noun search with the derivations of the search word option chosen yields nouns that support the function word leading to encompassing, yet focused results.

3.6.4 Redesign Phase

- Rework components to develop a more elegant solution
- Concept needs innovation

Perhaps the most interesting heuristic is that of redesign. The full potential of the organized search tool is realized when innovative or inspiring connections are the result. Increasing the elegance of an older design can be achieved by updating system components based on their respective function. Calling upon corresponding biological functions or functions at the next higher level (i.e., secondary if starting from tertiary) during a verb-noun search will greatly increase the designer's chances of discovering a direct solution. This goes back to primary flows achieving the function, thus an exact search word option verb-noun search is the best choice for this scenario.

3.6.5 User Defined Verb

The fifth heuristic is included for the anomalous case when the Functional Basis functions, or the terms of the engineering-to-biology thesaurus for this case, do not produce usable search results for the chosen non-engineering domain corpus. In this instance other verbs must be generated by the designer.

3.7 Example

To demonstrate the organized verb-noun search, a smart flooring example is presented. The organized search tool is utilized to search for biological systems that perform the function(s) within a functional model to inspire solutions that can be implemented in a product.

When using the Functional Basis for product design there are a few basic steps needed before the search for inspiration or solutions can be performed. First, one must define the customer needs and convert them into engineering terms (Kurfman et al. 2003). Second, one must develop the black box and conceptual functional models of the desired new product using the Functional Basis function and flow terms. The black box representation of the desired solution designates the main function of the system and the main flows needed to achieve that function. The conceptual functional model depicts the functions needed to achieve flow transformations. Examples can be found in (Nagel 2007; Nagel et al. 2008b; Stroble et al. 2008). The designer now has several Functional Basis functions that could be used with the organized search tool to gain inspiration.

3.7.1 Problem Definition

The customer wants to create a security/surveillance product that looks like ordinary carpet, mats, rugs, etc. to detect intruders, a presence or movement. Requirements for the "smart" flooring include being unseen by the human eye, durable, composed of common materials and a quick response. Also, the system needs to be autonomous. Meaning a signal generated can alert personnel and does not require a person to monitor the surveillance system. It is known that tagged systems require the user to carry a badge or other device to be tracked or monitored and simply removing the trackable item can defeat the system. Radar or similar systems require calibration and an area map to be created. Each time the area layout is changed, the map needs to be updated. Video surveillance and heat signature systems can be very expensive and often require a person to watch the real-time video feed who can be unreliable. The design should offer advantages over the others listed. With this knowledge the needs are mapped to flows (Table 3.1) for the creation of a black box model. Figure 3.6 shows the block box model. Focusing on the detection aspect, the the black box model is decomposed into the functional model of Figure 3.7. The main flow is electrical energy which will power the integrated system.

Table 3.1. Needs of Smart Flooring Example Mapped to Flows.

Needs/Constraints	Functional Basis Flow
Object/Human to detect	Solid Material
Quick detection response	Status Signal
System power	Electrical Energy

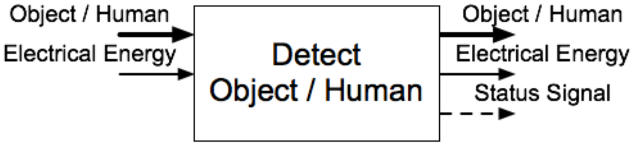


Figure 3.6. Smart Flooring Black Box Model.

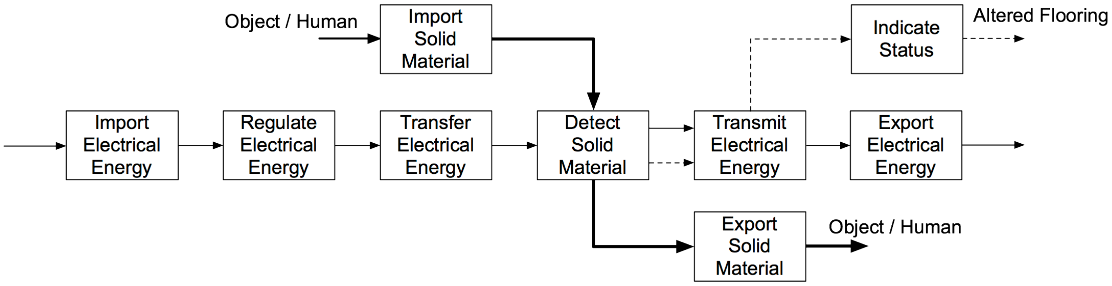


Figure 3.7. Smart Flooring Conceptual Functional Model.

3.7.2 Analysis of Version 1 Results

Following the general inspiration search heuristic, the main function of *detect* is input into version one of the organized search tool software for a verb-noun search using the partial word option. The search resulted in 28 text excerpts shown in Table 3.2 in the form of individual sentences. Both relevant and non-relevant text excerpts are displayed in Table 3.2 to demonstrate the format of the search results. For the purposes of this example, each result was given a number to make referencing individual results easier. Of the 28 results, 7 of them are relevant, which are bolded and italicized in Table 3.2: #5, 18, 20, 22, 23, 26 and 28. Notice that result 22 and 23 are referring to the same biological system. Thus, there are six biological systems that offer inspiration for the detection aspect of the smart flooring system design. All other matches were deemed irrelevant because the corresponding descriptions referred to performing the function *detect* using non-biological means or equipment operated by humans.

The relevant biological systems identified from Table 3.2 are summarized as: (1) the hair cell, a mechanoreceptor, found in the ear of most animals or on the body of most insects; (2) electric fields, produced by electroreceptors found in electric fish; (3) smell and taste receptors or epithelial cells; (4) genes that mark recombinant DNA; (5) echolocation used by bats; and (6) why birds flock in large groups. These biological systems are natural ways of detecting, which designers can use to formulate connections and inspire an engineered sensing solution. Of the six biological systems, “genes that mark recombinant DNA” only inspires a solution that leaves a mark, a color change or impression on the flooring, which does not fulfill the customer need of unseen to the human eye. A dye or mark that can only be seen under UV light most likely will not allow automated detection. Flocking birds is difficult to adapt to the smart flooring problem, but the idea of several sensors grouped together in an array would increase the detection rate. Remaining as sources for potential inspiration are the biological systems of hair cells, electroreceptors, echolocation and epithelial cells. Adapting the idea of epithelial cells, detection could occur by "tasting" materials. Electroreception and echolocation could be used like radar and even detect the presence of an object when it is just above the flooring. Perhaps the natural phenomenon that most readily allows a connection to engineering and inspiration is the hair cell. Hair cells are like cantilevers and would detect a presence when disturbed by deflection, such as being stepped upon.

3.7.3 Analysis of Version 2 Results

Following the algorithm of version two, all the function/flow pairs of the model in Figure 3.7 are searched in the biological and engineering knowledge bases. When searching the biological corpus, the terms of the engineering-to-biology thesaurus are swapped for the engineering terms and the partial word option is selected. The search resulted in an average of nine biological solutions and six engineering solutions per function/flow pair. Table 3.3 shows the resulting engineering and biological solutions.

Importation and exportation of solid material did return engineering results; however, in regards to the voluntary human/object that interacts with the flooring the results are out of context. Therefore, the solutions are ignored and not presented here. Considering the flow of electrical energy, and the respective functions, the Design Repository returned several engineering

Table 3.2. Version 1 Search Software Results for Smart Flooring Example.

Function: Detect
Results for chapter 11
(1) Paragraph 107 Sentence 0: Since both AT and GC pairs obey the base-pairing rules, how does the repair mechanism "know" whether the AC pair should be repaired by removing the C and replace it with T, for instance, or by removing the A and rThe repair mechanism can detect the "wrong" base because a newly synthesized DNA strand is chemically modified some time after replication.
(2) Paragraph 120 Sentence 2: This technique measures the length of the DNA fragments, and can detect differences in fragment length as short as one base.
Results for chapter 12
(3) Paragraph 8 Sentence 2: This fact is important because it means that even recessive mutant alleles are easy to detect in experiments.
Results for chapter 13
(4) Paragraph 155 Sentence 0: Sequencing has also provided the necessary information for the design of primers and hybridization probes used to detect these and other pathogens.
Results for chapter 17
(5) Paragraph 73 Sentence 0: In addition to genes for antibiotic resistance, several other marker genes are used to detect recombinant DNA in host cells.
(6) Paragraph 93 Sentence 4: The second is the use of "DNA chips" to detect the presence of many different sequences simultaneously.
(7) Paragraph 102 Sentence 5: This method may provide a rapid way to detect mutations in people.
(8) Paragraph 130 Sentence 2: Some diabetics' immune systems detect these differences and react against the foreign protein.
(9) Paragraph 176 Sentence 5: If an organism is present in small amounts, PCR testing will detect it.
Results for chapter 18
(10) Paragraph 106 Sentence 1: We will describe their use to detect the mutation in the ?-globin gene that results in sickle-cell anemia.
(11) Paragraph 145 Sentence 2: It is also possible to detect early in life whether an individual has inherited a mutated tumor suppressor gene.
(12) Paragraph 169 Sentence 1: Scientists attending this conference quickly realized that the ability to detect such damage would also be useful in evaluating environmental mutagens.
(13) Paragraph 169 Sentence 2: But in order to detect changes in the human genome, scientists first needed to know its normal sequence.
Results for chapter 19
(14) Paragraph 108 Sentence 1: For example, they have been invaluable in the development of immunoassays, which use the great specificity of the antibodies to detect tiny amounts of molecules in tissues and fluids.
Results for chapter 23
(15) Paragraph 78 Sentence 2: However, as soon as they detect homoplasies, systematists change their classifications to eliminate polyphyletic taxa.

Table 3.2. Version 1 Search Software Results for Smart Flooring Example (Continued).

Function: Detect
Results for chapter 24
(16) Paragraph 6 Sentence 1: Because modern molecular techniques enable us to detect substitutions at the level of nucleotides, molecular evolutionists can measure even these nonfunctional changes.
(17) Paragraph 23 Sentence 2: One way to detect homologous genes in distantly related organisms is to find identical or nearly identical families of genes that produce similar effects in a wide variety of organisms.
Results for chapter 40
(18) Paragraph 10 Sentence 6: Smell and taste receptors, for example, are epithelial cells that detect specific chemicals.
Results for chapter 45
(19) Paragraph 1 Sentence 6: Dogs can be trained to detect the signature odors of such items, so they are used by police, customs agents, and other investigators to identify those odors wherever suspicious activities are occurring.
(20) Paragraph 32 Sentence 16: The mammalian inner ear has two equilibrium organs that use hair cells to detect the position of the body with respect to gravity: semicircular canals and the vestibular apparatus.
(21) Paragraph 51 Sentence 5: Thus while the hawk is flying, it sees both its projected flight path and the ground below, where it might detect a mouse scurrying in the grass.
(22) Paragraph 67 Sentence 3: These sensory cells enable the fish to detect weak electric fields, which can help them locate prey.
(23) Paragraph 67 Sentence 6: Any objects in the environment, such as rocks, plants, or other fish, disrupt the electric fish's electric field, and the electroreceptors of the lateral line detect those disruptions.
(24) Paragraph 71 Sentence 5: Eyes vary from the simple eye cups of flatworms, which enable the animal to sense the direction of a light source, to the compound eyes of arthropods, which enable the animal to detect shapes and patterns, to the lensed eyes of cephalopods and vertebrates.
Results for chapter 49
(25) Paragraph 44 Sentence 4: Electrodes placed on the surface of the body at different locations, usually on the wrists and ankles, detect those electric currents at different times and therefore register a voltage difference.
Results for chapter 50
(26) Paragraph 35 Sentence 4: Bats use echolocation, pit vipers sense infrared radiation from the warm bodies of their prey, and certain fishes detect electric fields created in the water by their prey.
(27) Paragraph 110 Sentence 1: That is why urine tests are used to detect illegal drug use by athletes and other individuals.
Results for chapter 53
(28) Paragraph 72 Sentence 4: The larger a flock of pigeons, the greater the distance at which they detect an approaching hawk, and the less likely a hawk succeeds in capturing a pigeon.

component solutions. Solutions of electrical wire, electrical switch, circuit board and battery are commonplace, but offer a wide range of functionality. Although a biological solution may not have practical uses for importing, regulating, transferring, transmitting and exporting electrical energy, the biological system solutions are interesting and informative. Essentially, what an engineer can gain from these biological results is that natural systems do utilize electrical energy for communication, sensing, regulating metabolism, photosynthesis and many other processes.

Results that are more intriguing are the biological phenomena relevant to the function of *detect*. Of the 12 returned solutions, hair cells, electroreceptors, echolocation, carotiod and aortic stretch receptors, membrane receptor proteins, graded action potentials and DNA offer the greatest potential to inspire a detection mechanism. The hair cell operates like a cantilever and would detect a presence when disturbed through defection. Electroreception and echolocation could be used like radar and even detect the presence of an object when it is in contact or just above the flooring. Detecting a certain material could adapt the idea of carotiod and aortic stretch receptors, by monitoring the degree of deformation in a material. Membrane receptor proteins and graded action potentials alter the flow of ions, thus indicating a difference in the environment. Chemical modifications within the flooring material, as suggested by DNA, could also signal the presence of a solid object. Perhaps the biological systems that most readily offer analogy discovery and inspiration are the hair cells and carotiod and aortic stretch receptors. These two solutions offer natural tactile responses that could be exploited to achieve the customer requirements.

Table 3.3. Version 2 Search Software Results for Smart Flooring Example.

Function/ Flow	Engineering Solution	Biological Solution
Import/ electrical energy	Battery, circuit board, electric motor, electric wire, electric switch	1. The light energy absorbed by the antenna system is transferred from one pigment molecule to another as an electron. 2. To keep noncyclic electron flow going, both photosystems I and II must constantly be absorbing light, thereby boosting electrons to higher orbitals from which they may be captured by specific oxidizing agents. 3. Photosystem II absorbs photons, sending electrons from P680 to pheophytin-I-the first carrier in the redox chain-and causing P680 to become oxidized to P680+. 4. Electrons from the oxidation of water are passed to P680+, reducing it once again to P680, which can absorb more photons. 5. In sum, noncyclic electron flow uses a molecule of water, four photons (two each absorbed by photosystems I and II), one molecule each of NADP+ and ADP, and one Pi. 6. The attractive force that an atom exerts on electrons is its electronegativity. 7. Na+ ions would diffuse into the cell because of their higher concentration on the outside, and they would also be attracted into the cell by the negative membrane potential. 8. These positive charges electrostatically attract the negative phosphate groups on DNA. 9. Because opposite charges attract, the DNA moves toward the positive end of the field. 10. Leptin appears to be one important feedback signal in the regulation of food intake.

Table 3.3. Version 2 Search Software Results for Smart Flooring Example (Continued).

Function/ Flow	Engineering Solution	Biological Solution
Regulate/ electrical energy	Actuation lever, capacitor, circuit board, automobile distributor, electric switch, heating element, transistor, transformer, thermostat, regulator, volume knob	1. Changes in the gated channels may perturb the resting potential. 2. An opposite change in the resting potential would occur if gated Cl- channels opened. 3. The inactivation gate remains closed for 1-2 milliseconds before it spontaneously opens again, thus explaining why the membrane has a refractory period (a period during which it cannot act) before it can fire another action potential. 4. When the inactivation gate finally opens, the activation gate is closed, and the membrane is poised to respond once again to a depolarizing stimulus by firing another action potential. 5. The binding of neurotransmitter to receptors at the motor end plate and the resultant opening of chemically gated ion channels perturb the resting potential of the postsynaptic membrane. 6. The structure of many plants is maintained by the pressure potential of their cells; if the pressure potential is lost, a plant wilts. 7. Negatively charged chloride ions and organic ions also move out with the potassium ions, maintaining electrical balance and contributing to the change in the solute potential of the guard cells. 8. This unloading serves two purposes: It helps maintain the gradient of solute potential and hence of pressure potential in the sieve tubes, and it promotes the buildup of sugars and starch to high concentrations in storage regions, such as developing fruits and seeds.

Table 3.3. Version 2 Search Software Results for Smart Flooring Example (Continued).

Function/ Flow	**Engineering Solution**	**Biological Solution**
Transfer/ electrical energy	Battery, circuit board, electric wire, electric motor, electric socket, electric plate, electric switch, heating element, USB cable, light fixture, speaker	1. We have just noted proteins that function in blood clotting; others of interest include albumin, which is partly responsible for the osmotic potential in capillaries that prevents a massive loss of water from plasma to intercellular spaces; antibodies (the immunoglobulins); hormones; and various carrier molecules, such as transferrin, which carries iron from the gut to where it is stored or used. 2. Since the electronegativities of these elements are so different, any electrons involved in bonding will tend to be much nearer to the chlorine nucleus-so near, in fact, that there is a complete transfer of the electron from one element to the other. 3. Redox reactions transfer electrons and energy. 4. Another way of transferring energy is to transfer electrons. 5. A reaction in which one substance transfers one or more electrons to another substance is called an oxidation-reduction reaction, or redox reaction. 6. Thus, when a molecule loses hydrogen atoms, it becomes oxidized: Oxidation and reduction always occur together: As one material is oxidized, the electrons it loses are transferred to another material, reducing that material. 7. As we shall see, another carrier, FAD (flavin adenine dinucleotide), is also involved in transferring electrons during the metabolism of glucose. 8. The citric acid cycle is a cyclic series of reactions in which the acetate becomes completely oxidized, forming CO2 and transferring electrons (along with their hydrogen nuclei) to carrier molecules. 9. The transfer of electrons along the respiratory chain drives the active transport of hydrogen ions (protons) from the mitochondrial matrix into the space between the inner and outer mitochondrial membrane. 10. The light energy absorbed by the antenna system is transferred from one pigment molecule to another as an electron. 11. The high energy stored in the electrons of excited chlorophyll can be transferred to suitably oxidized nonpigment acceptor molecules.

Table 3.3. Version 2 Search Software Results for Smart Flooring Example (Continued).

Function/ Flow	Engineering Solution	Biological Solution
Transmit/ electrical energy	Electrical wire, battery contacts, motor controller	1. These electrical changes generate action potentials, the language by which the nervous system processes and communicates information. 2. Ganglion cells communicate information about the light and dark contrasts that fall on different regions of their receptive fields. 3. Whether or not the sensory cell itself fires action potentials, ultimately the stimulus is transduced into action potentials and the intensity of the stimulus is encoded by the frequency of action potentials. 4. In the rest of this chapter we will learn how sensory systems gather and filter stimuli, transduce specific stimuli into action potentials, and transmit action potentials to the CNS. 5. Auditory systems use mechanoreceptors to transduce pressure waves into action potentials. 6. Earlier in this chapter, we saw how crayfish stretch receptors transduce physical force into action potentials. 7. Sitting on the basilar membrane is the organ of Corti, the apparatus that transduces pressure waves into action potentials in the auditory nerve, which in turn conveys information from the ear to the brain.
Export/ electrical energy	Circuit board, electric wire, electric switch	1. Depending on the channel, this stimulus can range from the binding of a chemical signal to an electrical charge caused by an imbalance of ions. 2. This binding causes changes in the membrane potential of the sensory cells, which release neurotransmitters onto the dendrites of the sensory neurons. 3. When an action potential arrives at the neuromuscular junction, neurotransmitter from the motor neuron binds to receptors in the postsynaptic membrane, causing ion channels in the motor end plate to open.

Table 3.3. Version 2 Search Software Results for Smart Flooring Example (Continued).

Function/ Flow	Engineering Solution	Biological Solution
Detect/ solid material	Read head, line guide	1. Since both AT and GC pairs obey the base-pairing rules, how does the repair mechanism "know" whether the AC pair should be repaired by removing the C and replace it with T, for instance, or by removing the A and replacing it with G? The repair mechanism can detect the "wrong" base because a newly synthesized DNA strand is chemically modified some time after replication. 2. The cnidarian's nerve net merely detects food or danger and causes its tentacles and body to extend or retract. 3. Most sensory cells possess a membrane receptor protein that detects the stimulus and responds by altering the flow of ions across the plasma membrane. 4. The mammalian inner ear has two equilibrium organs that use hair cells to detect the position of the body with respect to gravity: semicircular canals and the vestibular apparatus. 5. These sensory cells enable the fish to detect weak electric fields, which can help them locate prey. 6. This change is detected by the carotid and aortic stretch receptors, which stimulate corrective responses within two heartbeats. 7. Any objects in the environment, such as rocks, plants, or other fish, disrupt the electric fish's electric field, and the electroreceptors of the lateral line detect those disruptions. 8. Bats use echolocation, pit vipers sense infrared radiation from the warm bodies of their prey, and certain fishes detect electric fields created in the water by their prey. 9. In addition to genes for antibiotic resistance, several other marker genes are used to detect recombinant DNA in host cells. 10. Length of the night is one of several environmental cues detected by plants, or by individual parts such as leaves. 11. Animals whose eyes are on the sides of their heads have nonoverlapping fields of vision and, as a result, poor depth vision, but they can see predators creeping up from behind. 12. How does the sensory cell signal the intensity of a smell? It responds in a graded fashion to the concentration of odorant molecules: The more odorant molecules that bind to receptors, the more action potentials are generated and the greater the intensity of the perceived smell.

Table 3.3. Version 2 Search Software Results for Smart Flooring Example (Continued).

Function/ Flow	Engineering Solution	Biological Solution
Indicate/ status signal	Light, tube, displacement gauge, LCD screen	1. The durability of pheromonal signals enables them to be used to mark trails, as ants do, or to indicate directionality, as in the case of the moth sex attractant. 2. To cause behavioral or physiological responses, a nervous system communicates these signals to effectors, such as muscles and glands. 3. The information from the signal that was originally at the plasma membrane is communicated to the nucleus. 4. A change in body color is a response that some animals use to camouflage themselves in a particular environment or to communicate with other animals. 5. The binding of a hormone to its cellular receptor protein, which causes the protein to change shape and provides the signal to initiate reactions within the cell. 6.Separation of the chromatids marks the beginning of anaphase, the phase of mitosis during which the two sister chromatids of each chromosome-now called daughter chromosomes, each containing one double-stranded DNA molecule-move to opposite ends of the spindle. 7.The lung tissues reacted to this onslaught by swelling-the hallmark of pneumonia. 8. When the substrate binds, the enzyme changes shape, exposing the parts of itself that react with the substrate. 9. This pathway consists of a series of redox reactions in which electrons derived from hydrogen atoms are passed from one type of carrier to another and finally are allowed to react with O2 to produce water. 10. This new oxaloacetate can react with a second acetyl CoA, producing a second molecule of citrate and thus enabling the cycle to continue. 11. In other combinations, the red blood cells of one individual form clumps because of the presence in the other individual's serum of specific proteins, called antibodies, that react with foreign, or "nonself," cells.

Functional results for indicating a status signal are a mixed set of analog and digital methods. Engineered solutions suggest lights, LCD screen, tube, or an analog gauge, and the biological solutions suggest a change in color or shape, swelling, molecule production and expelling of pheromones. Again, the biological results may be more informative than useful; however, in the event that the resultant engineered solutions are not useful the designer has the opportunity to be inspired by the biological solutions.

3.8 Summary

In efforts to bridge biology and engineering through functionality an organized search tool was developed. The search tool provides engineering designers with solutions from non-engineering domains for the engineering systems they wish to create. Time spent searching biological information for solutions or inspiration is reduced by utilizing functions of interest and subject domain specific nouns. Furthermore, the search extracts solutions to engineering problems from non-engineering domain texts and narrows the results based on functionality. Non-engineering flow terms (nouns) combined with engineering function terms create a powerful tool for designers seeking inspiration from a non-engineering domain to solve human problems or improve existing products. Engineering tools necessary for the organized search tool were discussed along with the search algorithm. A set of heuristics for generating specific types of results were also presented and discussed. The heuristics are in place to make searching a non-engineering corpus user-friendly and provide precise results.

Two software versions of the search were introduced and discussed. Version one of the software only returns biological solutions, while the second version returns biological and engineering solutions for the function/flow pairs of a black box or functional model. An example of smart flooring for security or surveillance was presented to demonstrate how the organized search tool is used to identify biological systems for inspiration. Results for both software versions were given.

Version one of the software focused on identifying biological systems that perform the function *detect*. It was shown through the general inspiration search heuristic that multiple biological systems to the desired function were found. Also, this software minimized the time spent searching, as suitable biological solutions were captured in the first search. Analogical reasoning points to hair cells as the best solution for the smart flooring example out of six resulting biological systems that perform the function of *detect*. The organized verb-noun search algorithm of the search tool provides targeted results, which quickly prompt creative solutions and stimulates designers to make connections between the biological and engineering domains.

Version two of the search software aims to provide the designer with a complete set of solutions to inspire a complete concept. Integrating the strategic search algorithm for indexing non-engineering information with an established computational concept generation method affords a computational foundation for accessing stored engineering information and, in this case, biological solutions for use with design activities. By placing the focus on function, rather than form or component, the algorithm of the second version of the search software was shown to successfully extract relevant biological solutions. The search software assists with developing biomimetic designs by presenting the designer with short descriptions of biological systems that perform a function of interest. From these descriptions the designer can make connections, that link the biological solutions to engineering solutions, principles, components and materials. A key part of the connection making process is considering the biological systems from several viewpoints. Multiple viewpoints can spur novel and innovative ideas.

It was shown that the organized search tool software was successful at extracting specific biological systems that perform engineering functions. Through the incorporation of the engineering-to-biology thesaurus in the second version of the software, a 33% increase of relevant biological solutions for the function of *detect* resulted when compared to results of the first version of the search software. It should also be noted that the 21 non-relevant results in Table 3.2 were ignored with the second version of the software. It can be concluded that the algorithm of version two of the software was successful at extracting accurate biological systems that perform the functions/flows of the conceptual functional model.

The biological domain provides many opportunities for identifying connections between what is found in the natural world and engineered systems. It is important to understand that the software does not make the connections between the domains to facilitate biologically-inspired design; that is the task of the designer. However, the search software does provide an tool for to discovering biological inspiration based on function, so that it may be easier for the designer to make the necessary connections leading to biologically-inspired designs. A more detailed case study of the smart flooring example that provides concepts with the results given in this chapter is presented in Chapter 7.

CHAPTER 4 - TRANSLATE: CHANGING THE CONTEXT FROM BIOLOGICAL TO ENGINEERING

4.1 Overview

Terminology of the biological domain is greatly different from the engineering domain. This fact is one of the major hurdles to biology-inspired design. Often it is difficult for a designer to understand detailed biological information or, in some respects, even converse with a biologist. One approach to addressing these hurdles is to translate the unfamiliar biological terminology into an engineering context. This chapter presents a tool to do just that. Biological terms were mined from a college level introductory biology textbook and paired with the engineering terms of the Functional Basis. The result is the engineering-to-biology thesaurus. This work-in-progress is slowly and steadily bridging the terminology gap between the two domains. Structure, population method, particulars, validation and applications of the thesaurus are presented in this chapter. Multiple examples are given to demonstrate application of the engineering-to-biology thesaurus, with a focus on comprehension and functional modeling. However, with few boundaries in the field of design, this thesaurus could be employed in ways that have not been considered.

4.2 Engineering-to-Biology Thesaurus

The engineering-to-biology thesaurus is envisioned as a tool that will enable collaboration between biologists and engineers, and encourage the discovery and creation of biologically-inspired engineering solutions. From the perspective of function-based design, biological information that can interface with exiting design tools (e.g., Functional Basis, concept generators) will lessen the burden on the designer and increase the probability of looking to nature for inspiration. A thesaurus groups synonyms and related concepts in a classified form. The Functional Basis modeling lexicon has a well-defined structure and affords designers a starting point to map terminology between domains. Therefore, the structure of the engineering-to-biology thesaurus was molded to fit the knowledge and purpose of function-based designers that utilize functional models for many design activities. Synonyms and related concepts to the Functional Basis terms are grouped at class, secondary and tertiary levels. The engineering-to-biology thesaurus does more than arrange terminology of one domain side-by-side with terminology of another, it serves as the intermediary between the biology and engineering domains. Furthermore, a tool such as the engineering-to-biology thesaurus increases the interaction between the users and the knowledge resource (Lopez-Huertas 1997). The thesaurus aims to increase a designer's efficiency when translating biological information into an engineering context, as opposed to using a reference (e.g., biology dictionary) to look up multiple biological terms for each potential biological system of interest.

A main advantage of choosing this structure is the application of functional modeling. Engineering correspondent terms currently assist designers with developing functional models of engineered products and systems. Biological correspondent terms facilitate biological functional modeling. However, the engineering-to-biology thesaurus provided in Tables 4.1 and 4.2 is not a comprehensive list of all possible biological terms. This is, and is envisioned to be a work-in-progress that slowly and steadily bridges the terminology gap between the two domains based on contributions of a community of researchers and practitioners. Biological correspondent terms to the Functional Basis functions and flows are shown in place of the original engineering correspondent terms.

Table 4.1. Engineering-to-Biology Thesaurus Functions.

Primary	**Secondary**	**Tertiary**	**Biological Function Correspondents**
Branch	Separate		Bleaching, meiosis, *react*, flower, replicate, segment, *electrophoresis*, dialysis, denature, free, detach, release
		Divide	Division, prophase, anaphase, cleave, cytokinesis, mitosis
		Extract	
		Remove	Deoxygenate, filtrate, deamination, liberate, expulsion, evacuate, shed
	Distribute		Circulate, diffusion, exchange, disperse, scatter, spread, spray
Channel	Import		*Absorb*, attract, consume, inhale, intake
	Export		*Bind*, block, breakdown, excrete, inactivate, *repel*
	Transfer		Migrate, transfer
		Transport	Circulate, conduct, diffuse, pump, shift, displace, fly, swim, jump, bounce
		Transmit	Communicate, *transduce*
	Guide		Orient, position, slide, tunnel
		Translate	*Synthesize*, transcribe
		Rotate	Oscillate, spin, turn, swivel, roll
		Allow DOF	Articulate
Connect	Couple		Recombination, mate, build, phosphorylate, bond, synthesis, latch, lock, extend, link, overlap, *stretch*
		Join	*Bind*, adhere, bond, fuse
		Link	Clamp, *activate*, *bind*, project
	Mix		Blend, *contract*, exchange, fragment

Table 4.1. Engineering-to-Biology Thesaurus Functions (Continued).

Primary	**Secondary**	**Tertiary**	**Biological Function Correspondents**
Control	Actuate		*Activate*, induce, trigger
Magnitude	Regulate		*Electrophoresis*, gate, organogenesis, respire, sustain, preserve, remain, stabilize, maintain, regulate, metaphase
		Increase	*Pinocytosis*, *grow*, expand, multiply
		Decrease	Compress, coil, divide, fold, shorten, *wrap*, hyperpolarize
	Change		*Pinocytosis*, *degrade*, alter, *bind*, catalyze, *contract*, hydrolysis, inflammation of, twist, *mutate*, radiate, charged, slip, acclimatize, alternate, fluctuate
		Increment	
		Decrement	Decarboxylation, *constrict*
		Shape	Elongate, *stretch*, attach, *spread*
		Condition	Osmosis, *constrict*
	Stop		Clog, extinguish, halt, interphase, seal, suspend
		Prevent	Constrain, obstruct
		Inhibit	Cover, destroy, inhibit, repress, *repel*, *surround*
Convert	Convert		Polymerize, *synthesize*, burn, gluconeogenesis, metabolize, *grow*, *transduction*, fermentation, glycolysis, hydrolyze, hydrolysis, respiration, ionize, decompose, *degrade*, *develop*, *mutate*, *photosynthesize*, digest
Provision	Store		Conserve, *hold*, *convert*, deposit, *photosynthesize*
		Contain	*Absorb*
		Collect	*Absorb*, catch, breakdown, concentrate, digest, reduce
	Supply		Feed, lactate
Signal	Sense	Detect	Detect, locate, see, smell
		Measure	Observe, monitor, gauge, watch
	Indicate		Fluoresce, communicate, *react*, mark
		Track	
		Display	
	Process		Learn
Support			*Develop*, *wrap*
	Stabilize		Homeostasis, cling, *hold*, *bind*, *connect*
	Secure		*Surround*, envelope
	Position		
Overall increasing degree of specification →			

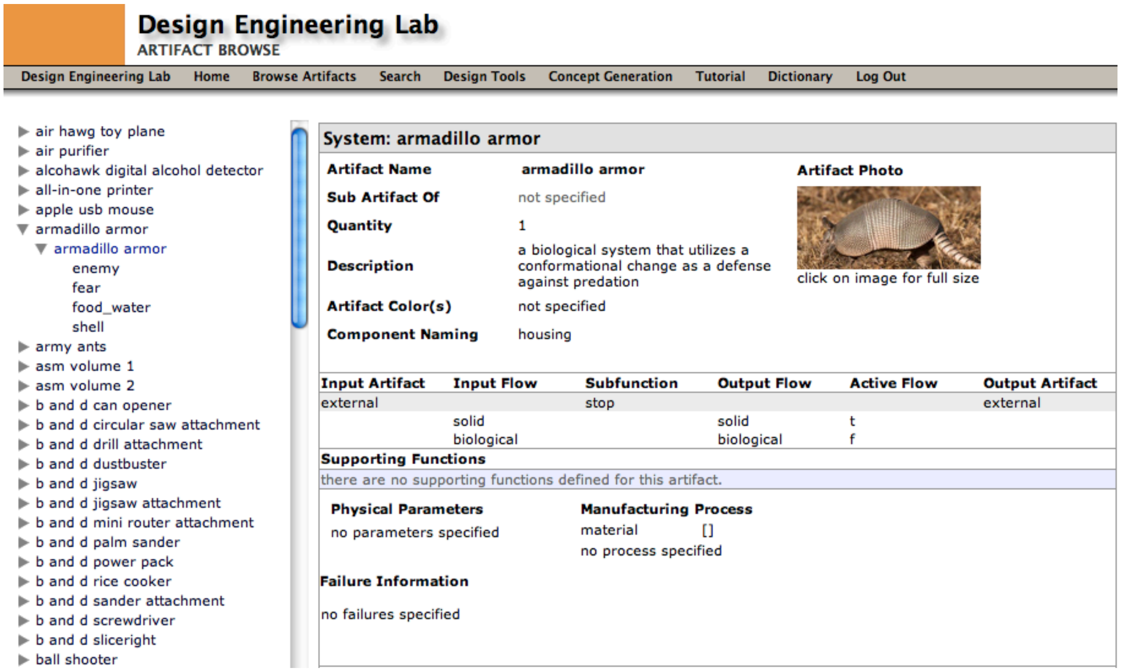
Table 4.2. Engineering-to-Biology Thesaurus Flows.

Primary	**Secondary**	**Tertiary**	**Biological Flow Correspondents**
Material	Human		Being, *body*
	Gas		Oxygen, nitrogen, chlorine
	Liquid		Acid, chemical, water, *blood, solution*, base, buffer, fluid, plasma
	Solid	Object	Fiber, *body*, substrate, microfilament, microtubules, structure, chain, *organ,* nucleus, *tissue*, muscle, cilia, flagella, tube, vein, heart, plant, ribosome, somite, apoplast, stem, kidney, egg, ovary, leaf, embryo, bacteria, chloroplast, carbon, sperm, glucagons, adipose, angiosperm, meristems, mineral, dirt, stoma, shoot, seed, capillary, receptors, hair, bone, tendon, neuron, sporangium, photoreceptors, mechanoreceptors, chromosome, petiole, lysosome, archaea, cone, strand, centriole, spore, zygote, sulfur, lipoprotein, nephron, hyphae, plasmodesma, conifer, plasmid, plastid, xylem, pigment, sperm, hippocampus, phloem
		Particulate	Cytokinin, pyruvate, nicotine, opium, glycerol, carotenoid, , GTP, ATP, urea, *RNA*, tRNA, mRNA, *DNA*, glucagon, parathormone, cryptochromes, *ligand*, promoter, gene, exon, intron, molecule, *enzyme, lipid*, *hormone*
		Composite	*Enzyme*, virus, ribosome, prokaryote, macromolecule, polymerase, nucleotide, polypeptide, organelle, symplast, mesophyll, brood, codon, messenger, *DNA*, *RNA*, cytoplasm, *organ, tissue*
	Mixture	Gas-gas	Air
		Liquid-liquid	*Hormone*, melatonin, thyroxine, calcitonin, thyrotropin, estrogen, somatostatin, cortisol, glucagon, adrenocrticotropin, testosterone, auxin, insulin, intracellular fluid, extracellular fluid, spinal fluid, poison, urine, peptide, *solution*, steroid
		Solid-solid	Adenosine, glomerulus, blastula, monosaccharide, membrane, phosphate, ribosome, centrosomes
		Solid-liquid	Algae, synapse, peptidoglycan, cell, glia, phytochrome, retina, protein, repressor, hemoglobin, *blood*, membrane, bacterium

Table 4.2. Engineering-to-Biology Thesaurus Flows (Continued).

Primary	**Secondary**	**Tertiary**	**Biological Flow Correspondents**
Signal	Status		Change, variation, lateral, swelling, catalyzed, translation, exposed, active, separated, cycle, formation, reaction, redox, deficient, saturated, diffusion, broken, hybridization, orientation, resting, cue, magnetic, volume, under, organized, fruiting, fatty, anaphase, metaphase, prophase, conjugation, osmolarity, senescence, signal, allele
		Auditory	Sound
		Olfactory	Smell
		Tactile	Pain
		Taste	Gustation
		Visual	Length, shortened, long, color, dark, full, double
	Control		Place, inhibit, release, excrete, development, match, induce, digest, integrate, translation, transduction, equilibrium, grown, splice, capture, distribute, phosphorylation
		Analog	Binding, center, synthesis, photosynthesis
		Discrete	Flower, translocation
Energy	Human		
	Acoustic		Echolocation, sound wave
	Chemical		Calorie, metabolism, glucose, glycogen, *ligand,* nutrient, starch, fuel, sugar, mitochondria, *lipid*, gibberellin
	Electrical		Electron, potential, feedback, charge, field
	Electro-magnetic	Optical	Light, infrared
		Solar	Light, sun, ultraviolet light
	Hydraulic		Pressure, osmosis, osmoregulation
	Magnetic		Gravity, field, wave
	Mechanical		Muscle contraction, pressure, tension, stretch, depress
		Rotational	
		Translational	
	Pneumatic		Pressure
	Thermal		Temperature, heat, infrared, cold
Overall increasing degree of specification ➔			

Applications include, but are not limited to, comprehension of biological information, searching for biological inspiration, functional modeling of biological systems, identifying biological analogies to engineered systems and creative engineering design. Representing biological functionally using the lexicon of the Functional Basis also allows biological solutions to be stored in an engineering design repository for future reuse, such as for concept generation or educational purposes. These archived biological solutions can then be recalled and adapted to engineered systems. An example entry of armadillo armor is shown in Figure 4.1. The black box functionality of *stop* solid material or biological energy is shown under the subfunction and flow headings, respectively.



System: armadillo armor

Artifact Name	**armadillo armor**
Sub Artifact Of	not specified
Quantity	1
Description	a biological system that utilizes a conformational change as a defense against predation
Artifact Color(s)	not specified
Component Naming	housing

Artifact Photo

Input Artifact	Input Flow	Subfunction	Output Flow	Active Flow	Output Artifact
external		stop			external
	solid		solid	t	
	biological		biological	f	

Supporting Functions

there are no supporting functions defined for this artifact.

Physical Parameters

no parameters specified

Manufacturing Process

material []

no process specified

Failure Information

no failures specified

Figure 4.1. Example Biological Repository Entry.

4.2.1 Thesaurus Structure

The purpose of a thesaurus is to represent information in a classified form to group synonyms and related concepts. A thesaurus of the English language has classes and categories with an index of terms directing the user to the correct instance (i.e., noun, verb, adjective) of the term under examination. The engineering-to-biology thesaurus presented here has a unique structure and classification; it is merged with the Functional Basis as a set of correspondent terms. It does not include an index nor does it include adjectives. Only verbs and nouns that are synonymous to terms of the Functional Basis are considered. The Functional Basis class level terms, however, do emulate the classes of a traditional thesaurus. Furthermore, the secondary and tertiary level Functional Basis terms emulate the categories of a traditional thesaurus. Biological terms that fit in the function and flow sets, and correspond to multiple functions or flows, are repeated and italicized to designate the special case. Thus, the classification is predetermined according to that of the Functional Basis model. The classification increases the interaction between the users and the knowledge resource by presenting the information as a look-up table. This simple format fosters one to make associations between the engineering and biological lexicons, thus, strengthening the designer's ability to utilize biological information.

4.2.2 Thesaurus Population

The correspondent functions and flows were gathered in two ways. Flows were gathered first through keyword searching and frequently occurring collocated nouns, where as functions were collected via research efforts from multiple universities and keyword searching. Population of the engineering-to-biology thesaurus flow terms is achieved through keyword searches of a biological corpus using the organized search tool of Chapter 3 (Stroble et al. 2009c). Functional Basis functions (verbs) were utilized for searching the biological corpus to extract biologically connotative words (nouns) that an engineering designer interested in function-based design might encounter. Every term of the Functional Basis was used to mine biological nouns. A list of collocated nouns that occur within the same sentence as the search word is generated, of which terms are chosen for placement. Chosen words were determined by their macrorelevancy, which is identified by frequency of use (Lopez-Huertas 1997). Terms that appeared more than two times were considered macrorelevent. At the time, variations of the stem function word were not considered during the searches. For example, detect is the stem function word and the variations of this verb–detection, detects, detected, and detecting–were not included in search results. Each macrorelevent term was researched to determine if it was of signal, material or energy type in the new Oxford American dictionary (McKean 2005) and Henderson's dictionary of biological terms (Henderson and Lawrence 2005) before being placed. Placement of flow terms in the engineering-to-biology thesaurus is at the discretion and best judgement of the author.

Population of the engineering-to-biology thesaurus function terms is achieved through keyword searches of a biological corpus using the organized search tool of Chapter 3 and consolidation of multiple research efforts (Nagel et al. 2010b). Keyword searches were performed to gather a list of collocated verbs that occur within the same sentence as the search word. Due to the lower number of terms in the generated lists, all words were analyzed for placement in the thesaurus. The biological functions were cross referenced in the Oxford American dictionary (McKean 2005), Henderson's dictionary of biological terms (Henderson and Lawrence 2005) and the Oxford Dictionary of Biology (Matrin and Hine 2000). All other function terms were obtained from research performed at the Indian Institute of Science and University of Toronto, which is made explicit in Section 4.3.1. It should be noted that some of the biological function correspondent terms are nouns that name a process corresponding to a Functional Basis function. Placement of function terms in the engineering-to-biology thesaurus is at the discretion and best judgement of the author.

4.2.3 Thesaurus Particulars

Key challenges to the approach for populating the thesaurus described in this research were the time required to search each term to generate a listing of collocated terms and understand the definition provided in the dictionaries used to understand the biological terms. To determine the material, energy or signal type of the flow term in question, generally multiple biological dictionary entries were referenced.

The majority of biological information is written in such a way that correlating biological verbs to Functional Basis functions is relatively straightforward. However, there are always exceptions. Well-known functional terms that appear in a biological text may not have the meaning an engineer would typically know. For instance, the term *bleaching* outside of the biological domain means to clean, sterilize or whiten, as most know. Within the biological domain, the meaning refers to the process of separation between the retina and opsin in vertebrate eyes and causes the retinal molecule to lose its photosensitivity (Campbell and Reece 2003). It is these types of exceptions that author was cognizant of when compiling the set of biological correspondent function terms for the engineering-to-biology thesaurus. Considering biological processes that perform a specific function within the system revealed many macorelevant terms that would have been overlooked if only verbs were analyzed. To signify which function terms are utilized in both domains, the Functional Basis term is repeated in the biological correspondent list.

The Functional Basis offers a definition and example for each class, secondary and tertiary term. However, definitions of the correspondent terms are not provided. Rather, the correspondent terms are synonyms to the Functional Basis terms to aid the designer when choosing the best-suited term. This is also true for the biological correspondent terms. Biological terms that fit in the function and flow sets, and correspond to multiple functions or flows, are repeated in the set of correspondent terms and are italicized to designate the special case of those terms. This treatment is similar to the repeated words of the engineering correspondent terms.

4.2.4 Thesaurus Validation

The thesaurus has been reviewed by a biologist in two instances: 1) when the biological correspondent flow listing was generated and 2) when the biological correspondent function listing was generated. The terms of Tables 4.1 and 4.2 represent the most recent validity check by a biologist. Validation of the placement, type, and structure of the thesaurus terms was initially performed by a biology student at Missouri University of Science and Technology once flows were placed and then by a professor of Zoology at Oregon State

University once functions were placed. Term placement analysis is the first step in the validation process. The professor of Zoology at Oregon State University reviewed both sets of biological corresponding terms and offered his insight (Brownell 2010a; Brownell 2010b). Biological terms that were incorrectly placed in the thesaurus were moved to better map the terminology to the engineering domain or were removed due to ambiguity per his suggestion. It is believed that term placement analysis by a biology student and professor of Zoology is adequate validation to facilitate all potential applications of the thesaurus, just as the reconciled Functional Basis is adequate for use with a variety of design activities. Application validation, the second step, will occur through future design studies.

4.3 Biological Correspondent Terms

The terms of the engineering-to-biology thesaurus represent an integration of three independent research efforts, which include research from Oregon State University, the University of Toronto, and the Indian Institute of Science, and their industrial partners. All flow correspondents were obtained independently from function correspondents as a first effort to create the thesaurus, where as the function correspondents were arrived at through a combination of research efforts. Function terms obtained from research performed at the Indian Institute of Science and University of Toronto are made explicit in Section 4.3.1.

4.3.1 Function Correspondents

Compiling multiple research efforts focused on language driven inspiration of innovative engineering designs strengthens the advantages of each effort. The terms utilized for Idea-Inspire (Srinivasan and Chakrabarti 2009a) must be broad enough to capture the principles of both biological and engineered systems, whereas, the carefully chosen terms of the Functional Basis were initially meant for engineered systems only. The biologically meaningful that correspond to Functional Basis functions discovered by semantic relationships (Cheong et al. 2008) utilized for creative design exercises demonstrate functional terms that yield good results when searching a biological text for inspiration. Integration of these two research efforts with the Oregon State University effort ensures the success of future design activities.

Functional terms from the University of Toronto were collected from the work by Cheong et al. whom identified biologically meaningful words to those of the Functional Basis (Cheong et al. 2008). Because background work was already performed on the semantic relationships of the biologically meaningful words, further investigation was not performed. Rather, the previously tested and successful terms of Table 4.3 were directly added to the biological correspondent function set of the thesaurus. Functional terms from the Indian Institute of Science were collected from the Idea-Inspire software. Every natural system entered into the software's database was indexed using the predetermined list of verbs, nouns and adjectives. Analyzing the list of verbs by cluster (Srinivasan and Chakrabarti 2009a) revealed scientific terms applicable to biological systems grouped with engineering terms exactly matching those of the Functional Basis. Utilizing multiple dictionaries as in the Oregon State University analysis, the verbs of Idea-Inspire were paired with Functional Basis functions. The broad scoping, yet easily overlooked, terms of Table 4.4 are included in the biological correspondent function set of the thesaurus.

Table 4.3. University of Toronto Functional Terms (Cheong et al. 2008).

Primary	Secondary	Tertiary	Biological Function Correspondents
Channel	Export		Bind, block, breakdown, excrete, inactivate
	Transfer	Transport	Circulate, conduct, diffuse, pump
		Transmit	Communicate, transduce
	Guide	Translate	Synthesize, transcribe
Connect	Couple		Extend, link, overlap, stretch
		Link	Activate, bind, project
	Mix		Contract, exchange, fragment
Control Magnitude	Stop	Inhibit	Cover, destroy, inhibit, surround
Convert	Convert		Decompose, degrade, develop, grow, mutate, photosynthesize
Provision	Store		Convert, deposit, photosynthesize
		Collect	Breakdown, concentrate, digest, reduce
Support			Develop, wrap
	Stabilize		Bind, connect

It is interesting to note that Table 4.4 does not include any terms for the function of convert because transform (the correspondent for convert) and change are considered as the same cluster for the Idea-Inspire software. Additionally, some of the biological correspondents in Table 4.4 are identical to the original Functional Basis set of correspondent terms. These terms were repeated to signify that the term is used in both domains. Table 4.3 is shorter, but offers on average more correspondent terms per Functional Basis term due to the rigorous method of determining biologically meaningful terms. Moreover, Table 4.3 offers a fascinating observation about the versitility of natural systems–multiple terms have multiple functions. Consider *connect*, it could mean bringing two objects together (from the Functional Basis side) or it could refer to stabilizing support (from the biological side). Also consider *bind*, this term could refer to stability, linking or exporting. Both research efforts provide substantial contributions to the engineering-to-biology thesaurus.

Table 4.4. Indian Institute of Science Functional Terms (Srinivasan and Chakrabarti 2009a).

Primary	Secondary	Tertiary	Biological Function Correspondents
Branch	Separate		Free, detach, release
		Remove	Evacuate
	Distribute		Disperse, scatter, spread, spray
Channel	Import		Consume, inhale, in take, absorb, attract
	Export		Repel
	Transfer	Transport	Shift, displace, fly, swim, jump, bounce
	Guide	Translate	Slide
		Rotate	Oscillate, spin, turn, swivel, roll
Connect	Couple		Latch, lock
		Join	Adhere, bond, fuse
		Link	Clamp
Control Magnitude	Actuate		Activate, trigger
	Regulate		Preserve, sustain, remain, stabilize, maintain
		Increase	Grow, expand, multiply
		Decrease	Compress, coil, divide, fold, shorten, wrap
	Change		Alternate, fluctuate
	Stop		Halt, extinguish, clog, seal, suspend
		Prevent	Constrain, obstruct
Provision	Store		Conserve, hold
		Collect	Absorb, catch
	Supply		Feed
Signal	Sense	Measure	Observe, monitor, gauge, watch
Support			Cling, hold

Table 4.5 lists the Oregon State University contribution of biological function correspondent terms to the engineering-to-biology thesaurus. All but four of the engineering functions have identified biological correspondents (which are omitted from the list).

Table 4.5. Oregon State University Functional Terms.

Primary	Secondary	Tertiary	Biological Function Correspondents
Branch	Separate		Bleaching, meiosis, replicate, mitosis, segment, abscission, electrophoresis, react, dialysis, denature
		Divide	Division, prophase, metaphase, anaphase, cleave, cytokinesis
		Remove	Deoxygenated, filtrate, deamination, liberate, expulsion
	Distribute		Exchange, circulate, diffusion
Channel	Transfer		Migrate, transfer
	Guide		Orient, position, tunnel
		Allow DOF	Articulate
Connect	Couple		Recombination, mate, build, phosphorylate, bond, synthesis
		Join	Bind
	Mix		Blend
Control Magnitude	Actuate		Induce, trigger
	Regulate		Gate, electrophoresis, respire, regulate, organogenesis,
		Increase	Hyperpolarize, pinocytosis
	Change		Pinocytosis, catalyze, degrade, alter, bind, contract, hydrolysis, twist, slip, spread, mutate, adiate, charged, acclimatize
		Increment	Attach
		Decrement	Decarboxylation, constrict
		Shape	Elongation, stretch, attach, spread
		Condition	Osmosis, constrict
	Stop		Interphase
		Inhibit	Repress
Convert	Convert		Polymerize, ionize, synthesize, hydrolysis, gluconeogenesis, metabolize, glycolysis, translation, respiration, photosynthesis, fermentation, burn
Provision	Store	Contain	Absorb
	Supply		Lactate
Signal	Sense	Detect	Detect, locate, see, smell
	Indicate		Fluoresce, mark, communicate, react
	Process		Learn
Support	Stabilize		Homeostasis
	Secure		Surround, envelope

4.3.2 Flow Correspondents

In the author's experience, understanding biological terms that were considered flows (material, signal and energy) when utilizing biological systems or phenomena for idea generation or design inspiration posed the most difficulty. Determining if a biological material is liquid, solid or a mixture by its name typically requires domain knowledge that most engineers do not have, which cause biological concepts to be perplexing. Similarly, needing a reference to look up biological terms each time a potential biological system is found made the research tedious, and disrupted thought patterns leading to decreased efficiency. Research shows that the flow correspondent terms have significant value in bridging the gap between biology and engineering.

4.4 Applications

The engineering-to-biology thesaurus was developed with the intention of promoting collaboration between the biology and engineering domains, resulting in discovery of creative, novel ideas. The following sections describe plausible applications of the presented thesaurus, which are summarized in Figure 4.2. However, with few boundaries in the field of design, this thesaurus could be employed in ways the author has not considered.

4.4.1 Searching for biological inspiration

Searching a natural-language corpus, such as a textbook, for biological inspiration based on engineering functionality or using engineering terms typically produces results that are mixed. Results containing the search word often use the search word out of context, not at all or in a different sense then the designer intended. By utilizing the biological correspondent terms of the thesaurus when searching for a specific function or flow that solves the engineering problem, search results improve (Stroble et al. 2009b; Nagel and Stone 2010) and become more focused on the desired biological systems or phenomena.

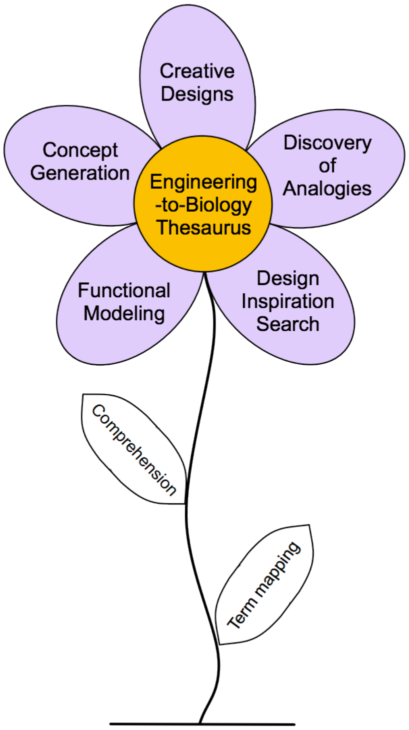


Figure 4.2. Engineering-to-Biology Thesaurus Applications.

4.4.2 Comprehension

Lopez-Huertas wrote that a thesaurus "...is thought of as a way of easing communication between texts and users in order to increase the interaction in information retrieval, and thus facilitate information transfer" (Lopez-Huertas 1997). The engineering-to-biology thesaurus has the potential to aid engineering designers with the comprehension of biological contexts and facilitate information transfer in two ways; (1) direct translation of biological text into engineering “speak” and (2) abstraction of a biological system or phenomena in engineering terms.

Direct translation can be achieved by substituting biological words that appear in the thesaurus with their corresponding Functional Basis terms. Essentially, this will rewrite the biological information in engineering “speak” and increase the likelihood of a designer making connections between the two sets of information and gaining inspiration as a result. Many design methods rely on abstractions and describing an abstracted biological principle in engineering terms is advantageous. Not only does it increase the likelihood of a designer understanding the biological principle, but also it lends itself to formulating connections between the biological and engineering domains and easy comparison to other abstractions. Efficient information retrieval through the engineering-to-biology thesaurus allows an engineering designer to cross into the biological domain and gain functional knowledge without becoming overwhelmed by unfamiliar biological systems and phenomena.

4.4.3 Functional Modeling of Biological Systems

The engineering-to-biology thesaurus provides direction when choosing the best-suited function or flow term to objectively model a biological system. A wide range of biological terms have been collected and placed into the thesaurus, which can accommodate a designer when developing functional models of well known to just introduced biological systems. Functional modeling of biological systems allows representation of solutions to specific engineering functions and direct knowledge discovery of the similarities and differences between biological and engineered systems, as viewed from a functional perspective. The creation of engineered systems that implement strategies or principles of their biological counterparts without reproducing physical biological entities is an additional benefit to biological functional models.

4.4.4 Concept Generation

Concept generation, manual or computational, aims to generate several conceptual design variants. During this process engineers draw on their prior knowledge, search design catalogs, use a knowledge basis and in some cases search patents (Otto and Wood 1996; Ulrich and Eppinger 2004; Voland 2004; Cross 2008). Biology is another resource available to engineers for design inspiration. Designers can use the terms of the thesaurus to understand how nature *removes* for example. From the biological correspondent terms one could relate the terminology to prior knowledge or develop an analogy that leads to design inspiration. Considering biological systems and phenomena through generalized engineering terms allow connections to be made between the domains, which facilitates knowledge transfer. Therefore, biological information can be used in function-based engineering design methods.

A computational method that has been pursued is the population of a biomimetic design repository, which enables the storage of biological knowledge indexed by engineering function. Refer to Figure 4.1. Storing the biological information based on the function the biological system or phenomena solves allows quick access to biological solutions. There are a total of 30 biological entries in the Design Repository housed at Oregon State University, 13 are phenomena and 17 are systems (organisms) for this purpose. The Design Repository facilitates computational concept generation and comparison of biological and engineered components. The designer chooses from resulting computational concept generator suggestions, engineered and biological, to develop a complete conceptual design. Example concept generator results for three function/flow pairs are provided in Figure 4.3. Notice biological solutions are only in the second and third rows. Multiple parts of the fly detect chemicals along with the chemoreceptors of the Animalia and Plantae Kingdoms. The butterfly and cobra change their shape to ward off predators, which is captured with *change* material.

Criteria	Artifacts				
Input Flow: mixture **Subfunction:** transfer **Output Flow:** mixture Search took: **0.736** seconds.	water tube 2 (13.33%)	shower head tube (10.0%)	shower head (10.0%)	faucet tube (6.67%)	lower gear housing (3.33%)
Input Flow: chemical **Subfunction:** detect **Output Flow:** chemical Search took: **0.334** seconds.	antenna (16.67%)	N/A chemo detection (16.67%)	N/A chemo detection plantae (16.67%)	chemoreceptor (16.67%)	mouthparts (16.67%)
Input Flow: material **Subfunction:** change **Output Flow:** material Search took: **0.502** seconds.	heating element (11.76%)	blade (3.92%)	butterfly (1.96%)	ceramic bowl (1.96%)	cobra (1.96%)

Figure 4.3. Example Design Repository Concept Generator Results.

4.4.5 Collaboration, Creation, Discovery

Terms contained within the engineering-to-biology thesaurus can be utilized for increasing creativity in engineering designs and to discover connections between biological systems and existing engineered systems and visa versa. Formulating connections often requires an interdisciplinary team to ensure the connection is properly represented, whatever the mix of domains. Exploration of biomimetic designs prompts collaboration between biology and engineering researchers.

4.5 Examples

In this section the various applications of the engineering-to-biology thesaurus are explored through examples. Searching for inspiration, comprehension, functional modeling, concept generation and collaboration are all highlighted. The applications with in-depth examples are comprehension and functional modeling. Insect chemoreception is presented as a case for translation that leads to greater comprehension. A two-part example exploring sensing, or signal transduction, in bacteria via the two-component regulatory system is considered to demonstrate the versatility of the engineering-to-biology thesaurus. This example demonstrates the thesaurus applications of comprehension and functional modeling.

4.5.1 Searching for Inspiration

Chapter 3 demonstrated how the terms of the thesaurus could be used for finding relevant biological solutions during an inspiration search. It was shown that by simply replacing the engineering Functional Basis term with biological correspondent terms during searching, accurate and relevant biological information was a result. Searching for inspiration is not limited to the search software. It will be shown in Chapter 7 how the terms can be used with an open source database of biological knowledge indexed by function.

4.5.2 Comprehension of Biological System

The majority of biomimetic designs have been modeled after physical biological phenomena that can be observed, or experienced first hand as mimicking unseen phenomena, such as activity at the cellular level, is more difficult. Biological terminology often becomes narrow and requires more knowledge of the subject. The following examples serve as a qualitative measure of the engineering-to-biology thesaurus to show that this tool can assist with translating narrow biological terminology into generalized engineering terms without requiring the designer to learn deep biological knowledge.

The engineering-to-biology thesaurus has the potential to aid engineering designers with the comprehension of biological contexts by substituting Functional Basis terms for biological terms. For example, consider the text excerpt describing insect olfaction through antennae taken from the section Chemoreception in The Encyclopedia of Insects (Mitchell 2003). The contextual difference between the original and "translated" forms shown below should, "eas[e] communication between texts and users in order to increase the interaction in information retrieval, and thus facilitate information transfer" (Lopez-Huertas 1997).

Original text from (Mitchell 2003): *In insects, odor molecules first contact the cuticular surface, and because it is waxy, they easily dissolve. From here they move in two dimensions, and some find their way into the opening of a pore canal. ... Eventually, however, before it arrives at the receptor surface of a dendrite, the hydrophobic odor molecule will encounter water. ... The other type binds less specifically [to] a variety of nonpheromone molecules (e.g., food odors) and are called general odor binding proteins (GOBP). The odorant binding proteins (OBP) act as shuttles and carry odor molecules through the aqueous medium to the surface of the dendrite. In the membrane of the sensory cell are receptors for various odors, depending on the specificity of the cell.*

By manually identifying unclear biological terms and substituting Functional Basis terms the translated text presents the information in a more generalized context, which can be used for engineering design inspiration. The translated insect olfaction text is as follows: In insects, odor composites first contact the solid material surface, and because it is waxy, they easily dissolve. From here the odor composite moves in two dimensions, and some find their way into the opening of a material channel. ... Eventually, however, before it arrives at the solid object surface of a an object that transfers electrical energy, the hydrophobic odor composite will encounter a liquid material. ... The other type binds less specifically [to] a variety of nonpheromone composites (e.g., food odors) and are called general odor binding solid-liquid mixtures. The odorant binding solid-liquid mixtures act as guides and transfer odor composites through the liquid material to the surface of the object that transfers electrical energy. In the solid-solid material of the sensory solid-liquid material are solid objects for various odors, depending on the specificity of the solid-liquid material.

The biological information is now presented in a more generalized context, which can be used to facilitate functional modeling or concept generation or follow a curiosity. Another example of simple translation of the two component regulatory system is presented. The next example covers what is the two-component regulatory system, the mechanism of sensing within bacteria, to further demonstrate comprehension.

The topic of signal transduction in prokaryotes explains how bacteria sense their environment for survival. Signal transduction occurs to alert the bacteria of stimuli via a two-component regulatory system (TCRS) (Parkinson 1995; Taiz and Zeiger 2006). Bacteria respond to nutrients, synthesizing proteins involved in uptake and metabolism, and non-nutrient signals both physical and chemical (Parkinson 1995; Taiz and Zeiger 2006). Signaling pathways in bacteria consist of modular units called transmitters (sensor proteins) and receivers (response regulator proteins), which comprise the TCRS. Example bacterial processes that are controlled by TCRS are chemotaxis, sporulation and osomoregulation (Taiz and Zeiger 2006).

Tiaz and Zeiger explain bacteria employ TCRS to sense extracellular signals as the following (Taiz and Zeiger 2006): *Bacteria sense chemicals in the environment by means of a small family of cell surface receptors, each involved in the response to a defined group of chemicals (hereafter referred to as ligands). A protein in the plasma membrane of bacteria binds directly to a ligand, or binds to a soluble protein that has already attached to the ligand, in the periplasmic space between the plasma membrane and the cell wall. Upon binding, the membrane protein undergoes a conformational change that is propagated across the membrane to the cytosolic domain of the receptor protein. This conformational change initiates the signaling pathway that leads to the response.*

By manually identifying unclear biological terms and substituting Functional Basis terms, the text excerpt above is translated to: Bacteria sense chemical energy in the environment by means of a small family of cell surface receptors, each involved in the response to a defined group of chemicals (hereafter referred to as chemical energy). A protein in the plasma membrane of bacteria joins directly to chemical energy, or joins to a soluble protein that has already attached to the chemical energy, in the periplasmic space between the plasma membrane and the cell wall. Upon joining, the membrane protein undergoes a conformational change that is propagated across the membrane to the cytosolic domain of the receptor protein. This conformational change initiates the detection that leads to the response.

Again, the biological information is now presented in a more generalized context, which can be used to facilitate functional modeling or concept generation or follow a curiosity. In the next section, a functional model is derived form the translated two-component regulatory system information.

4.5.3 Functional Modeling

Reconsider the two-component regulatory system presented in the preceding section. Figure 4.4 provides a visual representation of the TCRS sensing process; (A) Defining cellular boundaries and substances present in bacteria; (B) Conformational change sends a signal to cytosolic domain triggering the transmitter to release protein phosphate; (C) phosphate binds to the receiver initiating the output response. Abbreviations: T-Transmitter, R-Receiver, ATP-Adenosine triphosphate, ADP-Adenosine diphospahte, P-Phosphate. ATP and ADP are required to initiate communications between the transmitter and receiver proteins and phosphate is required to activate the receiver to produce a response (Parkinson 1995; Taiz and Zeiger 2006).

Ligands are found in the thesaurus under material-solid-object and chemical energy. In the case of TCRS, ligands are utilized as chemical signals, thus chemical energy was the chosen flow. Protein, an organic compound made of amino acids arranged in a linear chain and folded into a globular form (Parkinson 1995; Taiz and Zeiger 2006), is synonymous with material-solid-liquid-mix, as is cell. Bind was found under multiple classifications. Join was chosen to represent binding of chemical energy and a solid-liquid material. Binding causes detection of the stimulus signal. Detection causes a

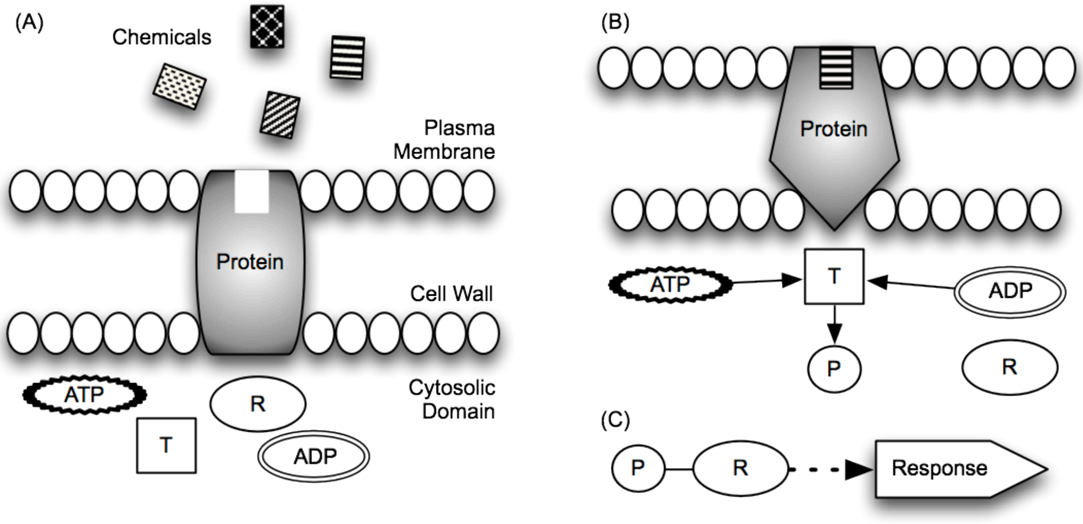


Figure 4.4. Visual Representation of the Two-Component Regulatory System.

status signal to be transferred to the cytosolic domain, which causes the release of protein phosphate. Communication is now initiated. Phosphate, which under goes phosphorylation, acts as a control signal that is transferred to the receiver protein to regulate and condition the chemical energy within the bacterium to produce a response. The two components of TCRS are transmitter and receiver proteins, however, from a functional standpoint chemical energy is needed to join with and change the bacterium material to elicit a response. The textual and diagrammatic abstractions of TCRS can now be utilized for developing connections between biology and engineering. A functional model of TCRS in bacteria is shown in Figure 4.5.

A more detailed example of biological functional modeling will be presented in Chapter 5. It will be demonstrated how one can model chemoreception of insects as well as how to manage the biological information to make it easer to create a functional model.

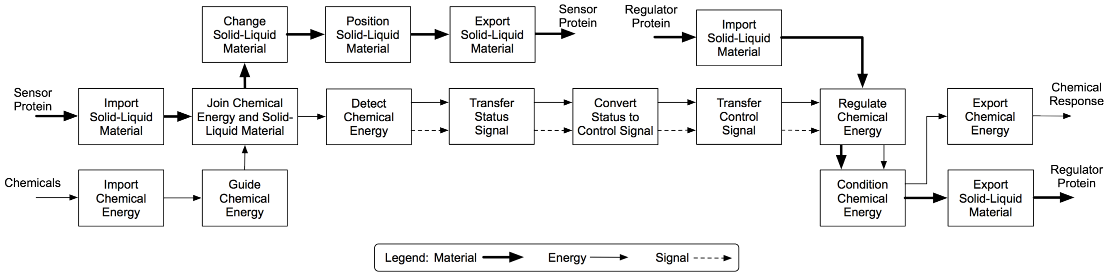


Figure 4.5. Functional Model of the Two-Component Regulatory System.

4.5.4 Concept Generation with Biological Information

A detailed explanation of concept generation with biological information, and its approaches, is given in Chapter 6. Detailed examples of concept generation with biological information will be demonstrated in Chapters 7, 8 and 9.

4.5.5 Collaboration with Biologists

This tool can aid the communication between engineers and biologists. Engineers get glimpse of how biological terms have multiple meanings and levels of interpretation. However, it could assist a designer with asking the right questions of experts in biology. For example, asking “how does a biological system transmit information?” is very open ended and may not lead to a useful answer. A better question to ask would be “what role does transduction play in communicating information?” Using the terms of the thesaurus can aid a biologist to reciprocate and give an answer that an engineer is more likely to understand.

4.6 Summary

The natural world provides numerous cases for inspiration in engineering design. From simple cases such as hook and latch attachments to articulated-wing aircrafts. Though biological systems provide a wealth of elegant and ingenious approaches to problem solving, there are terminology challenges that prevent designers from leveraging the full insight of the biological domain. Through this research, biological function (verb) and flow (material, signal, energy) correspondent terms were mapped to engineering terms and placed into pre-determined classifications set by the Functional Basis structure. Thus, leading to the engineering-to-biology thesaurus. The engineering-to-biology thesaurus aims to facilitate biologically-inspired design by lessening the burden on the designer working with knowledge from the biological domain. It provides a link between engineering and biological terminology and assists with establishing connections between the two domains. This research is a work-in-progress and is not a comprehensive list of all biological terms; however, it is among the first steps to bridging the terminology gap between the biology and engineering domains. The overall approach for term collection and integration was discussed. It was observed that the majority of biological flow correspondent terms are grouped at the tertiary level, whereas biological function terms are primarily grouped at the secondary level.

Implications of the thesaurus on the engineering and biology communities were also explored. Breaking down a biological solution into smaller parts, based on functionality, allows one to liken a biological system to an engineered system for ease of understanding and transfer of design knowledge.

Of the many engineering-to-biology thesaurus applications, insect olfactory chemoreception and the two-component regulatory system of bacteria were presented to demonstrate two of the applications. It is envisioned that the thesaurus will enable the engineering and biology communities to better collaborate, create and discover in the future. Furthermore, the engineering-to-biology thesaurus is a subject domain oriented, intermediary structure, which can be updated as needs are identified.

CHAPTER 5 - REPRESENT: FUNCTIONALLY ABSTRACTING BIOLOGICAL INFORMATION

5.1 Overview

The biological domain has the potential to provide inspiration at many levels–termed scales, such as cellular, organism and species. For instance, if a system level sensor design is desired that considers the details for interfacing, communicating or packaging, one can study the interaction of one species with another or look to any ecosystem for ideas. Biological inspiration can be found from a multitude of sources, and through the use of abstraction, designers can analyze a biological system in a manner similar to an engineered system. Abstractions, as discussed in Chapter 2, are critical because they allow a designer to draw parallels between domains through functionality. This research uses functional modeling to abstract biological systems in a repeatable and systematic manner that can be paired with existing function-based, engineering design tools and methods.

This chapter presents a general method for functionally representing biological systems. Mimicry categories and scales, in addition to answering a design question, aid the designer with defining boundaries or scope when developing a biological functional model. Biological category assists with framing the information in the right perspective, whereas biological scale deals with how much detail is required for an adequate representation of the biological system to utilize the information with a chosen engineering design method. Choosing a category serves to refine the boundary, but, like scale, its consideration might prompt the designer to consider the same biological system in a new and unique way leading to new ideas. Biological functional models translate key biological information from a biological context into a generalized, engineering context. Thus, the information is accessible to engineering designers with varying biological knowledge, but a common understanding of engineering design methods and lexicons. General guidelines for modeling biological systems at varying scales and categories are given, along with a modeling example.

5.2 Functionally Modeling Biology

Representing a system in terms of its function (i.e., what the system does) as opposed to its form (i.e., what comprises the system) is commonly used to abstract problems in engineering design. Abstraction plays a major role in the early stages of engineering design and is a valuable tool during the conceptual design phase (Voland 2004). Abstractions allow one to capture the essence of a product, process, or component within a succinct phrase, diagram, image or domain-independent terms. Finding an appropriate abstraction is a fundamental hurdle to the use of biology as a reliable source of inspiration in engineering design. This research uses functional modeling to abstract biological systems in a repeatable and systematic manner that can be paired with existing function-based, engineering design tools (Nagel et al. 2010a; Nagel et al. 2010c). Functional models allow a design problem to be quickly abstracted from customer needs and design requirements without requiring the design team to consider potential components, solution principles or potential feasibility. This research is based on the functional modeling method defined in (Stone and Wood 2000) and the Functional Basis lexicon defined by (Hirtz et al. 2002). The Functional Basis lexicon, provides the terminology to define all functions and flows required by engineered systems. Functions represent the transformation (verb) of flows (noun), either material, signal or energy, required by an engineered system. When viewed functionally, biological systems operate in much the same way as engineered systems (French 1994). Each part or piece in a biological system has intended functionality. Functional modeling of biological systems allows biological systems to be translated into an engineering context. The information is then accessible to engineering designers who possess varying levels of biological knowledge, but a common understanding of engineering design methods. The advantage of modeling the flow transformations within a biological system with the Functional Basis is that the biological information is now an abstraction of its true form. These abstractions can facilitate the creation of connections such as analogies or metaphors that lead to creative leaps. Functional representation of biological systems has the potential to provide several advantages for engineering design including:

- systematic approach for establishing and representing system functionality;
- translation of context from biological to engineering;
- physiology, morphology, behavior or strategy captured at multiple levels of fidelity;
- identification of characteristics that can be mimicked by engineering means;
- creativity in concept generation; and
- archival and transmittal of information.

Functional modeling is a useful tool for capturing the essence of an engineered product, process, or component through diagrammatical means. Physically decomposing a product, process or component for redesign or curiosity, and analyzing the interactions is a common method for creating a functional model. This method is popular because the scope or boundaries of the functional model are well defined by the physical pieces and/or modularity of those pieces. A functional model can also be used in the development of a new product, and as such, the model describes the desired product functionally within the bounds of the customer needs and constraints. However, modeling biological systems is not as straightforward as modeling engineered systems. To achieve a similar well-defined scope for a biological system, biological categories and scales are used during modeling. The following sections explain the process of mapping biological terms to the engineering domain, the selection of appropriate categories and scales for modeling, and the methodology to generate a functional model.

5.3 Mapping Biology to Function

Representing biological functionality using the lexicon of the Functional Basis allows biological solutions to engineering functions to be captured and stored in an engineering design repository. This information can then be used for comparisons to engineered systems and concept generation. These biological solutions can then be recalled and adapted to engineered systems. However, modeling biological systems is not a trivial task. One cannot easily take apart a biological system, examine the parts and associate function as one might an engineered system, nor are there customer needs to guide the designer. Rather, the designer must rely on biological literature or biologists for detailed information about the biological system in question. During the initial modeling steps, as described later in Section 5.6, a reference source should be identified to glean basic information about the biological system that offers inspiration. Biological terminology, however, could pose difficulty in learning about the biological system. To assist with terminological differences and to facilitate biological functional modeling, the engineering-to-biology thesaurus of Chapter 4 is employed. Also, while learning about the biological system key flows should be identified. These will assist with formulating a design question. The design question focuses a designer's efforts toward the modeling goal and the answer should be reflected in the biological functional model.

The approach to modeling biology with the Functional Basis presented in this chapter aims to accurately reflect the material, signal, or energy flows carrying out biological system functions. It should be noted that *biological* is included in the Functional Basis as a secondary-level energy flow; however, this approach discourages its use. Since engineered systems lack a biological energy, its use as the primary energy source in a biological system would limit or even inhibit a designer from making connections between the engineering and biology domains. To encourage connections, care should be taken to select material, energy and signal flows that would commonly appear in an engineered system. The engineering-to-biology thesaurus may be used to find appropriate function and flow terms.

5.4 Defining Mimicry Categories

Mimicking a biological system for the creation of biologically-inspired technology has occurred through several mechanisms. This research investigates biologically-inspired design through functional modeling. The fundamental difficulty in modeling biology occurs with comprehending the multiple viewpoints of a biological system. Understanding how biological knowledge is interrelated, yet categorizable, offers a designer insight on how to manage the non-engineering domain information such that it can best aid the design process. Researchers discovered (Raven and Johnson 2002; Campbell and Reece 2003) that biological organisms have three outlets for interacting with a changing environment: physiology, morphology and behavior. A biological organism will adapt new functionality (physiology) or structure (morphology), or learn a new behavior to obey the instinctual actions of protect, reproduce and sustain. Additionally, experience with modeling biological systems uncovered similar behavior (e.g., change shape, expose pores, drop offshoot) across multiple biological ranks (i.e., kingdom, phylum, class, order, family, genus, species) that were initiated and carried out for dissimilar reasons; these are termed strategies. Thus, four biological categories are provided for functional modeling and are defined as (Matrin and Hine 2000; Raven and Johnson 2002; Campbell and Reece 2003; Henderson and Lawrence 2005):

- Physiology: concerned with the vital functions and activities of organisms, as opposed to their structure.
- Morphology: the form and structure of an organism, and the associations amongst the structures of an organism.
- Behavior: the sum of the responses of an organism to internal or external stimuli.
- Strategy: a generic behavior that is exhibited among multiple biological ranks to achieve different goals.

Note that behavior is separate from strategy to allow insight into specific, within biological rank, actions a biological system takes that may or may not be part of the overall strategy. Strategy is kept as a separate term to alert the designer to repeating behavior across biological systems that results in different outcomes.

When creating an abstraction to represent a biological system, considering questions that each of these categories answers can help to clarify and direct how the model is created. For example, asking a question about behavior and/or strategy is exploring the question of why. Asking a question about physiology explores the question of what. Finally, asking a question about morphology explores the question of how. Mimicry categories can aid the designer with defining a boundary when developing a functional model for use with design activities, but can also stimulate the designer to consider the biological system from different viewpoints. Without customer needs and constraints to guide the initial design process it is easy to be overwhelmed by the quantity and unfamiliarity of the available biological information. Unless the biological system is well known and easily understood, it is easy to overstep (or under-step) the modeling scope with a biological functional model. Therefore, utilization of biological category is the first step to assist with putting the information into perspective. The designer must take cues from literature or biologists as to what information represents the category of interest. In addition to answering a design question related to the biological system (described in Section 5.3), the biological functional model must also comply with a chosen biological scale (described later in Section 5.5).

5.5 Identifying Biological Scales

The second viewpoint to assist with placing biological information within the right perspective is biological scale. Biological scale deals with how much detail is required for developing an adequate representation of the biological system, while adhering to the chosen biological category and posed design question. As an additional model boundary, biological scales assist with defining the level of detail required to create a functional model of a biological system. The goal is to use biological scales to assist with scoping the biological functional model for use with existing function-based, conceptual design tools. Biological computational models are used as a framework for biological scales. The biological computational models range from atomic level to population, and have the following order (White et al. 2009):

- atomic,
- molecular,
- molecular complexes,
- sub-cellular,
- cellular,
- multi-cell systems,
- tissue,
- organ,
- multi-organ systems,
- organism,
- population, and
- behavior.

Although the biological scale can be viewed as a constraint on the model, it is also a creative design challenge. It is possible to derive multiple connections to engineering from a single biological system by considering more than one scale of the same biological system. This has been demonstrated by (Shu et al. 2007). For example, considering the organism scale of a biological system might inspire an idea for a new and innovative consumer product, while considering the tissue scale of the same biological system might inspire a novel material. Advantageous starting points are the cellular, organ and organism biological scales as they are readily defined in biological literature.

When generating a biological functional model, the biological scale is often constrained to a single scale (e.g., the model contains only elements from the organ scale). Generating models constrained by a biological scale tends to be more analogous to how engineered systems are modeled; however, functional models can represent mixed biological scales to demonstrate specific biological phenomena of interest to the designer. Just as for category, the designer must take cues from literature or biologists as to what information represents the scale(s) of interest. It is important when developing mixed scale biological functional models to remember that any concepts derived from the connections made between natural and engineered systems will also be of mixed scale. This concept of mixed model connections is demonstrated in Chapter 9 by the lichen case study.

5.6 General Biological Modeling Methodology

During the course of this research several functional models of biological systems were created, edited and finalized. Based on these experiences, the following general methodology for functionally representing biological systems is presented. The motivation to functionally model biological systems stems from prior work by (Nagel et al. 2008b), which proved the feasibility of developing biological functional models. The methodology offers a designer direction when creating a biological functional model and provides empirical guidelines to improve model accuracy (Nagel et al. 2010a; Nagel et al. 2010d). The methodology is as follows:

1. Identify a suitable reference (e.g., biology text book) for the biological system of interest.
    - Similarly to performing a study of an engineering system, it is important to have the most current sources of information to guide the modeling process to ensure that the model represents the most current understanding of the strategy, behavior, physiology and morphology of the biological system in question.
2. Read the overview of the biological system to understand the core functionality of the system.
    - Take notes that capture the essence of the biological system.
    - Pay attention to categorical or scale cues in the literature (e.g., reading about dendrites cues the scale of cellular because the definition of a dendrite is "a short branched extension of a nerve cell" (Campbell and Reece 2003)).
    - Refer to the engineering-to-biology thesaurus for guidance on how biological flows relate to flows found in engineered systems.
3. Define the design question the functional model aims to answer.
    - This question posed about the biological system should direct the designer towards an answer, which is similar to defining an engineering problem statement that leads one toward a solution.
4. Define the category of the functional model.
    - Use the four categories to consider the biological system from different viewpoints and determine which category best aids with answering the design question.
5. Define the desired scale of the model.

  - Begin by modeling the black box for the biological system defining the overall functionality with the Functional Basis lexicon.
  - Investigate what occurs at the desired biological scale to achieve the black box functionality (i.e., sub-functions).
  - Read about the biological system noting the sequential and parallel events that occur to achieve the black box functionality.

6. Develop a functional model of the biological system using the Functional Basis lexicon within the bounds set by the design question, biological category and biological scale.
   - Use the engineering-to-biology thesaurus to choose the most suitable functions to accurately represent the biological system.
   - Make sure implied functions such as transfer, transmit, and guide are added to the model between major biological events.
   - Do not mix the function of the supporting structure with the core functionality of interest within the functional model (e.g., the stalk of a sunflower transports nutrients and water from the soil to the head for producing fruit, and should not be mixed with the stalk as a support for the sunflower).
   - Use a software program that allows quick rearrangement of blocks to make this process quicker (e.g., FunctionCAD[4], OmniGraffle[5], or MS Visio[6]).

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[4] http://www.designengineeringlab.org/functioncad/

[5] http://www.omnigroup.com/products/OmniGraffle/

[6] http://office.microsoft.com/en-us/visio/

7. Double check and/or validate (e.g., have a biologist review model at desired biological category and scale) the functional model against the design question and black box model.
    - Keep in mind that familiar terms to engineers could be used in a different context in the biological system description (e.g., the term bleaching does not refer to the removal of color; with respect to vertebrate eyes, it means the retinal and the opsin eventually separate, which causes lose of photosensitivity (Campbell and Reece 2003)).

The majority of, if not all, design processes are iterative and this modeling methodology follows the same convention. As models are formalized for a biological system, iterations will rearrange and change the functions used to represent biological functionality. Functional models are an abstraction; they help to formalize and develop an understanding of a design question. Therefore, it is natural that as models are generated, the designer's understanding of the biological system will improve, and consequently, the functional model will evolve. The goal of the general biological modeling methodology presented here is to provide a guideline from which engineering designers can build a functional model to create future biomimetic design opportunities.

When developing a biological functional model, it is important that a designer consider a number of key points: (1) The category and scale of the model must be chosen carefully such that the model may be valid to the design question and accurate to the biological system. (2) The energies associated with the biological system must be defined appropriately using analogous engineered system equivalents (e.g., Use electrical energy instead of biological or biochemical energy when referring to amplification of a sensory cell signal). (3) Biological scale based on the detail of information provided might be a good place to start, but when developing the final model, the scale must represent the design question originally posed. (4) Cleverly defining the design question can aid with keeping the model from becoming too complex. (5) Choosing a category serves to refine the boundary, but, like scale, it should be flexible through the concept generation process as it can allow a biological system to be considered in new and unique ways. (6) Utilizing the Functional Basis aids in concept generation and should be used when developing a functional model. The flows, however, should be changed to their biological correspondents when validating the functional model of a biological system. (7) Utilization of the engineering-to-biology thesaurus aids with choosing the correct terms from the Functional Basis during modeling.

Biological functional models will facilitate repository entries and the utilization of biological systems during concept generation. Other potential applications are identification of analogous engineered systems, design by analogy, and as an educational tool to teach engineering students about analogous design and design inspiration. Comprehension of biological material is also a plausible result of modeling biological systems. Overall, it is the designer who limits the engineering design applications of a biological functional model.

5.7 Example

Reconsider an insect's ability to sense, detect and measure chemicals through olfaction as a biological system to illustrate the general biological modeling methodology. Chemoreception is the biological recognition of chemical stimuli, by which living organisms collect information about the chemistry of their external environments; often associated with gustation (taste) and olfaction (smell) (Smith 2000). The focus of this example is insect olfaction, specifically the ability of the antennae, as described in the comprehension section of Chapter 4.

Antennae are made of a chitin-protein complex referred to as cuticle, which are porous, and covered in a waxy layer to prevent desiccation (Mitchell 2003). Multiple parts of the insect body, particularly the antennae, are covered in cuticular protrusions in the form of sensilla (e.g., hairs, pegs) that house the chemically sensitive cells for olfaction (Eguchi and Tominaga 1999; Mitchell 2003; Møller 2003; Klowden 2008). In order to detect the chemical stimulus the odor molecules must make contact with the waxy layer of a sensillum and travel through the porous cuticle. Once inside, odor molecules encounter an aqueous medium containing odor binding proteins and receptor sites on the dendrite surface (Eguchi and Tominaga 1999; Mitchell 2003; Møller 2003). As the name implies, the odor binding proteins bind to the odor molecules and essentially shuttle one odor molecule at a time to a receptor site. The dendrite is connected to a sensory cell that, in most cases, is activated by specific odor types (e.g., food, pheromones) through the receptor sites at the dendrite surface. Regardless, once an odor molecule comes into contact with a receptor site, a signal is generated, the signal is amplified and the odor binding protein then causes hydrolysis to separate the odor molecule from the receptor site and the protein itself (Eguchi and Tominaga 1999; Mitchell 2003; Møller 2003). The odor binding protein is responsible and required for receptor site activation and deactivation (Klowden 2008). Binding to a receptor site causes activation, conformational change and leads to the generation of an action potential (electrical signal), which is summarized as signal transduction. This is achieved through second messengers, typically cyclic adenosine monophosphate (cAMP), which increases the sensory cell's permeability to sodium ions and alters the electrical potential of the cell membrane (Eguchi and Tominaga 1999; Mitchell 2003; Møller 2003; Klowden 2008). After the signal has been generated and separation by hydrolysis is complete, esterase enzymes breakdown the odor molecule and the odor binding protein is recycled. This biological system is depicted in Figure 5.1. The flows of interest were mapped to the engineering flows of the Functional Basis and are provided in Table 5.1.

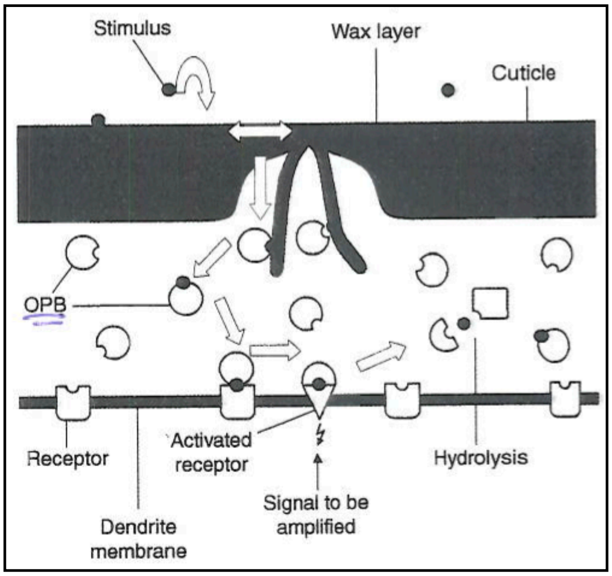

Figure 5.1. Inner Workings of Insect Antennae (Mitchell 2003).

To scope a functional model of an engineered system, a design question must be posed. The same holds true for biological systems and, more importantly, it provides a designer a starting point for researching the biological category and scale. Following Step 3, the following question for insect olfactory chemoreception is defined as: How does an insect interact, interpret and respond to an olfactory stimulus?

Table 5.1. Relationship between chemoreception flows (Eguchi and Tominaga 1999; Mitchell 2003; Møller 2003; Klowden 2008) and the Functional Basis (Hirtz et al. 2002).

Biological Information	**Functional Basis Flows**
Receptor site on dendrite surface	Liquid-solid mixture material
Protein	Liquid-solid mixture material
2nd messengers	Solid-solid mixture material
Chemical Stimulus	Chemical energy
Electrical signal to be amplified	Electrical energy

The flows of Table 5.1 aid in answering the design question posed about insect olfactory chemoreception functionality, however, they do not make explicit the category or scale of the biological information. Understanding how a stimulus is delivered to the receptor site on the dendrite surface requires knowledge of the principal functionalities of the supporting biological components. Defining the biological category to satisfy Step 4 requires investigation of possible biological conditions. The process of insect chemoreception of odorants is sequential and recursive. The conditions for this case would relate to the type of odorant being sensed. For odors, odorant binding proteins act as carriers, connectors and hydrolytic agents to make precise detection of the odorant possible (Eguchi and Tominaga 1999; Mitchell 2003; Klowden 2008). For pheromones, it is a pheromone binding protein that acts as a carrier, connector and hydrolytic agent to make precise detection of the pheromone possible (Eguchi and Tominaga 1999; Mitchell 2003; Klowden

2008). With the olfactory chemoreception sequence remaining the same for each type of odorant the principle functionality remained the same. Therefore, consider that one boundary of the chemoreception functional model is the category of *physiology*.

Step 5 of the methodology directs the designer to define a biological scale as another model boundary. The functional principle demonstrated by insect olfactory chemoreception was primarily found at the *cellular* scale. Investigating protein binding at a receptor site on the dendrite surface, which is simply an extension of a sensory cell, cues the category of cellular. Notwithstanding one might contemplate the category of *molecular* for this biological system. The definition of protein states, "any of a class of nitrogenous organic compounds that consist of large molecules composed of one or more long chains of amino acids and are an essential part of all living organisms" (McKean 2005), however, this definition negates the scale of *molecular*. Signal transduction is defined as any process by which a cell converts one kind of signal or stimulus into another (Spudich and Satir 1991), which also points towards the category of *cellular*. Researching second messengers reveals that cAMP is a diffusible signaling molecule that is rapidly produced within a cell to produce a change internally thereby producing a response (Spudich and Satir 1991). Although the second messengers and odorants are molecules, they are necessary for the cellular processes to be achieved and should not heavily influence the scale defined for the biological functional model. Thus, a *cellular* scale boundary is defined for Step 5. Realizing that olfactory chemoreception occurs at the receptor site on the dendrite surface, the black box model of the system is described as detect (i.e., to discover information about a flow (Hirtz et al. 2002)). The primary flows, include the receptor site, protein and second messengers as materials, and the chemical stimulus that is transduced into electrical energy. This black box model is provided in Figure 5.2.

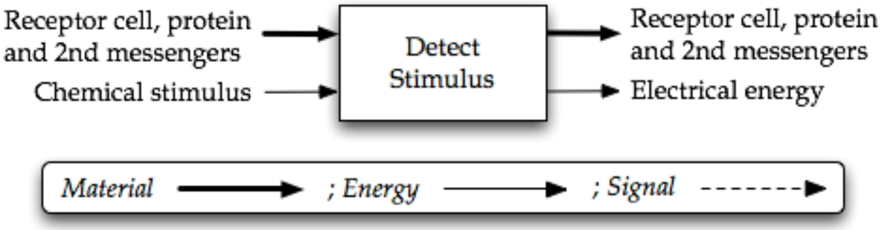

Figure 5.2. Black Box Representation of Insect Olfactory Chemoreception.

Investigating insect olfactory chemoreception functionality, the flows required, and the biological system scales and category in Steps 1-5 resulted in a well-defined scope and boundary. Now following Step 6, the functional model, shown in Figure 5.3, is decomposed from the black box model of Figure 5.2. The functional model represents the biological category of *physiology* and the scale of *cellular*. When the chemical stimulus (odorant) enters the insect cuticle the odor binding proteins immediately *sense* their presence and begin the detection process. The function of *join* represents the protein binding to the chemical stimulus, which is then carried to the receptor site noted by the function of *transport*. The *couple* function denotes mating of the odor molecule and odorant binding protein to the receptor site. *Change* represents the activation, conformational change of the receptor site and generation of an action potential, and is why the flows of chemical energy and mixture materials are all present for that function. Signifying the receptor site deactivation in parallel with the electrical signal that is sent to the nervous system to be identified are the functions of *separate* and *actuate*, respectively. The final portion of the chemoreception process is transmission of the electrical signal to the brain to produce a response. The associations established by the engineering-to-biology thesaurus assisted with choosing the function terms for modeling insect olfactory chemoreception.

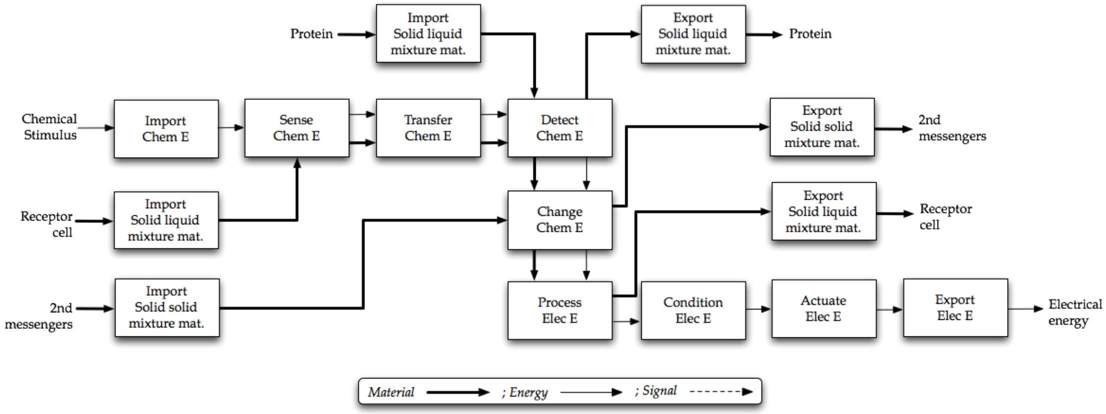

Figure 5.3. Insect Olfactory Chemoreception Functional Model.

To satisfy Step 7, validation, the biological functional model was validated through comparison to existing model abstractions in biological texts and known flows, and confirmation of the model's ability to answer the designated design question. The functionality in question is of insect olfactory chemoreception and how an insect interacts, interprets and responds to an olfactory stimulus. At the *cellular* scale, the functional model of chemoreception represents an odor stimulus in the aqueous layer between the cuticle and dendrite membrane surface, which is bound and carried to the receptor site to produce an electrical signal that will be interpreted by the brain to produce a reaction. At the black box level, insect olfactory chemoreception is modeled as having the function of *detect*. Discovering information about a stimulus is a natural occurrence during chemoreception.

It is evident that both abstractions are similar and both answer how an insect interacts, interprets and responds to an olfactory stimulus. As a final check, both the black box and functional models have the same number of input/output flows. All requirements initially identified through flow mappings have been satisfied. It is therefore concluded that the biological functional model is valid. If the functional model would not have considered how the odor binding protein carries the odor molecule to the receptor site to produce a conformational change and electrical signal, but rather, the functional model had simply summarized those events with convert chemical energy to electrical signal, then the functional model would not have correlated to the question posed by the black box or to the functional model. Thus, the biological functional model would need to be revised. Furthermore, had the flows of protein or second messengers been omitted from the black box, they would have not been included in the subsequent functional model resulting, again, in a failure to answer the posed design question. This validation further supports the *cellular* scale functional model for satisfying the design question.

5.8 Summary

Utilization of engineering design tools, such as functional models, with biological systems allows designers to be inspired by nature such that its insight might be more readily incorporated into engineering design. Biological systems operate in much the same way that engineered systems operate (French 1994); each part or piece in the overall system has a function, which provides a common ground between the engineering and biology domains.

To facilitate biologically-inspired design, a general method for functionally representing biological systems through functional models was presented and illustrated through an example. By representing a biological system's functionality at a specified category and scale, the biological system can be viewed from an engineering perspective in manageable parts from which a designer can identify parallels between the engineering and biological domains. Mimicking nature offers more than just the observable aspects that conjure up engineering solutions performing similar functions, but also less obvious strategic and sustainable aspects. It is these less obvious aspects that this research aims to facilitate as they hold the greatest potential impact for engineering as a whole.

Olfactory chemoreception of insects was modeled at a scale of *cellular* and the category of *physiology*. Each step of the methodology and the corresponding results were presented. Justification regarding the choices of category and scale for the modeling example was provided. It was shown how a designer with little biological knowledge could take cues from the biological literature when developing a functional model. This research demonstrates that using functional representation and abstraction to describe biological functionality presents the natural designs in an engineering context. Thus, the biological system information is accessible to engineering designers with varying biological knowledge, but a common understanding of engineering design methods. An advantage to developing biological functional models is that the information can be archived for future design reuse and create a biomimetic design repository. This would enable a dynamic search of natural systems for concepts to be employed in an engineered system. Biology contributes a whole different set of concepts and ideas that a design engineer would not otherwise have.

To facilitate the future development of biological system functional models, key points that are important for the designer to consider were summarized. But to follow these points, the designer must remain flexible throughout the process and be open to considering biological systems from different viewpoints, which might prompt the discovery of novel and innovative ideas. However, by placing the focus on function rather than form or component, biological system information is easily placed in an engineering context, which facilitates the transfer of design knowledge. The learned representations from the decomposition of design solutions, engineered and biological, organized at different levels of abstraction allow connections to be discovered with cues taken from each level. The biological domain provides many opportunities for inspiration, and this research assists with identifying connections between what is found in the natural world and engineered systems.

CHAPTER 6 - CONCEPTUALIZE: APPROACHES THAT INCORPORATE BIOLOGICAL INFORMATION

6.1 Overview

Concept synthesis is perhaps the most exciting, important, and challenging step of engineering design. Concept generation methods and tools help to stimulate a designer's creativity and encourage exploration of the solution space beyond an individual designer's knowledge and experience. There are multiple approaches to concept generation for engineering design, however, most do not intuitively integrate with biological knowledge. Furthermore, identifying and presenting the valuable knowledge from the biological domain to an engineering designer during concept generation is currently a manual and somewhat disorganized process. A method that offers guidance, computational assistance and integrates with biological knowledge would greatly aid generation of biologically-inspired concepts. The two approaches presented in this chapter enable conceptual design of biologically-inspired engineering solutions using existing function-based design tools and methods.

6.2 Related work

6.2.1 Manual Concept Generation

Generating concepts for engineering designs can be arrived at in a multitude of ways. Several manual methods have been developed. A well-known method is brainstorming. Brainstorming techniques include the 6-3-5 method, gallery, brain-ball, C-sketch, and morphological analysis (Otto and Wood 2001). Sketches and lists are created to capture and spur creative ideas. These methods are generally performed in a team setting, allowing for a greater opportunity for design diversity. The morphological matrix introduced by Zwicky is a now a classic technique for use in conceptual design (Zwicky 1969). A morphological matrix is created by listing all of the desired functions for a design and brainstorming solutions to each, listing the solutions as columns and the functions as rows (Hubka and Eder 1984; Otto and Wood 2001; Ulrich and Eppinger 2004; Pahl et al. 2007; Ullman 2009).

In Design by Analogy, an abstraction is created of the product being designed. Examining analogous products or components that perform the same function(s) captured by the abstraction generates solutions to the design problem. The designer then evaluates these similar components for appropriateness in solving the given design problem (McAdams and Wood 2000). One Design by Analogy method widely recognized in the engineering design community is the Theory of Inventive Problem Solving (TRIZ) developed by Altshuller based on the examination of large numbers of existing patents (Altshuller 1984). Once a set of specific conflicts that occur in a design are identified, this approach provides a set of principles that can be applied to generate solutions that solve these conflicts.

Another manual technique that can be applied to engineering design problems for concept generation and ideation is Synectics. Synectics promotes the use of familiar associations, recalling past experiences, and making the familiar strange, while disregarding creative inhibitions. This method was developed for design teams. Also, this approach encourages idea "spring boarding" through analogies and metaphors (Gordon 1961; Prince 1967; Prince 1970). Thus it is possible for new and surprising solutions to emerge.

6.2.2 Automated Concept Generation

Automated concept generation methods promise engineers a faster realization of potential design solutions based upon previously known products and implementations. Most methods require the designer to input desired functionality and based on an algorithm, several tens to hundreds of concept variants are presented to the designer. Functionality is a useful metric for defining a conceptual idea, as functional representation has been shown to reduce fixation of how a product or device would look and operate. The two automated concept generation methods utilized in this research are a web-based morphological matrix[7] (Bohm et al. 2008) and an interactive morphological matrix entitled MEMIC[7] (Bryant et al. 2005a; Bryant et al. 2005b; Bryant et al. 2007; Bryant Arnold et al. 2008), which rely on the designer's ability to develop functional descriptions of a desired product utilizing the Functional Basis. Both of these methods also make use of a repository of design information to return potential solutions for each function in a system.

The morphological matrix tool is an automated online tool that designers can use to filter and browse through the product knowledge contained within the Design Repository housed at Oregon State University. The interactive morphological matrix combines the solution accessibility that the web-based morphological search method provides a user by listing the solutions for each function in a matrix form and component connectivity information (Bryant et al. 2007). As components are chosen connectivity information is updated decreasing the chance for a designer to choose incompatible compo-

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[7] Concept Generation link after logging into the Design Repository at repository.designengineeringlab.org

nents. This allows a designer to easily choose between multiple solutions for a given function and interactively build a complete feasible solution. The Design Repository currently houses descriptive product information such as functionality, component physical parameters, manufacturing processes, failure, and component connectivity (Bohm et al. 2003; Bohm and Stone 2004) for over 113 consumer products and 30 biological systems amounting to over 5,600 physical artifacts. Where the web-based morphological matrix tool returns all possible solutions for each function, the MEMIC software ranks viable concepts with a matrix algebra based algorithm to provide those concepts that are feasible by considering the engineering component relationships, thus only components with a predetermined relationship are provided to the user for concept generation.

A computational tool that supports generation of design solutions from existing design knowledge during the conceptual stage of design is the A-design approach (Campbell et al. 2000; Campbell et al. 2003). This approach employs a sophisticated algorithm to produce multiple conceptual configurations based on evolving user preferences within the electro-mechanical domain. However, the concepts produced are generally restricted to energy flows or components for which a bond graph can be readily utilized.

A more rigorous approach that grew out of the A-design approach is the use of graph grammars. Graph grammars are comprised of rules for manipulating nodes and arcs within a graph that represents desired functionality, much like a functional model. This computational approach is embodied in the software GraphSynth[8]. Sridharan and Campbell defined a set of 69 gram-

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[8] www.graphsynth.com

mar rules that guide the design process from an initial functional goal to a detailed function structure (Sridharan and Campbell 2005). Through the application of each grammar rule the design is transformed into a new state. This offers exploration of different design decisions and different design alternatives, which incrementally evolves the design towards a desired solution (Kurtoglu et al. 2008; Kurtoglu and Campbell 2009).

Catalog design is another automated approach. It is based on a catalog of physical elements (components, assemblies, etc.) that can be browsed for solutions that match required performance specifications. The data in a design catalog is generally a subset of previously designed systems. However, a major benefit of catalog design is the ability to utilize design knowledge that falls outside human memory (Roth 2002). The chi-matrix method of Strawbridge relies on a catalog of design information that stores components and the functions they perform (Strawbridge et al. 2002). This approach allows a designer to generate several possible solutions without having to search the entire catalog of knowledge manually.

Case-based reasoning is another automated approach. Case-based reasoning relies on the ability of a designer to apply previous experiences and learned knowledge to solve current problems (Kolodner et al. 1985; Goel and Chandrasekaran 1988; Birnbaum et al. 1991; Slade 1991; Haas et al. 1993; Kolodner 1993; Maher and de Silva Garza 1996; de Mantaras and Plaza 1997). This type of reasoning is applied if the old and new problem are very similar and has been adopted in the cyber community. Also, case-based reasoning affords identifying commonalities between a retrieved case (past problem) and the target problem (new problem).

6.3 Concept Generation Approaches

Two concept generation approaches were formulated to enable conceptual design of biologically-inspired engineering solutions using existing function-based design tools and methods. Rather than task the designer with deciding when to consider biological information during concept generation, these two approaches provide guidance through the process and reduce the time and effort required. Overall, they aim to eliminate the element of chance and facilitate systematic discovery of innovative connections between engineering and biology.

Function-based automated concept generation may be extended in two ways with the addition of biological information (Nagel et al. 2010a; Nagel et al. 2010d). The typical design approach would generate a conceptual functional model based on customer needs. Automated concept generation techniques would then be used to identify potential engineering solutions for each function of the functional model. This traditional approach is modified by the two extensions shown in Figure 6.1, which can lead to biologically-inspired conceptual designs. Both use functional models to focus queries of a design repository. Furthermore, both concept generation approaches encourage one to make connections, similar to the creative process of Synectics, between biological and engineered systems, which are used for concept synthesis. Making connections is generally achieved due to prior knowledge and experience, similar to case-based analogical design. Prior knowledge of a broad range of engineered systems and processes is not required for concept generation of biologically-inspired solutions; however, that knowledge provides the impetus for readily recognizing the connections between systems of two dissimilar domains. The first approach, shown as a dashed line in Figure 6.1, uses a functional model developed from a biological system (discussed in Chapter 5) to discover corresponding engineering components that mimic the functionality of the biological system. The second approach, shown as a solid line in Figure 6.1, uses a conceptual functional model developed from customer needs to discover which biological components currently stored in a design repository inspire functional solutions to fill engineering requirements.

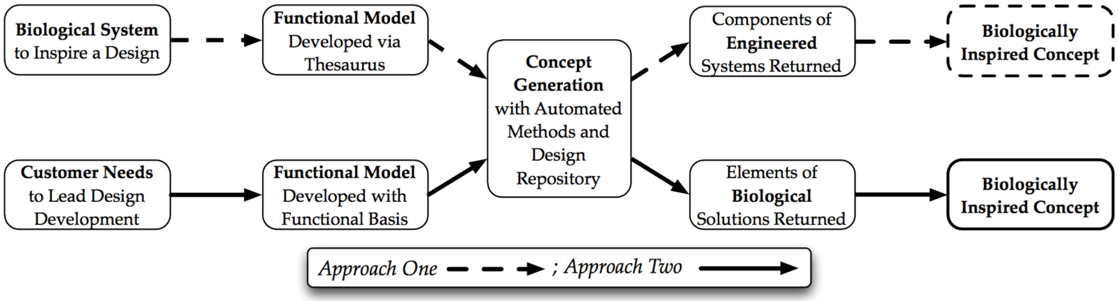

Figure 6.1. Summary of Concept Generation Approaches.

6.3.1 Approach One

Concept generation approach one is a technique for concept generation of innovative products that begins with functional models based on systems of interest, rather than deriving a product directly from customer needs. A form of this method has been used for the redesign or improvement of failed products by modeling a product originally derived from customer needs and identifying the functions that need improvement. This approach may also be used when inspiration is taken initially by a chance observation of a biological system to gain more insight or to follow a curiosity. To meet customer expectations for a redesign when following approach one, the designer takes inspiration from another system or domain—in this case biology—to discover how the product can be improved. A designer would use this approach to explore the possibilities that other systems offer for the redesign of a product or use it as a creative exercise to make connections between biology and engineering.

To follow concept generation approach one, a biological system of interest must first be identified. A biological functional model is then created and used to query a design repository for potential engineered solutions to each function using an automated concept generator. The input is processed, and a set of engineering components is returned for each function/flow pair in the biological functional model. The designer then chooses from the resulting engineering component suggestions to develop a complete conceptual design that mimics the biological system. The systematic methodology of approach one is as follows:

1. Generate a functional model of the biological system of interest following the procedure outlined in Chapter 5.
2. Generate concepts by querying a design repository for solution principles for each function/flow pair in the biological functional model.
3. Review and reflect upon the engineering components returned by the automated concept generator that fulfill the same functionalities as the biological system.
4. Choose conceptual design variants by mixing and matching the engineering solutions identified through queries to a design repository.
5. Continue with the conceptual design process and/or proceed to embody and detail the design.

This concept generation approach is limited by the data available in the design repository being queried; when data is available. The multiple engineering solutions returned, however, may not make immediate sense. Thus, this approach requires a large amount of insight from the designer to be able to make the necessary connections leading to a feasible engineering concept. This approach therefore lends itself more toward innovative design problems where novel solutions tend to dominate.

6.3.2 Approach Two

The second concept generation approach leading to biologically-inspired solutions follows the typical method of automated concept generation outlined in (Bryant et al. 2005b). First, the potential customer is interviewed to identify customer needs. The customer needs are translated into engineering specifications and functional requirements for the product being designed. A black box model and conceptual functional model are developed and used to query a design repository for solutions to each function. In order for biological inspiration to occur using this typical method, the design repository being queried requires biological entries. Then, when the designer queries the repository, biological solutions are returned for functionality in the conceptual functional model. The designer would then have the choice to use or ignore the biological solutions for further concept generation.

Entries into the design repository can be any of the biological categories or scales previously described in Chapter 5, and often one biological system will offer multiple functional models where each describes a different category and/or scale. Descriptions and images are provided with each biological artifact to assist a designer with overcoming any potential knowledge gap between biology and engineering, thus facilitating inspiration and connection making during the design process. The 30 biological systems contained in the Design Repository can be returned with both the automated morphological matrix tool and with the MEMIC software. The systematic methodology of approach two is as follows:

1. Create a conceptual functional model of the desired engineering system based on mapping customer needs to flows (Otto and Wood 2001; Ulrich and Eppinger 2004; Pahl et al. 2007; Ullman 2009).
2. Use an automated concept generator to query potential solutions for each function/flow pair in the conceptual functional model.
3. Review and reflect upon engineered and biological solutions retrieved by the automated concept generator.
4. Explore biological solutions for inspiration to functionalities (i.e., read the repository entry, look over the functional model, read more about it in a biological text).
5. Identify novel engineering solutions for functions that are inspired by biology, or if none are identified, choose alternative solutions from the automated concept generator.
6. Continue with the conceptual design process and/or proceed to detailed design.

This concept generation approach is limited by the biological data available in the design repository being queried; when data is available. However, because the engineered and biological systems are both indexed by the Functional Basis lexicon connections can be readily discovered between systems that share the same functionality. Understanding how two dissimilar systems each achieve the functionality allows the knowledge of one domain to be utilized in another.

6.3.3 Additional Considerations

Using functional models during concept generation has shown to provide two approaches for biology-inspired engineering solutions. Following approach one, a biological functional model drives concept generation. Engineering solutions in a design repository map to the functionality of modeled biological systems. This first approach assists with making the leap from biology to engineering, and places the design connection process within the engineering domain—a familiar working environment for the designer. Following approach two, a functional model is generated from customer needs; when a design repository is queried with those functions, biological solutions may be returned as potential options. This second approach places the design connection process within the biological domain, and requires the designer to analyze each of the biological results for potential inspiration. Where approach one helped to link biology to engineering, approach two reverses this by assisting with the link from engineering to biology. Both approaches, however, allow a designer to systematically consider biological systems during the conceptualization phase of the product design process.

Querying a repository of information not only saves time during the design process, it also provides a wealth of solutions for the designer to consider one function block at a time. It is common, when using automated concept generators, to look over the lists of resulting solutions and choose a single solution for each function/flow pair that best suits the design problem. However, when the solution space is filled with engineering and biological solutions a different thought process is needed to develop a concept. The concept generation approaches of this research allow a designer to be inspired by multiple query results simultaneously, thereby molding the solution space to his or her thought patterns. Experience shows that there are three emergent thought patterns when dealing with biological and engineering information. Figure 6.2 depicts the thought patterns of integration (a), progression (b) and a mix of integration and progression (c). The unshaded shapes represent a query result and the shaded shapes represent a concept.

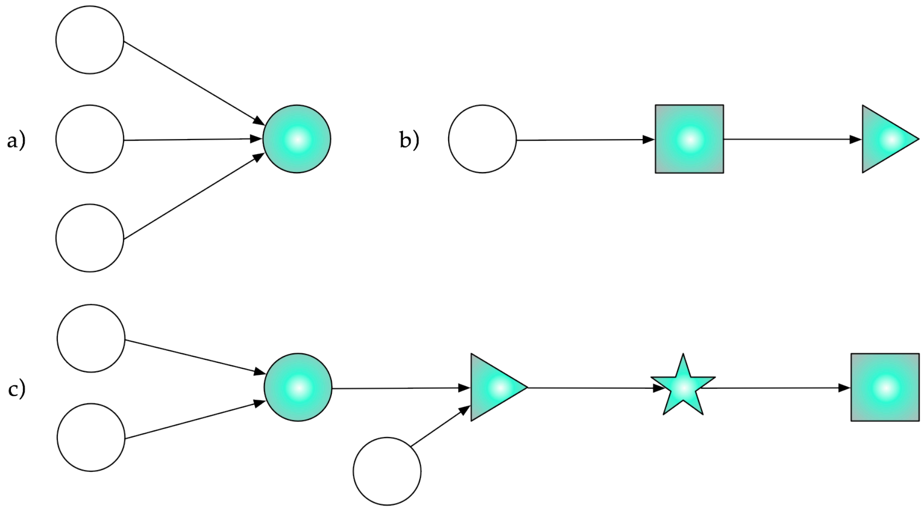

Figure 6.2. Concept Synthesis Patterns.

Combination of two or more separate attributes from different query results represents the thought pattern of integration. Vattam et al. follows this process by combining attributes of multiple biological systems that solve the same design problem and calls the resultant concept a compound analogy (Vattam et al. 2008). Nagai and Taura also recognize the integration of attributes to develop a concept, however, they suggest that the integration is by thematic relationships (Nagai and Taura 2006). Influence from different query results or different aspects of query results throughout concept development represents the thought pattern of progression. For example, using solution A for the all the second function/flow pairs of a model results in concept variant 1. After an “a-ha” moment, the designer updates the concept using inspiration from solution B of the first function/flow pair of the model to create concept variant 2. As the concept progresses, more of the solutions returned are used and build off of previous thoughts. A form of this thought pattern is described as the “blending” of concepts by (Nagai and Taura 2006) where two abstract concepts are blended to form a new concept that inherits abstract, not concrete, features. Finally, mixing integration and progression thought patterns are another avenue for arriving at a concept using engineering and biology information. This thought pattern does not follow step-by-step logic and is similar to “lateral thinking” by Edward de Bono (de Bono 1968; de Bono 1970). The advantage to mixing thought patterns is that concepts that are not immediately obvious or even obtainable by conventional methods are afforded.

Concept synthesis with biological information can also produce a modular solution that solves a collection of function/flow pairs. Identifying the modules that potentially exist using heuristics (Stone 1997; Stone et al. 1998) can lead to consideration of biological and engineered solutions as a group. Again, with the possibility of following one of the aforementioned thought patterns. Further research may be required to quantify the feasibility of the biologicaly-inspired design.

The two concept generation approaches discussed in the preceding sections share similarities with the methods proposed by Vattam et al. (Vattam et al. 2008) and Chakrabarti et al. (Chakrabarti et al. 2005; Sarkar et al. 2008; Srinivasan and Chakrabarti 2009b). In the approach proposed by Vattam et al. a designer first poses a design description. From this design description, a design question is posed in the terms of biology; this process is called "biologizing" the design problem. The "biologized" design question is used to seed the designer's search of a biology-based problem space where inspiration may lead to compound, analogical designs. This is similar to the concept generation approach number one presented herein in that both approaches start by first posing a design question based on a biological system of interest.

The two approaches of this research, however, rely on engineering and biological information stored in a design repository. Results from the design repository can, like in the approach of Vattam et al., lead to compound, analogical designs if multiple biological systems are returned for desired functions. Engineering solutions also may be mixed with the biological solutions in our approaches. A key difference between these approaches is the framework provided by our research. Where Vattam et al. takes a freeform approach to biologically-inspired design, methods and tools of this research support the designer from the initial point of framing the design problem to translating and representing the biological information in an engineering context to completion of the concept generation phase. In the approach proposed by Chakrabarti et al., databases of natural and artificial systems are indexed by function, behavior and structure. To achieve inspiration the designer uses the databases by (1) defining the problem based on behavior-focused constructs that may match existing natural or artificial solutions or (2) browse the database to gain understanding of how alternative natural and artificial solutions solve similar problems. This is similar to both of the approaches of this chapter in that all three rely on a database populated with existing natural and artificial solutions. Approach one of this research, however, uses multiple levels of abstraction based on categories and scales to capture different levels of function information related to biological systems. This process also encourages the designer to explore biological systems outside those within the Design Repository – adding systematic exploration to the chance observation and inspiration.

Concept generation is considered to be successful when a designer can analyze a biological system through the creation of a biological functional model or the Design Repository entries and identify connections between biology and engineering through function that lead to inspiration of a concept, innovative or existing.

6.4 Summary

Concept generation helps to enable biological inspiration during the design process; however, it is still limited by the knowledge and skill of the designer and the database from which connections are drawn. To develop connections between the biological systems and engineered systems it is necessary to study the biological system either initially when making a functional model or during concept generation when biological systems are presented as possible design alternatives. It is important to understand that the approaches do not generate concepts; that is the task of the designer. They do, however, provide opportunities for connections between the domains to be identified, so that it may be easier for the designer to make the final connections leading to biologically-inspired designs.

Two distinct advantages emerge from the use of a design repository and automated concept generation tools with the presented concept generation approaches. First, the process is automated to the extent that engineering and biological solutions are identified computationally through repeatable algorithms rather than through mental retrieval. Secondly, the aggregation of biological and engineering knowledge per function/flow pair of a functional model offers a greater degree of diversity than human recollection and inhibition is likely to provide. The process for retrieving solutions from the knowledge base is quick and does not require the efforts of an entire design team.

Using engineering design tools such as functional models and automated concept generation software with biological systems can bridge the gap between the engineering and biology domains and facilitate a the use of biology's insights. Viewing the biological system from an engineering perspective and breaking it down into manageable parts can clarify the parallels that exist between engineering and biology.

Two concept generation approaches were presented in this chapter. One begins from the traditional viewpoint of understanding customer needs to develop a solution, while the other follows curiosity and begins from the viewpoint of a biological system. The two concept generation approaches also point to the utilization of multiple biological solutions for inspiration or, in some cases, a single biological solution can offer inspiration in multiple categories (i.e., physiology, morphology, behavior, strategy). Three emergent thought patterns from interfacing with biological and engineered solutions housed in a design repository were presented. Combining key attributes of multiple biological systems can result in an analogy that otherwise would be overlooked. The same can be said for analogies derived from multiple engineering components. A progressive concept may begin as a direct imitation of a biological system and then evolve into a more complex concept that blends inspiration from multiple categories and/or query results. Mixing of thought patterns is another possibility and generally results in innovative concepts. Concept generation is considered to be successful when a designer can analyze a biological system through the creation of a biological functional model or the Design Repository entries and identify connections that lead to inspiration of a concept.

All biomimetic conceptual designs utilizing the two concept generation approaches could be entered into the Design Repository housed at Oregon State University for future reuse or design inspiration. This allows for immediate integration of the results with previous design knowledge of engineered and biological systems. Also, the biological solutions will be available to other designers as the research is performed.

CHAPTER 7 - SYSTEMATIC BIOLOGICALLY-INSPIRED DESIGN

7.1 Overview

In this chapter, the "big picture" of how the tools and techniques of the previous four chapters are used to support systematic biologically-inspired design is provided. The overall methodology for identifying opportunities based on functional representations of biological systems for systematic biologically-inspired design is also provided. This methodology relies heavily on the designer's ability to make connections between dissimilar domain information. An overview of approaches that facilitate connection making is briefly reviewed, followed by the method and validation of the method. Biologically-inspired design is a young field within engineering design. Consequently, validation of the design methodology is more difficult than, say, a purely mechanical topic. Two approaches to validation are pursued. One examines current biologically-inspired products either in production or exposed in literature to see if the proposed biologically-inspired design methodology can reproduce the existing design. The second investigates three needs-based design problems that lead to plausible biologically-inspired solutions.

7.2 Framework to Support Method

The previous four chapters introduced and explained in detail each tool and technique that comprises the framework. Here it is discussed how the tools and techniques combine or interact to support the overall methodology of systematic biologically-inspired design. The engineering-to-biology thesaurus is the backbone of this framework, as it assists with modeling biological systems and searching for inspiration or solutions. Consequently, the thesaurus also assists with concept generation, both directly and indirectly. Indirect assistance is through the modeling method and organized search tool, and direct assistance is through designer knowledge of a biological process (e.g., the conversion of sunlight to sugars) that could solve a set of needs. The following section makes this more explicit.

A framework by definition is an arrangement of parts that provides a system or concept a basic form (McKean 2005). The parts are identify, translate, represent and conceptualize. The system or concept being supported is the systematic biologically-inspired design methodology. What makes this framework particularly useful for design is the flexibility a designer is afforded when working toward a biologically-inspired solution. Each tool and technique can be used individually and in multiple combinations. Chapter 3 already discussed how the engineering-to-biology thesaurus integrates with and improves the organized search tool. Chapter 4 broadly covered how the engineering-to-biology thesaurus can integrate with the other three parts of the framework. Chapter 5 demonstrated how the biological functional modeling method benefits from the engineering-to-biology thesaurus. Chapter 6 broadly covered how the other parts of the framework integrate with the concept generation approaches. Specific interaction benefits are pointed out in the framework venn diagram of Figure 7.1. Using all four parts results in systematic biologically-inspired design.

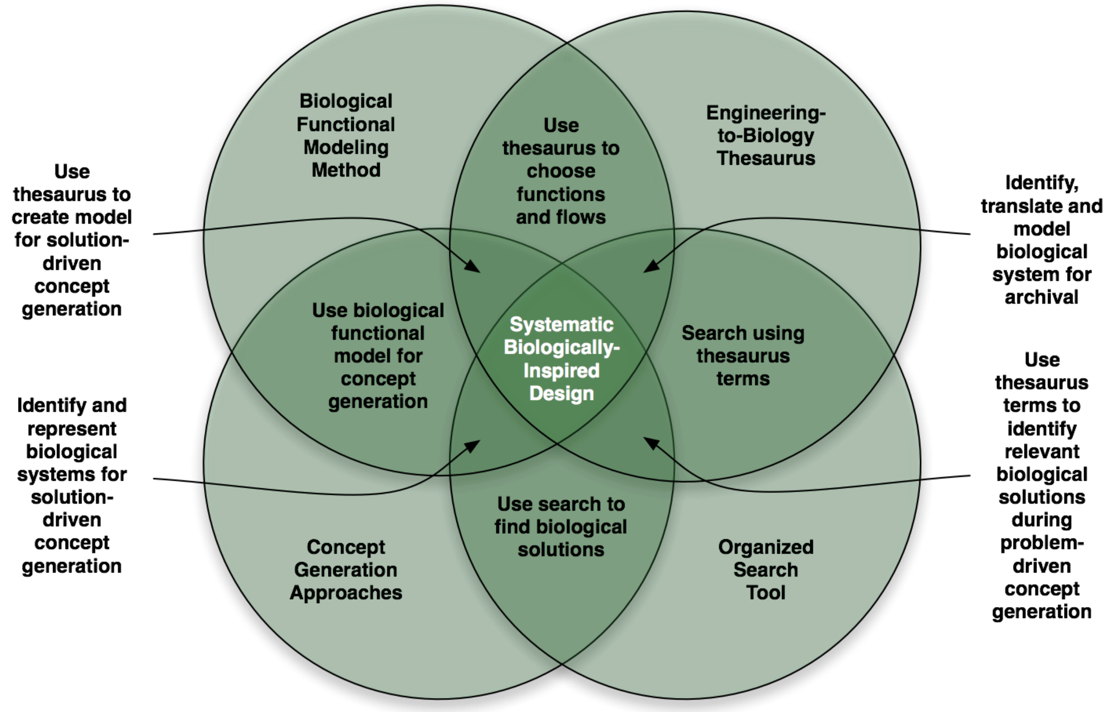

Figure 7.1. Framework Details

As previously mentioned, knowledge requirements for working between domains can be alleviated with design methods that integrate the existing engineering design tools. This framework does just that by integrating the function-based design methodologies, in particular, the systematic design process defined by Pahl and Beitz (Pahl et al. 2007). The framework also leverages existing design tools to further integrate within function-based design methodologies, as shown in Table 7.1. The existing design tools include a functional modeling lexicon, a repository of design information, and automated concept generation methods.

Table 7.1. Framework Integration with Existing Design Tools

Framework Tool or Technique	Existing Tool Leveraged by Framework
Engineering-to-Biology Thesaurus	Functional Basis
Biological Functional Modeling Method	Functional Basis
Organized Search Tool	Functional Basis, Design Repository
Concept Generation Approaches	MEMIC, Automated Morphological Matrix, Design Repository

7.3 Biologically-Inspired Design Methodology

In this section the overall design methodology is given. The preceding four chapters presented the individual parts of the framework. In support of the systematic biologically-inspired design methodology they coalesce to guide the designer from initial curiosity or customer needs to complete concept. The concept of making connections between biology and engineering is presented first followed by the design methodology.

Chapter 2 presented two holistic approaches by the Biomimicry Institute (Biomimicry Institute 2010) and Helms et al. (Helms et al. 2009) to biologically-inspired design. These approaches, however, do not offer a framework to support the designer other than the high level steps. Additionally, they do not follow a specific design perspective. Everything is at the discretion of the designer. While the design method of this chapter is modeled after systematic design, there are still many avenues a designer can take to arrive at a biologically-inspired design. The systematic design method of this chapter provides enough structure without hindering the creativity and inventiveness of the designer. Rather, this method fosters and guides the abilities of the designer and encourages objective evaluation of results. The systematic approaches of this method help to render designing based on biological inspiration comprehensible and steer the efforts of designers down purposeful paths.

7.3.1 Making Connections

This research relies heavily on the designer's ability to identify and formulate connections between the biological and engineering domains. Connections are the leaps that enable the ingenuity of nature to be discovered and adapted for use in engineered systems. There is not a wrong or right way to make a connection between the domains. Just as there are different learning styles there are multiple ways to make connections. Analogies (Gick and Holyoak 1980; Gentner 1983; Gentner 1988; Hofstadter 1995; Bhatta and Goel 1997; Goel 1997; Smith 1998; Balazs and Brown 2001; Mak and Shu 2004; Casakin 2006b; Nagai and Taura 2006; Linsey et al. 2008; Tsujimoto et al. 2008) are the most widely used and have multiple forms. Direct, indirect, and compound analogies have all been used to connect a biological system to an engineering solution. A direct analogy mimics the biological system one-to-one. An indirect analogy uses the biological system to spur analogies for inspiration but does not mimic every aspect of the biological system. A compound analogy is the combination of multiple biological system attributes that lead to analogous engineered systems. The level of difficulty in accessing and transferring an analogy is largely dependent on how remote or close the distance between the domains is (Johnson-Laird 1989). Because most things in nature exhibit functionality and behavior, analogies with engineering are possible. To exemplify the connection making process for analogies, consider a few textual examples.

A micro flow detection sensor directly mimics the physiology and morphology of hair cells that make up the lateral line system in a fish. The connection is through the principle of a bending moment that is created from perpendicular flow against vertical hair cells. Mimicry is achieved through fabrication of “hair-like” vertical structures on the end of a horizontal cantilever beam (Fan et al. 2002; Motamed and Yan 2005). An indirect analogy was created between the common strain gage and the physiology of the campaniform sensillum or flexible exocuticle that many insects possess. An elliptical opening in the insect’s cuticle, which is covered by a thin membrane layer, senses deformation because of the stress concentration (Gnatzy et al. 1987; Grunert and Gnatzy 1987). The connection for this system is that the opening causes mechanical coupling and global amplification to occur. Mimicry is achieved by optically measuring the stress concentration at a circular or elliptical hole in a rigid material when pressure is applied; resulting in a novel sensor that can sense strain in all directions (360°) (Wicaksono et al. 2004). In the case of designing an electronic display that can be viewed in bright sunlight a compound analogy was used to solve the problem. Hummingbird feather and morpho-butterfly wing attributes were combined to develop a solution (Vattam et al. 2008). Hummingbird feathers contain a series of alternating layers of thin-films with different thicknesses instead of the intricate christmas tree-like structures within an air gap that butterfly wings possess. The connections here are the air gap and “thin-film like” structures, which are readily used in electronics processing today. Adding an air gap between thin-films of varying thicknesses provided the right inspiration to develop the BrightView project (Vattam et al. 2008).

A designer must also be aware of analogies that hurt the design or ones that are overly complicated. Consider the biological phenomenon of abscission. When a leaf of a plant is damaged it stops the flow of auxin and allows abscisic acid to dominate, thus forming a seal around the base of the leaf stem and over a period of time the leaf falls off (Campbell and Reece 2003). This biological system was used to inspire a solution to the problem of tiny parts sticking to a robot gripper in a microassembly process (Shu et al. 2006). Considering indirect analogy for this case allowed the researchers to develop a sacrificial tool assembly. To highlight the analogy, consider the gripper as analogous to the plant, the sacrificial part of the tool analogous to the abscission zone, and the tiny screw as analogous to the leaf that is released. Separation is achieved through the breakdown of the sacrificial part of the tool (abscission zone). Notice liquids that are analogous to auxin and abscisic acid are not present in the final design. Developing a direct analogy of abscission would require a flowing chemical that secures and releases the tiny screw. Release of the tiny screw would occur some time after the chemical flow stops and a chemical reaction takes place to loosen the part from the gripper. This analogy is time consuming, costly and not very efficient. The indirect analogy that disregards liquids is the stronger design. Therefore, another analogy form should be considered if the results lead to a bad design.

Two other approaches to formulating connections are through first principles (Hubka and Eder 1984; Otto and Wood 2001; Vincent and Mann 2002; Lindemann and Gramann 2004) and metaphors (Forty 1989; Casakin 2006a; Casakin 2007; Hey et al. 2008). Analysis of physiology, structure or behavior can lead to a connection made through first principles. Physical laws and concepts, such as the conservation of energy, that govern science as we know it also apply to natural systems. Identifying a first principle shared by both domains leads to a connection and possibly and innovation. Consider how ducks and other birds regulate their temperature during the winter to stay alive. The principle of heat exchange between the body and the legs is carried out to reduce the amount of heat lost though blood that is circulated through the legs (Lindemann and Gramann 2004). To date, metaphors for biologically-inspired design have only been documented for architectural structures (Dollens 2009). The multiple approaches to formulating connections allow a designer to discover and become inspired in a manner that best suits him or her.

7.3.2 The Methodology

Taking inspiration from nature is another way for designers to develop innovative solutions to the needs of man. This methodology can be used as a stand alone process to identify biologically-inspired solutions to pursue or implement within a larger system, or it can be seamlessly integrated into other function-based design methodologies. As previously stated, the systematic biologically-inspired design methodology enables designers with limited biological background to begin learning and becoming inspired by the world around them. A pictorial representation of the method is given in Figure 7.2. The flower is used to show that the methodology is an organic process that has systematic design roots. Each of the steps is discussed in greater detail below. The majority of, if not all, design processes are iterative and this methodology follows the same convention. Cues for when to iterate are provided. Furthermore, the design methodology here should not be viewed as a rigid

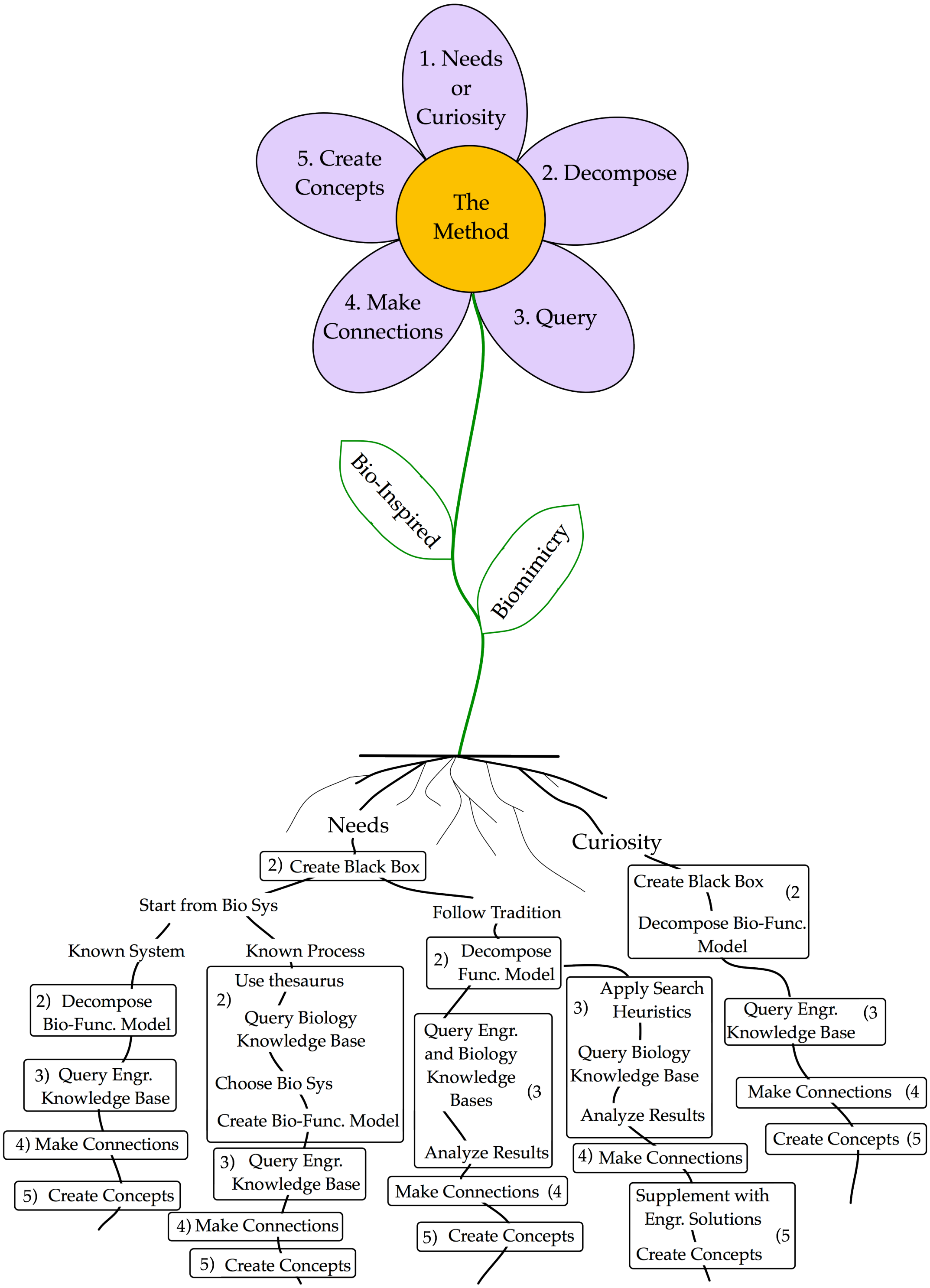

Figure 7.2. An Overview of the Five Steps of the Systematic Biologically-Inspired Design Methodology.

sequence and that one must follow each minute detailed step. Rather, it should be viewed as a starting point or a set of guidelines that aim to arrive at a biologically-inspired design. Figure 7.3 summarizes the avenues of the problem-driven approach that closely follow traditional systematic design and the avenues of the problem-driven approach that start from a known biological solution are summarized in Figure 7.4. Figure 7.5 is a flow chart of the solution-driven approach that starts from curiosity. Also, the parts of the framework and existing design tools used in each step of the method are made explicit in Table 7.2.

Table 7.2. Framework Parts and Existing Design Tools Used in Each Step of the Methodology.

Tools ↓	**Steps →**	**Needs or Curiosity**	**Decompose**	**Query**	**Make Connections**	**Create Concepts**
Frame-work	**E2B Thesaurus**	X	X	X	X	
	Search Tool	X		X		
	Biological Func. Model		X	X	X	X
	Biological Con. Gen.			X		X
Existing	**Design Repository**			X	X	X
	Functional Basis	X	X	X		
	MEMIC			X		
	Auto Morph Matrix			X		

Step 1: Needs or Curiosity

The first step determines which direction the design will take. A designer can choose to start from a traditional set of customer needs or explore a curiosity. These two routes are identified as problem-driven and solution-driven, respectively. Taking the problem-driven route means the designer must gather a set of needs, requirements and constrains. Many sources exist to aid the designer with proper needs gathering (Hyman 1998; Otto and Wood 2001; Dym and Little 2004; Ulrich and Eppinger 2004; Voland 2004; Ullman 2009). Identifying customer needs is the most critical part of the design process as they form the basis for device functionality and specifications. Taking the solution-driven route means a designer already knows of an interesting biological system in which he or she would like to investigate. However, the organized search tool can be used to find a biological system to investigate.

Step 2: Decompose

The second step involves decomposing the needs or interesting biological system into, first, a black box model and, second, a functional model. All models created with this method use the Functional Basis modeling lexicon. With regards to traditional systematic design, the black box aims to abstract the overall function of the device that is to be designed. Where as for a biological system the black box model describes an interesting function, structure, behavior or strategy of the system. Next, the input and output flows to the black box are determined. These flows are prompted by the customer needs from the first step or the needs/attributes of the biological system needed to achieve the black box functionality. The next task is to create the functional model. Decompose the black box description into sub-functions connected by flows of energy, material or signal (Stone 1997; Stone and Wood 2000; Otto and

Wood 2001; Pahl et al. 2007). Functional model creation is often an iterative task. Before moving on to the next step, check to see that all customer needs have been met by identifying the flows and sub-function chains that address them (Stone 1997; Stone and Wood 2000; Otto and Wood 2001; Pahl et al. 2007). With regards to the solution-driven route, refer to the biological functional modeling method in Chapter 5.

Step 3: Query

Step three involves querying a knowledge base to identify solutions to each function/flow pair of the functional model. Two knowledge bases are required: one containing successful engineered systems and the other containing biological systems. To integrate with this method, both are required to be indexed by engineering function and flow. The Design Repository housed at Oregon State University containing descriptive product information serves as the engineered systems body of knowledge. It also includes product information such as functionality, component physical parameters, manufacturing processes, failure, and component connectivity, now contains detailed design knowledge on over 113 consumer products and 30 biological systems. Instead of creating a large knowledge base containing functionally decomposed biological systems, similar to the design repository, an introductory biology textbook serves as the biological systems body of knowledge. Although it is not indexed by engineering function, the engineering-to-biology thesaurus provides a starting point to find inspiration with engineering function and flow.

The tasks that comprise step three begin with using the MEMIC software or automated morph matrix tool to query the Design Repository and the second version of the organized search software to query the biological corpus. Based on the number of results for engineered and biological solutions, the search may need to be repeated. For engineered solutions, it can be helpful to roll-up terms to the next level in the hierarchy. For example, if *transport*, a tertiary level term, does not return any repository entries then the secondary level term *transfer* should be used. The same applies to flows. Another trick is to first reduce the detail of the flow. For example, try *energy* if one of the secondary level terms does not return a match. Reducing the flow detail can often lead to repository entries. Furthermore, making a connection between electrical and mechanical energy is generally easy as they are within the same domain, just different specialties.

Step 4: Make Connections

Step four involves making connections. Connections through analogies, metaphors and first principles assist with bridging the biology and engineering domains. Please refer to Section 7.3.1 for a thorough discussion of how connections are formulated.

Step 5: Concept Generation

The fifth step involves performing concept generation and creating biologically-inspired conceptual solutions. Concept sysnthesis involves analysis, reflection and synthesis. Analysis of the returned engineered and biological solutions from Step 3. Reflection on the connections to the engineering domain formulated in Step 4. Synthesis of existing engineering solutions, engineering solutions inspired by biology and inventive solutions inspired by biology to derive a new idea. This can be done by making charts, lists, rough sketches, background research, consulting experts, etc. Just as with making connections there is no wrong or right way. The designer must figure out what will work best for him or her. Once synthesis takes place the result will

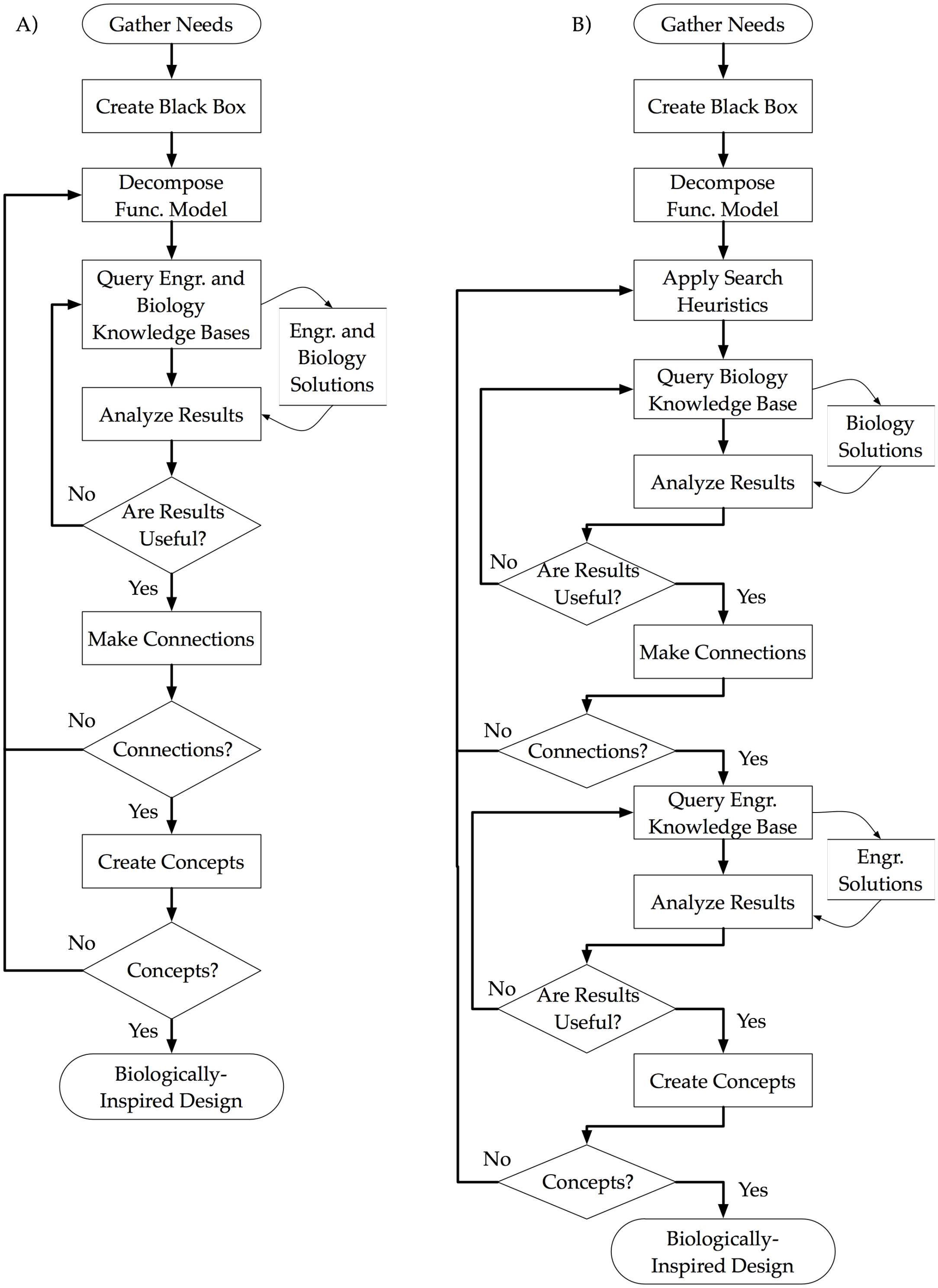

Figure 7.3. Flow Chart of the Problem-Driven Approach that Closely Follows Traditional Systematic Design.

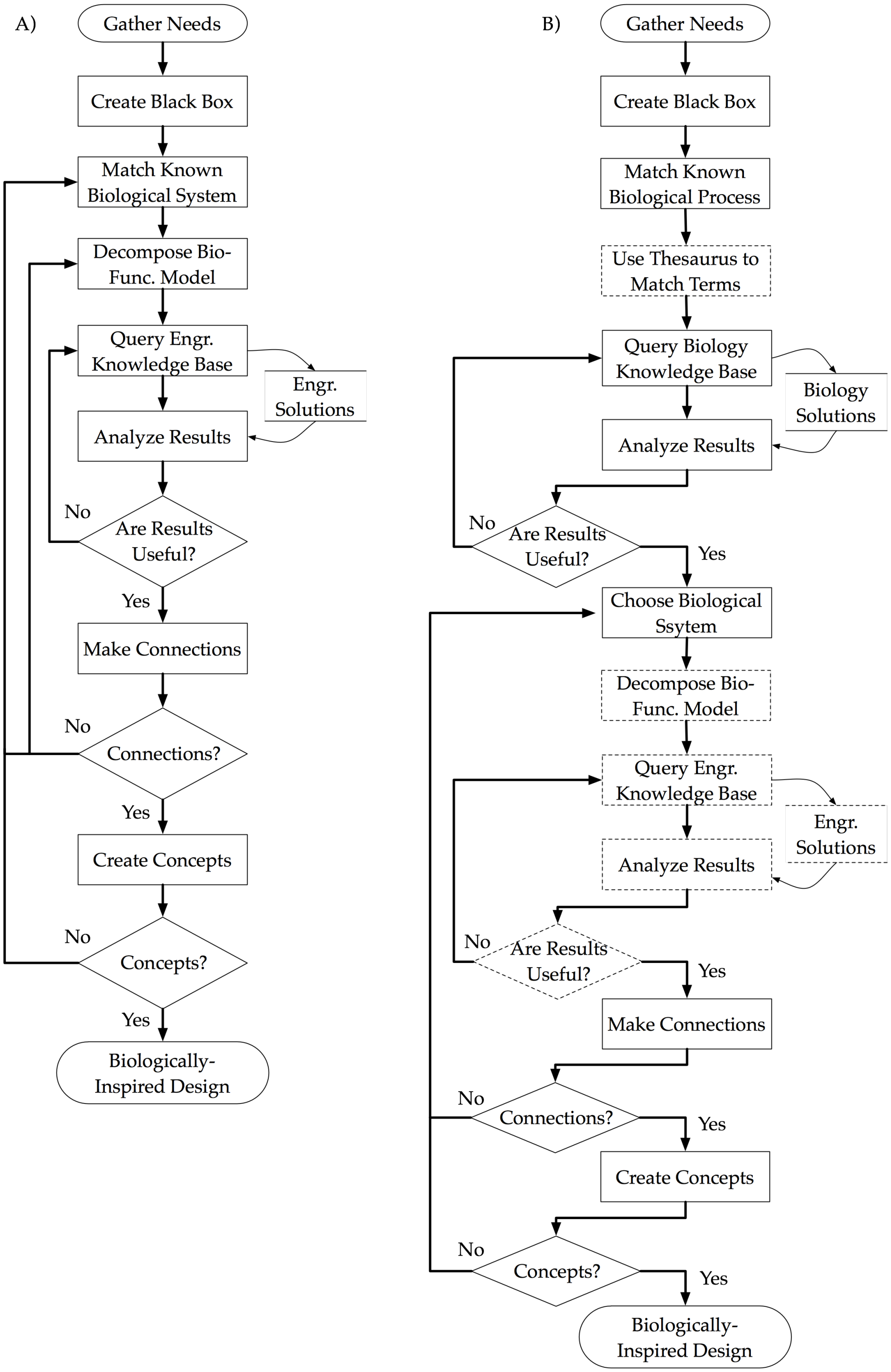

Figure 7.4. Flow Chart of the Problem-Driven Approach that Starts from a Known Biological Solution.

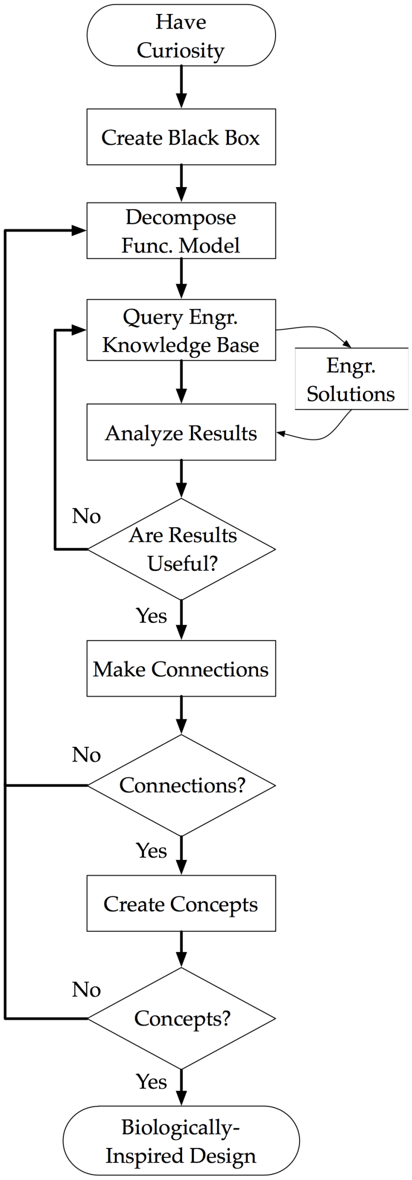

Figure 7.5. Flow Chart of the Solution-Driven Approach.

be at least one concept. Depending on the number of solutions returned during Step 3 and the connections made during Step 4, multiple concepts may result. Evaluation of concepts follows systematic design; pugh charts are used to rank concepts and narrow the selection to the top one or three concepts

(Hyman 1998; Otto and Wood 2001; Dym and Little 2004; Ulrich and Eppinger 2004; Voland 2004; Ullman 2009). Once a final concept has been reached the next phase of systematic design, in Figure 1.3, can initiate.

7.3.3 Comparison of Methodology Approaches

Notice that the major difference between the avenues to biologically-inspired design as shown in Figure 7.3 and 7.4 are within Step 2. When a designer follows traditional systematic design, flow chart A of Figure 7.3, and decomposes a functional model from a black box model, the resultant model is referred to as a conceptual functional model. This is because the model describes the desired functionalities of a solution rather than an existing solution. The conceptual functional model is used to query the engineering and biology knowledge bases. In the event that no connections can be formalized then the designer should return to the query step and try different levels of functions and flows. The same holds true for when no concepts are synthesized.

Following flow chart B of Figure 7.3 instructs the designer to use the organized search tool heuristics for the initial query. Once biological solutions are gathered, then the Design Repository is queried to supplement the biological solutions with engineering solutions. One difference here is that the results of the search tool should be screened first before moving on. In the event that no connections can be formalized then the designer should return to the query step and try a different heuristic. The same holds true for when no concepts are synthesized.

If a designer knows of a biological system that can solve the black box functionality then a biological functional model can be created to drive the methodology as shown in flow chart A of Figure 7.4. In the event that no connections can be formalized then the designer should return to the decompose step and either modify the biological functional model or choose a different biological system for exploration. The same holds true for when no concepts are synthesized. Consider the scenario of when a designer can describe a known biological process that solves the black box functionality. As shown in flow chart B of Figure 7.4. If connections between the biological process and engineering cannot be readily defined then the designer can search for biological systems that perform that process using the organized search tool. Once a biological system is chosen, then the designer can define the biological system with a functional model and use it to discover engineered solutions that perform the same functions to make connections or skip to the connection making step. In the event that no connections can be formalized then the designer should return to the decompose step and either choose a different biological system for exploration or, if no model was created, develop a biological functional to be used with the query step. The same holds true for when no concepts are synthesized. In both flow charts of Figure 7.4, if the Design Repository results are are slim or non-existent then the designer should try different levels of functions and flows to broaden the search.

The fifth approach under this methodology is driven by curiosity and the possibility of creating a solution that can be fit to a problem. However, the main use for this approach is the creation of archivable biological knowledge that is in an engineering context. This type of knowledge can be reused in future design activities when stored in a knowledge base. The main tasks of this approach, as shown in Figure 7.5, follow the steps of the systematic biologically-inspired design method. In the event that no connections can be formalized then the designer should return to the decompose step and modify the biological functional. The same holds true for when no concepts are synthesized. Another option is to return to Step 1, choose a different biological system for exploration and start over. Also, if the Design Repository results are meager or non-existent then the designer should try different levels of functions and flows to broaden the search.

7.4 Validation of Method

Validation of the systematic biologically-inspired design methodology is achieved through application of the methodology to (1) check if it reproduces existing biomimetic products and (2) identify a closely related development version of a concept through literature review. Analysis and reproduction of existing biomimetic products through primary function allows the verification of the methodology as the result is known. Validating the methodology for non-existing biomimetic products requires a review of literature to quantify if the concept variants are realistic or science-fiction. Finding a closely related development version of the biologically-inspired conceptual design indicates that the concept is feasible. Similarity is based on functionality and components chosen to achieve functionality.

Six existing biomimetic products are analyzed through application of the method to demonstrate that the method can reproduce what is known. To further demonstrate the validity of this method, the smart flooring example of Chapter 3 is revisited and two new examples of a chemical sensor and heat exchanger are provided. The methodology is considered to be successful when a designer can analyze a biological system and identify connections between biology and engineering through function that lead to inspiration of a concept. Further, more detailed validation cases are shown in Chapters 8 (how the methodology can result in innovative solutions following the problem-driven approach) and 9 (how the methodology can result in an innovative solution following the solution-driven approach).

7.4.1 Proof Through Existing Biomimetic Technology

Validation of a scientific method is crucial to its adoption. Reproducing familiar results through application of the method is often a first step towards validation. Validation of this method will follow a similar course. The first exercise is to analyze existing biomimetic products, apply the systematic design methodology and verify that the biological system used to inspire the original design is utilized in the results in such a way that would lead to a reproduction. The approach taken is through primary function analysis.

Table 7.3 lists six existing biomimetic products that one can find searching the internet. These technologies represent electrical, civil and mechanical engineering and material science. Not having physical access to analyze the technologies results in relying on textual descriptions to perform validation. From the descriptions, primary function/flow pairs were identified and represented with Functional Basis terminology. The primary function/flow pairs are then used to query the biological knowledge base. Both, representation and querying utilizes the engineering-to-biology thesaurus. If the mimicked biological system is within the query results and described in a way that would make a connection and result in a similar concept to the existing biomimetic technology, then is determined that the method can reproduce the design. A limitation of the biological corpus that comprises the biological knowledge base was determined–not all of the mimicked biological systems exhibited in current biomimetic products are included. For example, the lotus which inspired self-cleaning surfaces is not described in the introductory biology corpus. Also, the morpho-butterfly is mentioned in the corpus, but only to demonstrate the classification of its species. Therefore, a different biological knowledge base is employed. The open source project, AskNature[9], is an online database that biologists, engineers, designers, chemists, etc. can contribute to so bio-inspired breakthroughs can be born. AskNature is an attractive alternative knowledge base because the biological knowledge contained within the database is organized by function.

Table 7.3. Analysis of Existing Biomimetic Products to Validate Methodology.

Existing Biomimetic Products	Mimicked Biological System	Primary Function/Flow Pair(s)	Source	Can Method Reproduce Design?
Walking stick for visually impaired that uses sonar	Echolocation of bats	Detect Solid	Biological Corpus	Yes
Passive heating and cooling buildings	Termite mounds	Regulate Thermal Energy, Distribute Thermal Energy, Distribute Gas, Remove Gas	Asknature.org	Yes
Self-cleaning surfaces	Lotus	Inhibit Solid, Inhibit Liquid, Decrease Solid	Asknature.org	Yes
Motion detector	Compound vision	Detect Solid, Sense Solid	Biological Corpus	Yes
Color changing material without harmful chemicals	Morpho-Butterfly	Change Visual Signal	Asknature.org	Yes
Microassembly with sacrificial gripper	Abscission of plants	Separate Solid	Biological Corpus	Yes

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[9] asknature.org

Following the five steps of the methodology, all six existing biomimetic technologies were reproduced. The three found with the organized search tool required the substitution of biological function and flow terms of the thesaurus, while the three found within the AskNature database needed substitution of only the flow term. Additionally, other biological systems were identified that also solve the function/flow pair, which, if a redesign were undertaken, could result in compound analogical design.

7.4.2 Smart Flooring Case Study

Recall from Chapter 3 the example of smart flooring. The first three steps of the systematic design methodology were completed. In this case study, the final two steps of make connections and concept generation, are completed. This design began with customer needs, which were decomposed into black box and functional models. From here the search heuristics were applied, following flow chart B of Figure 7.3. Using the general inspiration heuristic, several interesting biological systems were found to perform the function of detect. Recall from Sections 3.8.2 and 3.8.3 that the organized search of a biological corpus resulted in the following query results:

1. The hair cell
2. Electroreceptors found in electric fish
3. Epithelial cells
4. Genes that mark recombinant DNA
5. DNA
6. Why birds flock in large groups
7. Echolocation
8. Carotiod and aortic stretch receptors

9. Membrane receptor proteins
10. Graded action potentials

Next, following Step 4 of the methodology, the biological systems returned for the function of *detect* are analyzed and reflected upon to formalize connections. Of the query results, many offer connections. Hair cells are analogous to cantilevers and would detect a presence when disturbed, such as being stepped upon. In a similar manner, the carotiod and aortic stretch receptors link to flexible materials such as polymers. A polymer would detect a disturbance when pressure is applied, such as being stepped on. Echolocation is analogous to radar. Radar is already used to detect objects, however, it is not a distributed system, as would be needed for a smart flooring concept. The final connection made from the above list is with the electroreceptor of fish. Electroreceptors generate an electric field for navigation of the environment, to locate objects, which is also analogous to radar. Echolocation uses sound waves where electrolocation uses electric waves.

Now that connections have been established, the next step is to query the engineering knowledge base and supplement the biologically-inspired solutions with engineering solutions to complete the design. This has already been performed. Table 3.3 lists engineering solutions along with biological solutions for seven of the nine function blocks. Import and export of the solid object will occur spontaneously, which will create the altered flooring signal. With the components of Table 3.3 and the established analogies the final step of concept generation can begin. Recall that the critical need is unseen by the human eye. The biological system of the hair cell prompts two concept variants. Considering the hair cell as a cantilever and flooring shaped as individual tiles, each tile could act as one cantilever to detect a load. The array of cantilever load sensors would then sense a pressure differential as a person walks across the smart flooring. A concept sketch is shown in Figure 7.6.

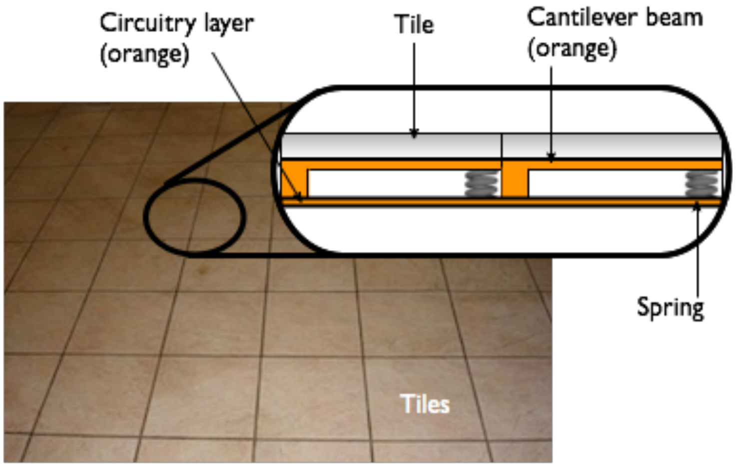

Figure 7.6. Concept Variant One for Smart Flooring.

The second concept variant stems from considering the hair cells and carotiod and aortic stretch receptors simultaneously. Hair cells are vertical structures, while stretch receptors are found in multiple orientations. Taking inspiration from the hair cell and stretch receptor morphology leads to a detector design that is comprised of a vertical structure that can be stretched in multiple orientations. Offering flexibility and ruggedness for being stepped on. This detector design would not be a good choice for hard tiles, but could work for woven flooring such as carpet. Since pressure is not used in this concept variant, an electrical signal would need to be generated. Flexion should result in a change of resistivity, similar to a strain gage or generate a voltage by the principle of piezoelectricity. Polyamide is a high performance synthetic polymer and is commonly used in textiles. Fabricating polyamide tubes with a conductive gel or paste, that can be woven into carpet to form an array would achieve the biologically-inspired design. Materials research would need to be completed to determine if the polyamide and conductive gel or paste would last in a high traffic environment. A concept sketch is shown in Figure 7.7.

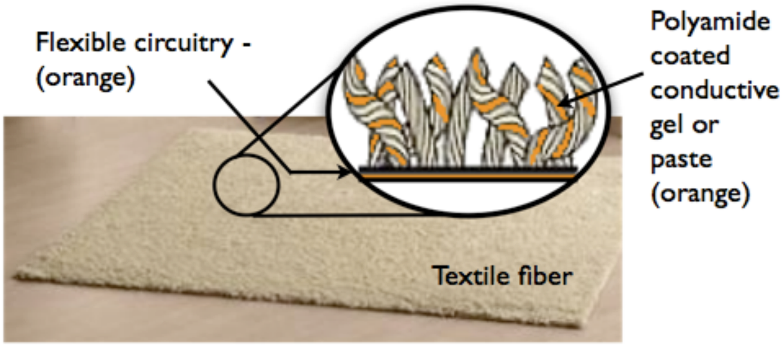

Figure 7.7. Concept Variant Two for Smart Flooring.

Following the progression thought pattern leads to considering the hair cell as a strand of hair or thread, which also possesses high flexibility similar to the carotiod and aortic stretch receptors. Conductive thread exists and is used in garments and accessories that merge technology into clothing. Therefore the concept in Figure 7.7 progresses into conductive thread woven into carpet fibers to replace the polyamide coated conductive gel or paste. For both concept variants, a flexible circuitry layer and buffer layer would need to be underneath the flooring to connect the array to a computer or processor and to protect the underlying circuitry, respectively.

Looking to literature for a similar surveillance device uncovered a handful of attempts to create a "smart" floor or flooring. The first concept described above, individual tiles that detect a load placed in an array, has been done. Richardson et al. have developed hexagonal, puzzle-like pieces called nodes that are placed in an array to detect pressure (Richardson et al. 2004). Their tiles contain force sensitive resistors and interlock to form a self-organizing network that passes data to the tile with an external data connection. An earlier approach to the smart floor involved only one measuring tile made of load cells, a steel plate, and data acquisition hardware, and was not intended to be hidden (Orr and Abowd 2000). Rather, it was created as an alternative to biometric identification by recognizing a person's unique footstep profile. Two other approaches that utilize load cells and layered flooring to conceal the sensors are nearly identical to the first concept variant. Liau et al. place a sensor in the center of every 60cm x 60 cm wood covered tile (Liau et al. 2008), where Addlesee et al. place a sensor at each intersection of four carpet covered tiles (Addlesee et al. 1997). Load cells are similar in principle to cantilever beams in that deflection is transduced into an electrical signal that can be interpreted. Literature review revealed that the first biologically-inspired concept is feasible and has been attempted.

Investigating the second concept variant for smart flooring revealed only one existing design that is similar. Researchers at Infineon Technologies have woven conductive fibers into carpet and attached them to tiny sensor modules inlaid into the fabric to build a mesh network (IEE-Institution of Electrical Engineers 2003). The flooring can report where a person is located, which way they are moving and if a sensor module has failed. Each conductor in the design is a copper wire coated with silver to prevent corrosion and then covered with polyester (IEE-Institution of Electrical Engineers 2003). A German textile company, Vorwerk, has teamed up with Infineon to develop the smart carpet (Vorwerk & Co. 2004; Crane 2005). The Vorwerk/Infineon product is similar in structure to the second concept variant in that a conductor is concealed and woven into a textile product. Again, a literature review revealed that the biologically-inspired concept is feasible.

This case study demonstrated that it is possible to systematically design using the search heuristics and take inspiration from biology in the process. By analyzing the biological system and making connections a designer can become inspired. It is through these correlations that the designer can recognize existing designs that are similar or develop an innovative design.

7.4.3 Chemical Sensor Case Study

As stated in the introduction, this method aims to inspire more than mechanical and electro-mechanical devices. This case study presents the design of a chemical sensor following the approach closest to traditional systematic design (flow chart A of Figure 7.3). The needs and constraints of the chemical sensing device are derived from the Handbook of Modern Sensors (Fraden 2004): selectivity (only senses the desired chemical in the presence of other species), quick response time, reusable, and utilizes an indirect sensing mechanism. These needs and constraints are mapped to flows as shown in Table 7.4 to complete the first step of the methodology. Next, the black box model is created to guide the decomposition of the flows into a functional model. Figure 7.8 provides the black box model. Figure 7.9 provides the conceptual functional model. The model is created at a system level, which is comparable to majority of the Design Repository information, to aid with connection formulation.

Table 7.4. Chemical Sensing Needs Mapped to Conceptual Flows.

Customer Need/Constraint	Functional Basis Flow
Selectivity	Status signal
Response time	Electrical energy
Reusable	Sensing layer (material)
Indirect sensing mechanism	Sensing layer (material)/Chemical stimulus (energy)

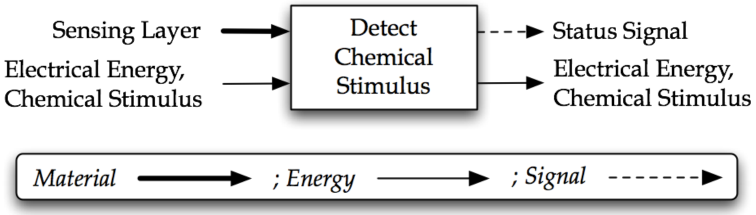

Figure 7.8. Chemical Sensor Black Box Model.

The chemical sensing device black box and conceptual functional models show the generalized form of a chemical stimulus (i.e., chemical energy). This allows the designer to query all possible forms of a chemical stimulus. The device substrate is also generalized as material to include all possible forms of material in the knowledge base. Figure 7.8 demonstrates the indirect sensing mechanism with *couple* and *change*, and the sensing element or transducer with *detect*. Electrical energy is utilized to power the sensor and transfer the detection status signal to the device capable of interpreting such signals, such as a computer. The boundary of the conceptual functional model includes the sensing layer and powered sensing element.

To query the engineering and biology knowledge bases, the model of Figure 7.9 was created in FunctionCAD and exported as an adjacency matrix to MEMIC. Half of the function/flow pairs returned engineering components;

for the remaining half the morphological matrix tool was used to find solutions. Utilizing both tools, components for each function/flow pair were returned. For 10 of the 12 functions the component list was short and easy to choose from. The functions of change, detect and export signal returned many possible components. The five engineering components identified that change materials are: a heating element, impeller, filter, punch, staple plate, and blade. The four biological components identified that detect chemical energy are: a protein of the two component regulatory system, a chemoreceptor of the fly, chemoreception of the Plantae Kingdom and chemoreception of the Animalia Kingdom. Export signal returned the components: LCD screen, speaker, electric wire, cord, level gauge, and circuit board.

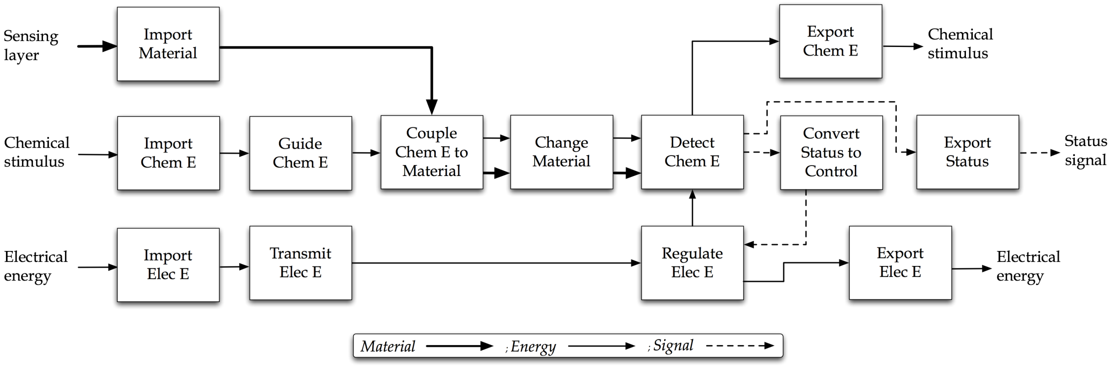

Figure 7.9. Chemical Sensor Conceptual Functional Model.

Considering the conceptual device as a whole and how one would use the device is an advantageous thought process for determining the suitable component from a list. The impeller, blade and punch require mechanical movement to change a material, where as the staple plate, filter and heating element could change the chemical stimulus without mechanical movement.

The conceptual design is not fully determined up to this point and could be influenced by the component(s) chosen from biological inspiration. Therefore, the functions of change and detect will be considered together.

Following Step 4, connections need to be established to assist concept generation. Recall from Chapter 4 the biological systems two component regulatory system and fly chemoreceptors. Bacteria employ the two component regulatory system for detection of extracellular signals and the signaling pathways consist of modular units called transmitters and receivers, both of which are proteins (Stock et al. 2000). Fly antennae contain chemically sensitive cells (chemoreceptors) hidden deep within pores, which allow the insect to experience olfaction (i.e., sense of smell) (Mitchell 2003). The Animalia and Plantae mechanisms of chemoreception are not descriptive, and are meant to guide a designer in a direction of research. Analysis of the biological components leads to the choice of fly chemoreceptor for the detect function block.

Further exploration of the fly antennae reveals that the insect cuticle (a chitin-protein outer cover) has elaborations in the form of trichoids (hairs), pegs, pegs in pits and flat surfaces, all of which provide multiple pores for chemicals to travel through (Mitchell 2003). Within the pore is a fluid-protein pathway to the dendritic (sensory) cell membrane. Once the chemical molecule reaches the fluid surrounding the dendrite membrane it bonds to an odorant binding protein and is carried to one of the receptor sites of the membrane (Mitchell 2003). When the two make contact in the cation concentrated fluid, a signal occurs as a voltage potential change across the membrane, which is the signal to be transduced. The sensing principles of fly antennae are complex and offer the designer inspirations for the function of detect, and, as expected, for the function of change.

A filter is analogous to the porous cuticle, which would narrow down the selection of chemicals or allow only one to interact with the sensing layer. The heating element is analogous to the odorant binding proteins and cell membrane surface with receptor sites, in that, an electrified element is capable of attracting polarized molecules (disregarding the heating aspect). An impeller could be used to steer the desired chemical stimulus, after sorted from other stimuli, to the sensing element, which is analogous to the odorant binding proteins. Biological inspiration via morphology leads to a sensing element that has specifically shaped cavities or is uniformly porous, and is a good conductor. Any material that can be patterned by photolithography can achieve the desired surface. Morphology of the fly antennae itself offers inspiration for a "stick-like" sensing element. Another connection exists between the engineering component filter and permeable or ion-selective membranes, which are used in current sensor technology. Therefore, permeable or ion-selective membranes are analogous to the porous cuticle. Further analogies exist between the heating element and electrical energy traveling through a conductor, which could be a copper wire, semiconductor, conducting polymer, etc. Semiconductor electrodes that allow absorption and desorption of chemical species are analogous binding and removal of odorants from the cell membrane receptor sites within the fly antennae, which could also be used in the final concept.

The collection of engineering and biological components presented here, and the identified connections between biology and engineering lead to the functional model with chosen components for concept generation in Figure 7.10. Multiple conceptual variants for this design are possible, just as there are a number of materials applicable for the sensing layer and element.

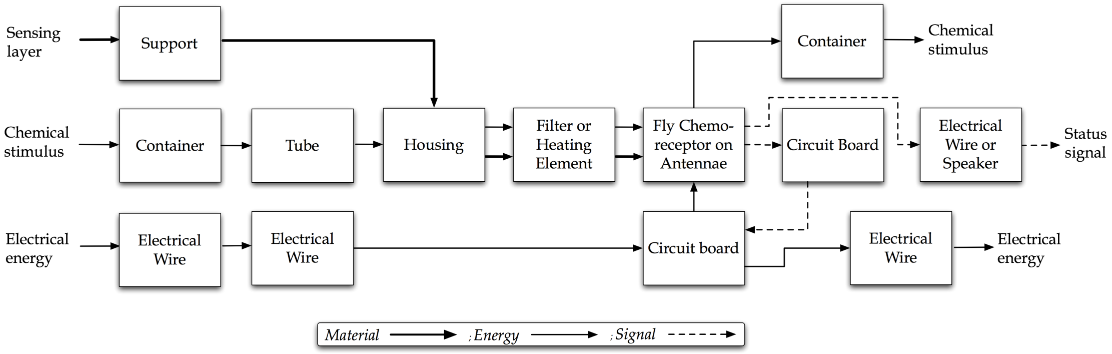

Figure 7.10. Chemical Sensor Conceptual Functional Model with Engineering Components.

Performing Step 5, concept generation, with the components of Figure 7.10 conjures up two concept variants. The first device supports a housing containing an electrified element (not for the production of heat) acting as a barrier to the transducer that chemical energy is guided to from the container, or space. The subsequent chemical energy is attracted to the electrified element and once bonding occurs, the electrical properties of the electrified element change and generate a signal to be transduced. The electrical property change of the electrified element fulfills the requirement of an indirect sensing mechanism, which also supports reusability as the absorbed particles could be removed by heating the element. An electronic circuit powers the transducer, decodes the sensor signal and produces an electrical signal analogous to the input. The second device supports a housing containing an a filter covering the sensing layer, which rests on the sensing element. Only the chemical species that pass through the filter interact with the sensing element. This interaction generates a signal to be transduced. An electronic circuit powers the transducer, decodes the sensor signal and produces an electrical signal analogous to the input. Further material research is needed to accurately define the sensing layers for the concept variants.

When researching if a sensor with an electrified element on a transducer exists, the first concept described above, conducting polymer sensors that are typically used for detection of gases was found. The conducting polymer is deposited atop interdigital electrodes, which make it the dielectric material for the electrodes. When a gas interacts with the polymer the capacitance between the electrodes changes and the output signal decreases (Bai and Shi 2007; György 2008). These sensors are sometimes referred to as chemiresistors. Functionally, a chemiresistor is identical to the first concept.

The second concept is similar to an ion-selective electrode (ISE) or ion-selective field effect transistor (ISFET) used to measure pH. An ISE has high specificity to single charged ions and is made of a doped glass. The glass allows only single charged ions, such as hydrogen, to pass through to an internal solution of neutral pH monitored by an electrode. Concentration of hydrogen ions is correlated to a pH value by taking the logarithm of the concentration (Eggins 2002; Grundler 2007). An ISFET is the microelectronic version of an ISE and is similar in structure to a MOSFET (Liao et al. 1999; Eggins 2002; Grundler 2007). Instead of glass, the membrane is made as a thin film over an insulation layer of metal oxide or nitrate on a p-doped substrate. Two n-type doped regions are added to the substrate for connection of the source and drain, while the gate is connected to the sensing layer beneath the membrane. Here the sensing layer is a liquid or insulation material and the sensing element is an electrode. Functionally, an ISE is identical to the second concept.

This case study demonstrated that it is possible to systematically design a sensor and take inspiration from biology in the process. By analyzing the biological system and making connections a designer can become inspired. It is through these correlations that the designer can recognize existing designs that are similar or develop an innovative design.

7.4.4 Heat Exchanger Case Study

This case study presents the design of a heat exchanger for use in future hydrogen vehicles following the approach of a known process before querying is performed (flow chart B of Figure 7.4). The needs for the heat exchanger design are set by another research group at Oregon State University that are in need of inspiration for distributing hydrogen on the micro scale. Without deep knowledge of the project, researchers of the Design Engineering Lab created a functional model of a heat exchanger to assist with finding inspiration and concept generation. The model is given in Figure 7.11.

Knowing that the solution needs to involve the distribution of hydrogen, the engineering-to-biology thesaurus was consulted for biological terms that achieve the function of distribute. Of the seven terms listed, *exchange* is one of them and is the natural choice for this design problem. Next, the biological knowledge base was queried to identify biological systems that perform the function of exchange. Several systems are returned. The resulting query results from (Purves et al. 2001) are:

1. *Heat exchange between the internal environment and the skin occurs largely through blood flow.*

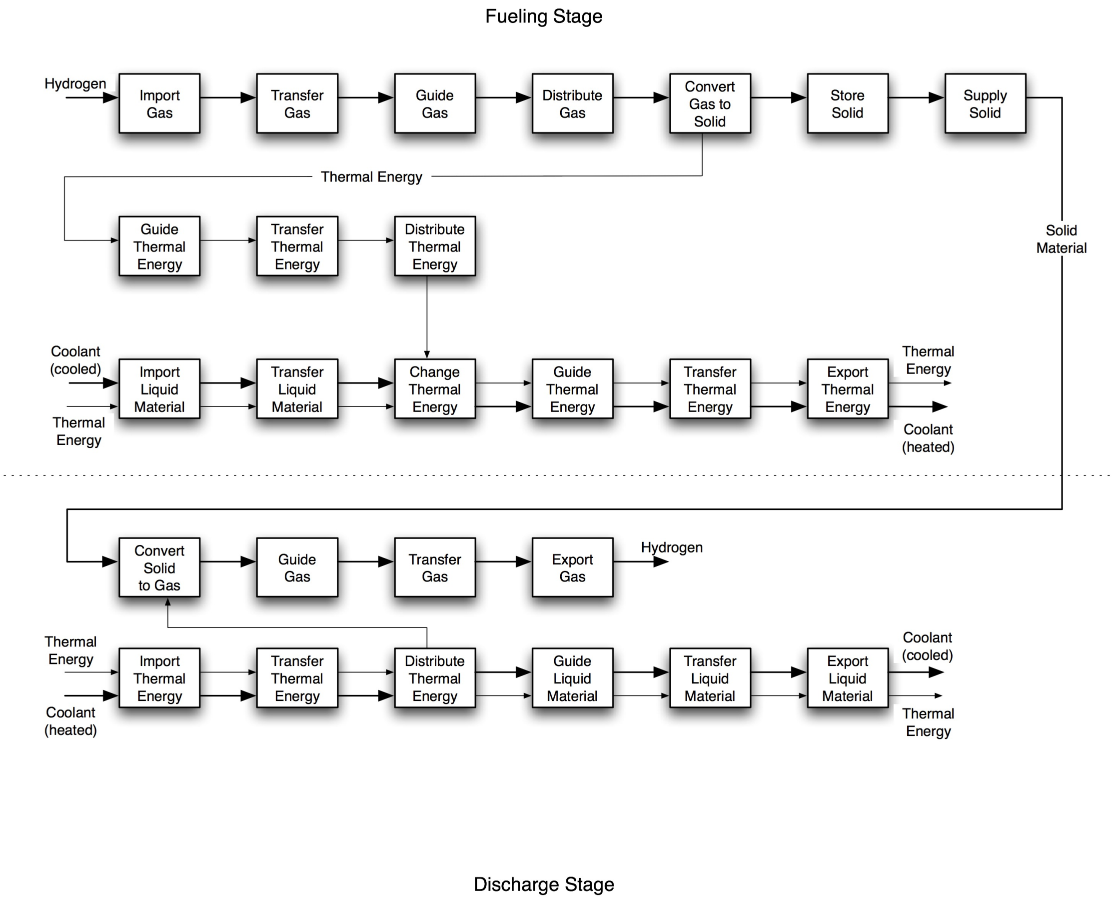

Figure 7.11. Functional Model of a Heat Exchanger.

2. *Both ectotherms and endotherms can alter the rate of heat exchange between their bodies and their environments by controlling the flow of blood to the skin. The skin is the interface between the internal and the external environment, and heat exchanges that alter body temperature occur across this interface.*
3. *When an animal breathes, it does work to move water or air over its specialized gas exchange surfaces.*
4. *External gills are highly branched and folded elaborations of the body surface that provide a large surface area for gas exchange with water. Because they*

consist of thin, delicate membranes, they minimize the length of the path traversed by diffusing molecules of O_2 and CO_2.

5. *As in other air-breathing vertebrates, air enters and leaves a bird's gas exchange system through a trachea (commonly known as the windpipe), which divides into smaller airways called bronchi (singular bronchus).*
6. *Most air-breathing invertebrates are insects, which have a unique respiratory gas exchange system consisting of a highly branched network of air-filled tubes called tracheae that branch through all the tissues of the insect's body.*
7. *Because heat is exchanged between blood vessels carrying blood in opposite directions, this adaptation is called a countercurrent heat exchanger. It keeps the heat within the muscle mass, enabling the fish to have an internal body temperature considerably above the water temperature.*
8. *Leaves exchange gases, including water vapor, with the environment by way of the stomata.*
9. *Abscisic acid also regulates gas and water vapor exchange between leaves and the atmosphere through its effects on the guard cells of the leaf stomata.*
10. *The movement of ions into and out of cells is important in many biological processes, ranging from the electrical activity of the nervous system to the opening of pores in leaves that allow gas exchange with the environment.*

It is important to note that the ten listed results are not the only results provided by the query. These ten were the most interesting and provided the most information. Lungs, skin, gills, stomata of plants, fish, and insects all offer inspiration for this case study. Not as many heat exchange results were identified as for gas exchange; however, as the topics are within the same domain in mechanical engineering applying the concepts of one to the other should be possible. Keeping in mind that the problem is with distribution of hydrogen, results 4, 5, 6, and 8 were chosen for further investigation. The detailed information on gills, bird's lungs, insects and stomata, also extracted from (Purves et al. 2001), is as follows:

4. *Water flows unidirectionally into the fish's mouth, over the gills, and out from under the opercular flaps, so that the gills are continuously bathed with fresh water. This constant flow of water moving over the gills maximizes the* O_2 *on the external surfaces. On the internal side, the circulation of blood minimizes the* O_2 *by sweeping the* O_2 *away as rapidly as it diffuses across. The gills have an enormous surface area for gas exchange because they are so highly divided. Each gill consists of hundreds of leaf-shaped gill filaments. The upper and lower flat surfaces of each gill filament have rows of evenly spaced folds, or lamellae. The lamellae are the gas exchange surfaces. Their delicate structure minimizes the path length for diffusion of gases between blood and water. The surfaces of the lamellae consist of highly flattened epithelial cells, so the water and the red blood cells are separated by little more than 1 or 2* μm*. The flow of blood perfusing the inner surfaces of the lamellae, like the flow of water over the gills, is unidirectional. Afferent blood vessels bring blood to the gills, while efferent blood vessels take blood away from the gills. Blood flows through the lamellae in the direction opposite to the flow of water over the lamellae. This countercurrent flow maximizes the* O_2 *gradient between water and blood, making gas exchange more efficient than it would be in a system using concurrent (parallel) flow.*
5. *Bird lungs have a unique structure that allows air to flow unidirectionally through the lungs, rather than having to flow in and out through the same*

airways, as it does in mammalian lungs. In addition to lungs, birds have air sacs at several locations in their bodies. The air sacs are interconnected with the lungs and with air spaces (another unique feature of birds) in some of the bones. The air sacs receive inhaled air, but they are not gas exchange surfaces. The composition of air in an air sac does not change rapidly, as it would if O_2 *were diffusing into the blood and* CO_2 *were diffusing into the air sac. As in other air-breathing vertebrates, air enters and leaves a bird's gas exchange system through a trachea (commonly known as the windpipe), which divides into smaller airways called bronchi (singular bronchus). In air-breathing vertebrates other than birds, the bronchi generate trees of branching airways that become finer and finer until they dead-end in clusters of microscopic, membrane-enclosed air sacs, where gases are exchanged. In bird lungs, however, there are no dead ends; air flows unidirectionally through the lungs. In bird lungs, the bronchi divide into tubelike parabronchi. Running between the parabronchi are tiny airways called air capillaries. Air flows through the lungs in the parabronchi, but crosses between parabronchi through the air capillaries. The air capillaries are the gas exchange surfaces. They are tiny but numerous, so they provide an enormous surface area for gas exchange. Another unusual feature of bird lungs is that hey contract less during a breathing cycle than mammalian lungs do. Also, bird lungs contract during inhalation and expand during exhalation! Because the air sacs keep fresh air from the outside flowing unidirectionally and practically continuously over the gas exchange surfaces, the* O_2 *on the environmental side of those surfaces is maximized.*

6. *Respiratory gases diffuse through air most of the way to and from every cell of an insect's body. This diffusion is achieved through a system of air tubes, or*

tracheae, that open to the outside environment through holes called spiracles in the sides of the abdomen. The tracheae branch into even finer tubes, or tracheoles, until they end in tiny air capillaries. In the insect's flight muscles and other highly active tissues, no mitochondrion is more than a few micrometers away from an air capillary. Some species of insects that dive and stay underwater for long periods make use of an interesting variation on diffusion. These insects carry with them a bubble of air. A small bubble may not seem like a very large reservoir of oxygen, yet these insects can stay underwater almost indefinitely with their small air supplies. The secret has to do with the O_2 *in the bubble. When the insect dives, the air bubble contains about 80 percent nitrogen and 20 percent* O_2*. As the insect consumes the* O_2 *in its bubble, the bubble shrinks a little. The bubble doesn't disappear, however, because it consists mostly of nitrogen, which the insect doesn't consume. When the* O_2 *in the bubble falls below the* O_2 *in the surrounding water,* O_2 *diffuses from the water into the bubble. For these small animals, the rate of* O_2 *diffusion into the bubble is enough to meet their* O_2 *demand while they are underwater.*

8. *The epidermis of leaves and stems minimizes transpirational water loss by secreting a waxy cuticle, which is impermeable to water. However, the cuticle is also impermeable to carbon dioxide. This poses a problem: How can the leaf balance its need to retain water with its need to obtain carbon dioxide for photosynthesis? Plants have evolved an elegant compromise in the form of stomata (singular stoma), or gaps, in the epidermis. A pair of specialized epidermal cells called guard cells controls the opening and closing of each stoma. When the stomata are open, carbon dioxide can enter the leaf by diffusion, but water vapor is also lost in the same way. Closed stomata prevent water loss, but also*

> *exclude carbon dioxide from the leaf. Most plants open their stomata only when the light intensity is sufficient to maintain a moderate rate of photosynthesis. At night, when darkness precludes photosynthesis, the stomata remain closed; no carbon dioxide is needed at this time, and water is conserved. Even during the day, the stomata close if water is being lost at too great a rate. The stoma and guard cells are typical of eudicots. Monocots typically have specialized epidermal cells associated with their guard cells. The principle of operation, however, is the same for both monocot and eudicot stomata. In what follows, we describe the regulation and mechanism of stomatal opening, the normal cycle of opening and closing, and the modified cycle used by some plants that live in dry or saline environments.*

As this design is for another research group, a meeting was held to discuss these biological systems that were identified. While reviewing the detailed descriptions, a researcher immediately made a connection between the gills of fish and hydrogen distribution (Paul, B., personal communication, April 8, 2010). Considering the fish blood as the coolant and the water surrounding the fish as hydrogen, a distribution scheme inspired by the morphology and physiology of fish gills was discussed. In this case, the biological functional model was not required, nor the engineering knowledge base query. The concept generation step began during the meeting, however, a final concept will be finalized by the other research group. Another connection established during the meeting is the similarity of engineering mass transfer concepts and the diffusion of respiratory gases into an insect. Discussing the respiratory system of birds led to a connection that revealed the solution of a competing research group in the area of heat exchangers for hydrogen vehicles. During the first inhale/exhale cycle of a bird, air travels to the trachea and into posterior air sacs, then is moved to the parabronchi area where the exchange takes place (Campbell and Reece 2003). During the second inhale/ exhale cycle the air moves forward to the cranial air sacs and then exits the bird (Campbell and Reece 2003). Realizing that the air within a bird's lungs essentially travels in a circle, this sparked discussion of a spiral shaped surface that would effectively distribute hydrogen (Paul, B., personal communication, April 8, 2010). In fact, that is what a competing research group did. Figure 7.12 shows the prototype with coiled tubing. They did not take inspiration from nature to get to that solution, but they are experts in their field.

Figure 7.12. Heat Exchanger Design Similar to the Discussion about Respiratory System of Birds (Venere 2010).

This case study demonstrated that it is possible to systematically design for a portion of a larger problem with only a small amount of information and take inspiration from biology in the process. By analyzing the biological system and making connections a designer can become inspired. It is through these correlations that the designer can recognize existing designs that are similar or develop an innovative design.

7.5 Summary

The design methodology presented here represents a specific design approach devoted to developing biologically-inspired solutions. It challenges and guides a designer to make connections between the engineering and biology domains to facilitate innovative design. It takes an organic approach to systematic design by providing a designer many avenues that lead to an inspired design. It also is envisioned as an inventive and iterative process, in terms of developing connections between systems at multiple levels of fidelity. As one level, or scale, of the biological system becomes understood it leads to a deeper understanding and a greater curiosity to explore further. Thus, leading to multiple innovative designs. The preceding four chapters presented the individual parts of the framework. They coalesce in the systematic biologically-inspired design method as demonstrated by the smart flooring, chemical sensor and heat exchanger cases studies. Validation of the design methodology was proven through matching each of the generated concepts in the case studies with existing solutions or technologies. It was shown how the connections made between biological systems and engineered were key to arriving at the biologically-inspired inspired designs.

Two detailed case studies in Chapter 8 and 9 demonstrate the application of the systematic biologically-inspired design methodology to the design of innovative solutions. They show that the methodology is more than an academic exercise, but a useful tool in the creation of innovative designs that can be applied to current worldly needs without being an expert in the respective fields.

CHAPTER 8 - PROBLEM-DRIVEN CASE STUDY

8.1 Overview

This chapter will demonstrate how one of the problem-driven approaches of the systematic biologically-inspired design methodology was used to develop an innovative concept. Beginning from the chemical sensor case study presented in Chapter 7, a more detailed chemical sensor design is derived. Where the previous design only utilized the biology knowledge stored in the Design Repository housed at Oregon State University, this case study queries the biological corpus for biological inspiration. Following the five steps of the systematic design method leads to a sensor device that is conductometric or electrochemical with the added benefit of "up-front" processing through mechanical filtering. Chemomechanical polymers, nanowires and porous substrates are explored for implementation of the sensor conceptual designs. The following sections will walk the reader through the thought processes, model iterations and connections formed that lead to the leaps from insect chemoreception, structures involved in muscle contractions, guard cells of plants, and protein structure to sensor.

8.2 Starting from Needs

Recall from Chapter 7 the case study of a chemical sensor. All steps of the method were completed, which arrived at known sensor technology. In this case study, a more detailed sensor design is presented and an innovative sensor concept is generated. This design follows flow chart A of Figure 7.3. Beginning with the customer needs of Table 7.4, the first step is satisfied.

8.2.1 Decompose

A black box and conceptual functional model of the chemical sensor needed to satisfy Step 2 has been given in Chapter 7. The black box model of Figure 7.8 demonstrates that the overall objective of the design is to detect a chemical stimulus. The decomposed conceptual functional model from the black box and needs mapped to flows is given in Figure 7.9.

8.2.2 Query

Following flow chart A of Figure 7.3 requires the designer to query the engineering and biological knowledge bases in the same step. In the Chapter 7 case study, only the biology knowledge stored in the Design Repository was used for biological inspiration. Here, the query is expanded to include all entries in the Design Repository and the knowledge contained within the biological corpus that is utilized for the organized search. This query utilizes the second version of the search software. Function/flow pairs that did not return engineering solutions via MEMIC were used with the automated morph matrix tool. Results of querying the Design Repository and the biological corpus are provided in Tables 8.1 and 8.2, respectively. To reduce the amount of data and increase readability, only the sensing mechanism function/flow pairs are presented in Table 8.2. Several more results than shown in Table 8.2 were returned and the more interesting ones were chosen for the table.

8.2.3 Make Connections

Analyzing the biological solutions for the change material function/ flow pair reveals some very interesting, and inspiring, biological systems. Additionally, a biological strategy emerges. Of the listed biological systems, the change made tends to be physical through shape or conformation change. Shape or conformation change mean the shape or structure of something is changing or the atoms in a molecule may convert between any adopted spacial arrangement. The biological strategy connects with the engineering principle of stress and strain through mechanical deformation. Next, more detailed information on each of the biological solutions of Table 8.2 for are explored (Purves et al. 2001) to assist with developing connections. For *change material,* troponin and tropomyosin (result 10 & 11), guard cells (result 14) and the silk protein (result 15) as shown in Figure 8.1 offer strong connections with engineering and will be the focus of the case study.

Table 8.1. Design Repository Query Results for the Chemical Sensor Conceptual Functional Model.

Function/Flow	Design Repository Results
Import Material	Housing, reservoir, spring
Import Chemical Energy	Container, nozzle
Guide Chemical Energy	Tube
Couple Chemical Energy to Material	Basket, container, iron, nozzle, carburetor, burner, housing
Import Electrical Energy	Battery, wire, circuit board, motor, cord, switch
Transmit Electrical Energy	Wire, battery contacts, circuit board, compound eye
Change Material	Blade, impeller, heating element, punch, filter, staple plate, popcorn popper
Detect Chemical Energy	Fly chemoreceptor, protein, animalia chemoreception, plantae chemoreception
Regulate Electrical Energy	Circuit board, actuator, heating element, switch, resistor, diode
Convert Status to Control Signal	Circuit board
Export Chemical Energy	Nozzle, bowl, tube, exhaust, bucket
Export Electrical Energy	Wire, circuit board, cord, switch
Export Status Signal	LCD screen, circuit board, wire, cord, level, speaker

Table 8.2. Biological Corpus Query Results for the Chemical Sensor Conceptual Functional Model.

Function/Flow	Biological Corpus Results
Change Material	1. The resulting change in membrane potential causes the sensory cell either to fire action potentials itself or to change its secretion of neurotransmitter onto an associated cell that fires action potentials. 2. Photosensitivity depends on the ability of rhodopsins to absorb photons of light and to undergo a change in conformation. 3. Dynein is a enzyme that catalyzes the hydrolysis of ATP and uses the released energy to change its shape, thereby generating mechanical force. 4. A gated channel opens when something happens to change the shape of the protein. 5. Microtubules change the shapes of cells and move cells by polymerizing and depolymerizing the protein tubulin. 6. Cell movement is generated by two structures, microtubules and microfilaments, both of which consist of long protein molecules that can change their length or shape. 7. Actin microfilaments can change the shape of a cell simply by polymerizing and depolymerizing. 8. Nets of actin and myosin beneath the cell membrane change a cell's shape during endocytosis. 9. Chromatophores are pigment-containing cells in the skin that can change the color and pattern of the animal. 10.Because the troponin is bound to the tropomyosin, this conformational change of the troponin twists the tropomyosin enough to expose the actin-myosin binding sites. 11.The Ca2+ ions bind to troponin and change its conformation, pulling the tropomyosin strands away from the myosin binding sites on the actin filament. 12. Ionizing radiation (X rays) produces highly reactive chemical species called free radicals, which can change bases in DNA to unrecognizable (by DNA polymerase) forms or break the sugar-phosphate backbone, causing chromosomal abnormalities. 13.Because the viruses are too large to go through these channels, special proteins bind to them and help change their shape so that they can squeeze through the pores. 14.Guard cells are modified epidermal cells that change their shape, thereby opening or closing pores called stomata, which serve as passageways between the environment and the leaf's interior. 15.The silk protein that stretches contains amino acids that allow it to curl into a spiral, and when these spirals associate into silk fibers, they can slip along each other to change the fiber's length.

Table 8.2. Biological Corpus Query Results for the Chemical Sensor Conceptual Functional Model (Continued).

Function/Flow	Biological Corpus Results
Detect Chemical Energy	1. Smell and taste receptors, for example, are epithelial cells that detect specific chemicals. 2. Most sensory cells possess a membrane receptor protein that detects the stimulus and responds by altering the flow of ions across the plasma membrane. 3. Eukaryotic cells carry out cellular respiration in their mitochondria, which are located in the cytoplasm-an aqueous medium. 4. Chemoreceptors are responsible for smell, taste, and the monitoring of aspects of the internal environment such as the level of carbon dioxide in the blood. 5. Crabs and flies, for example, have chemoreceptor hairs on their feet; they taste potential food by stepping in it. 6. After a fly tastes a drop of sugar water by stepping in it, its proboscis (a tubular feeding structure) extends to feed. 7. Since both AT and GC pairs obey the base-pairing rules, how does the repair mechanism "know" whether the AC pair should be repaired by removing the C and replace it with T, for instance, or by removing the A and replacing it with G? The repair mechanism can detect the "wrong" base because a newly synthesized DNA strand is chemically modified some time after replication. 8. So the unique drug resistance phenotype of the cells with recombinant DNA (tetracycline-sensitive and ampicillin-resistant) marks them in a way that can be detected by simply adding ampicillin and/or tetracycline to the medium surrounding the cells. 9. Whether the receptor protrudes from the plasma membrane surface or is located in the cytoplasm, the result of ligand binding is the same: the receptor protein changes its three-dimensional structure and initiates a cellular response. 10.This receptor is located at the plasma membranes of vertebrate skeletal muscle cells and binds the ligand acetylcholine, which is released from nerve cells.

Guard cells (Figure 8.1a) are modified epidermal cells (cells on the surface of a leaf or other plant tissue where bark is absent) that change shape to open and close pores called stomata. Stomata serve as passageways between the environment and the leaf's interior. Carbon dioxide can enter and oxygen can leave when stomata are open, which are activated by light and low levels of CO_2. A proton pump of potassium and hydrogen ions governs the opening and closing of the guard cell pores. This biological system is analogous to chemomechanical polymers and electroactive polymers that change shape in the presence of a chemical species and electrical current, respectively (Shahinpoor and Schneider 2008).

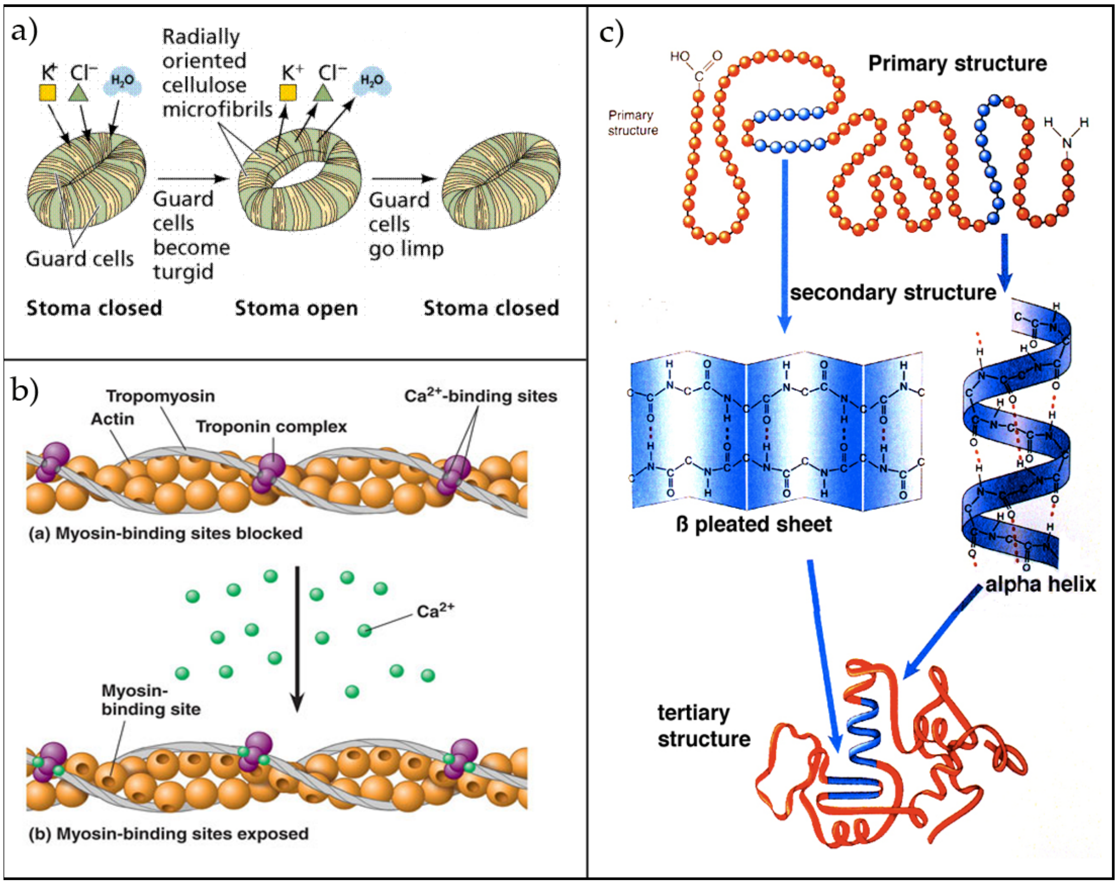

Figure 8.1. Biological Systems for Concept Generation (Adapted from: a) (Farabee 2000), b) (Campbell and Reece 2003), c) (Raven and Johnson 2002)).

Troponin, a polypeptide chain complex found on an actin filament, is bound to tropomyosin, a protein with two elongated strands that run the length of an actin filament (Figure 8.1b). When calcium ions bind to troponin, a conformation change twists the tropomyosin to expose actin binding sites, which allows myosin to interact with actin to cause muscle contraction. Learning more about the structures involved in muscle contractions conjures up thoughts of cantilevers and bi-metallic strips that are used in thermostats. A cantilever and bi-metallic strip are individually analogous, but also form a compound analogy when considered together.

The silk protein curls into a spiral at rest and when stretched the silk fibers slip along each other which provide strength and flexibility. The fibers are made of amino acids that fold the individual proteins into flat sheets with jagged ends, similar to ratchets, that fit parallel sheets together so the fibers are hard to pull apart. The properties associated with a precise sequence of amino acids, the primary structure, determine how the protein can twist and fold. Each protein adopts a specific stable structure of secondary (curling or pleating), tertiary (folding or bending) and quandary (special subunits) states that distinguishes it from every other protein (Figure 8.1c). This biological system offers three morphological analogies. The secondary structure of the protein links to springs and coils. The tertiary structure leads to connections with branched and folded (zig-zag) morphologies while the overall combinations lead a to modular morphology.

Fly antennae and chemoreceptor hair morphology offers inspiration at the organism scale for a "stick-like" sensing element. Analogous engineered components are carbon nano tubes and nanowires. Morphology of the fly antennae at the cellular scale inspires a porous sensing element after the receptor sites on the cell membrane surface (Figure 5.1). Analogous porous engineered components are porous silicon, nano-imprinted silicon and aluminum oxide templates. These analogous components are nano or micro sized structures. Although the size of the sensing element was not specified in the needs, these morphological analogies are advantageous. Nano structures for sensing offer many advantages: sensitivity, large surface-to-volume ratio, low power, fast response, fast calibration, surfaces can be functionalized and metal oxides work well at elevated temperatures (Lu and Lieber 2006; Kalantar-zadeh and Fry 2008; Harnett 2010).

8.2.4 Generate Concepts

From the connections made in the previous section and the query results of Step 3, many concept variants are possible. Following the integration, progression and a mix of the two thought patterns leads to multiple concept variants stemming from insect chemoreceptor morphology, physiology of guard cells, physiology of the silk protein, physiology of troponin and tropomyosin and the biological strategy of change shape. Four main concept variants are explored.

Combining insect chemoreceptor "stick-like" morphology and the morphology of the silk protein leads to the sensor element concept of nanowires or carbon nano tubes with branched, folded and spiral morphologies. Figure 8.2 demonstrates this concept. Several morphologies, including the concepts in Figure 8.2, have been created with nanowires as shown in Figure 8.3. A group of researchers at Georgia Tech University have fabricated nanowires and nanobelts in several shapes: spiral, spring, comb (branches on only one side), ring, propellers (equidistant branches), helix, saw (branches on opposite sides), bows and tetrapoles (Figure 8.3a) (Wang 2005; Wang 2007).

Zig-zig or kinked nanowire structures have also been fabricated (Figure 8.3b) (Tian et al. 2009b). Other researches have created ribbons coated with perpendicular branching structures that look like holiday tinsel (Figure 8.3c) (Gao and Wang 2002). While this concept is interesting, it does not employ the indirect sensing requirement.

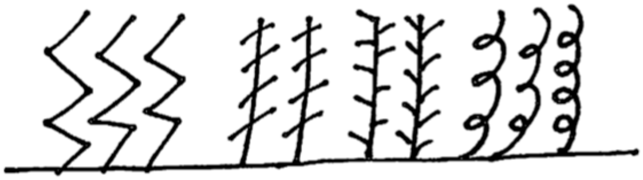

Figure 8.2. Sensor Element Concept Variant Inspired by Morphology of Insect Antenna and Silk Protein.

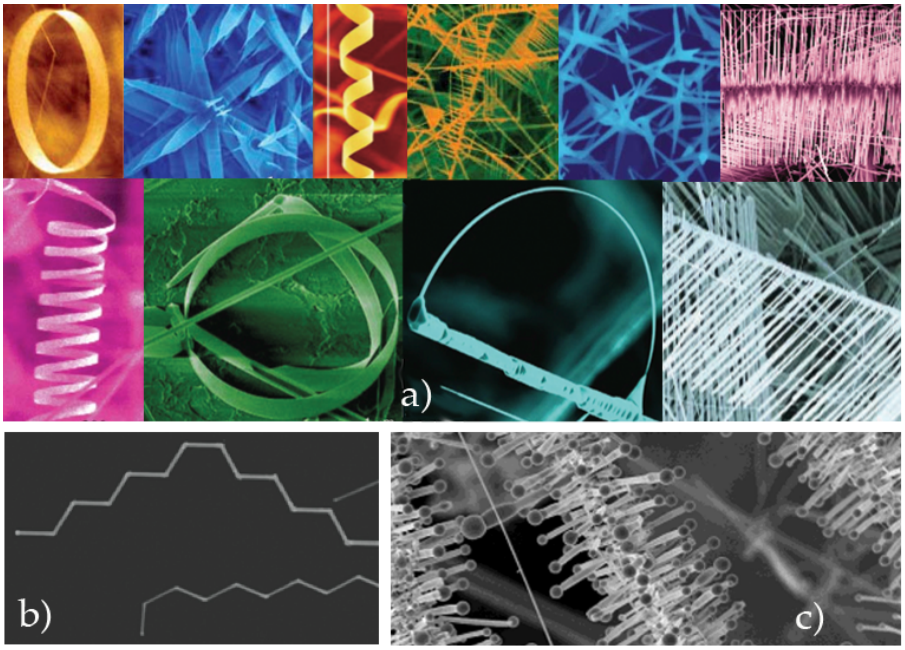

Figure 8.3. Existing Nanowire Morphologies (Adapted from: a) (Wang 2005; Wang 2007), b) (Tian et al. 2009b), c) (Gao and Wang 2002)).

Combining the strategy of change shape, insect chemoreceptor porous morphology and the physiology of guard cells leads to the concept variant shown in Figure 8.4. This concept variant uses a chemomechanical polymer (shown in yellow) as the sensing layer covering a porous semiconductor. When the desired chemical species interacts with the polymer it would contract to open pores (shown in orange to denote a change in the chemomechanical polymer), similar to the guard cells and shape change strategy. The sensing element; however, would come into direct contact with the chemical to change the output signal and also does not employ the indirect sensing requirement.

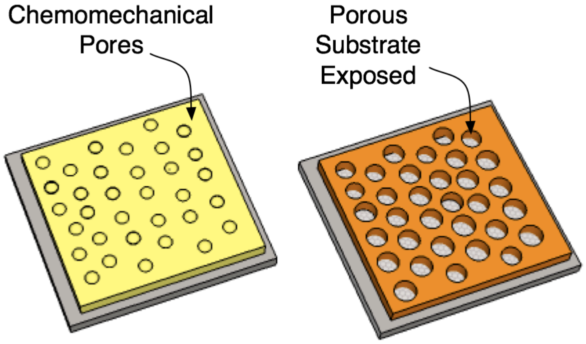

Figure 8.4. Concept Variant Inspired by Guard Cells.

Combining the strategy of change shape, insect chemoreceptor porous morphology and the physiology of troponin and tropomyosin leads to the concept variant that directly copies the interaction of troponin and tropomyosin. Figure 8.5 shows a concept sketch. This concept variant uses a chemomechanical polymer (shown in yellow) as the sensing layer covering a porous semiconductor. When the desired chemical species interacts with the polymer it would curl up to expose the sensing element below (shown in orange to denote a change in the chemomechanical polymer), similar to troponin and tropomyosin and the shape change strategy. Again, while this concept is interesting, the sensing element would come into direct contact with the chemical to change the output signal and does not employ the indirect sensing requirement.

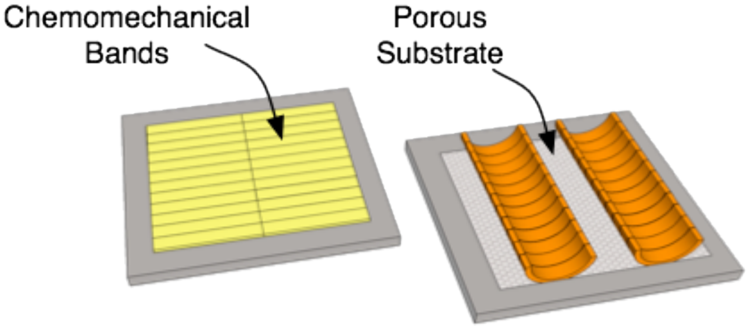

Figure 8.5. Concept Variant Inspired by Troponin and Tropomyosin.

Combining the strategy of change shape, insect chemoreceptor “stick-like” morphology and the physiology of troponin and tropomyosin leads to a concept variant that emulates the cantilever with a chemically activated polymer on one side (shown in yellow) as shown in Figure 8.6a. Ideally, the cantilevers would be vertical to take advantage of existing nanowire technology with a single-sided coating of a chemomechanical polymer tuned to the desired chemical species. This concept fulfills the indirect sensing requirement, if the strain on the cantilever can be measured. Cantilever structures with chemically activated coatings or binding sites have been fabricated and successfully implemented (Bhushan 2004; Lavrik et al. 2004; Harnett 2010). The mechanics of nanowires have also been thoroughly researched (Bhushan 2004;

Law et al. 2004; Menon and Srivastava 2004; Postma et al. 2005) and shows that they can handle a great deal of bending. Transduction of the deformation and fabrication of a single-sided coating are two concerns for this type of design. Signal generation by bending a vertical nanowire is currently an unsolved problem. One theoretical approach is to exploit the quantum wells created in the heterojunction of the substrate the nanowires are grown on (Tonisch et al. 2007; Lübbers et al. 2008; Niebelschütz et al. 2008; Brueckner et al. 2009). An electron gas in the quantum well changes resistance proportional to the deflection of a nanowire. Considering fabrication capabilities, coating only one side of a nanowire could be nearly impossible. However, dip-coating an array of vertical nanowires with a chemomechanical polymer or using a deposition process would be feasible. Using a progressive thought pattern results in radially coated nanowires (shown in yellow) as shown in Figure 8.6b.

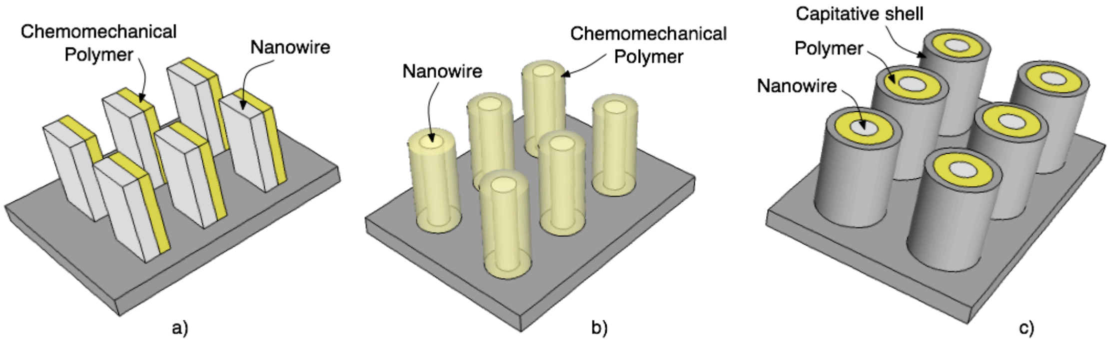

Figure 8.6. Evolution of Second Concept Variant Inspired by Troponin and Tropomyosin.

Radial nanowires exist and generally involve multiple shells of different materials (Lauhon et al. 2002; Lu and Lieber 2006; Lu et al. 2008; Tian et al. 2009a). Although the manufacturing process is feasible, would a completely coated nanowire result in a significant mechanical deformation to measure by strain? An alternative is to add another shell over the chemomechanical polymer (shown in yellow) to create a cylindrical capacitor (Figure 8.6c). This design, following the progression thought pattern, would use the polymer as a dielectric and would produce a change in signal as the target is absorbed into the polymer, which would expand or contract. Would the polymer be able to absorb a significant amount of a desired chemical species to generate a signal? Assuming worst case, this design would not be adequate.

A feasible, innovative, design can be formulated if the morphology of troponin and tropomyosin is also considered. Following the mix of integration and progression thought pattern results in a spiral nanowire or nanobelt that this coated with the chemomechanical polymer (shown in orange). Two configurations can be considered: connected at both ends to a substrate (Figure 8.7a) or suspended between two grids (Figure 8.7b) that allow current to flow through the nanostructure. This design fulfills the indirect sensing requirement by completely coating the nanowire with the polymer that contracts or expands in the presence of the desired chemical species. Also, the spiral shape allows the mechanical action of the polymer to be maximized. The change in the polymer would be proportional to the concentration of the chemical species and the change in resistance of the nanowire. Considering manufacturability, the nanowires connected at both ends to a substrate could most likely utilize dip-coating for applying polymer and conventional microelectronic assembly. Where as the sensor suspended between two grids could be impossible to even fabricate, at least on the nano scale.

Applications of the biologically-inspired chemical sensor include environmental sensing (Mulchandani and Sadik 2000; Fryxell and Cao 2007), breath analysis for diseases (Amann and Smith 2005; Cao and Duan 2006) and point-of-care testing (Spichiger-Keller 1998; Zhang et al. 2008). These areas require accurate responses for what could be critical situations. Additionally, nanotechnology enabled sensors could assist with creating disposable sensors for medical applications that are economical.

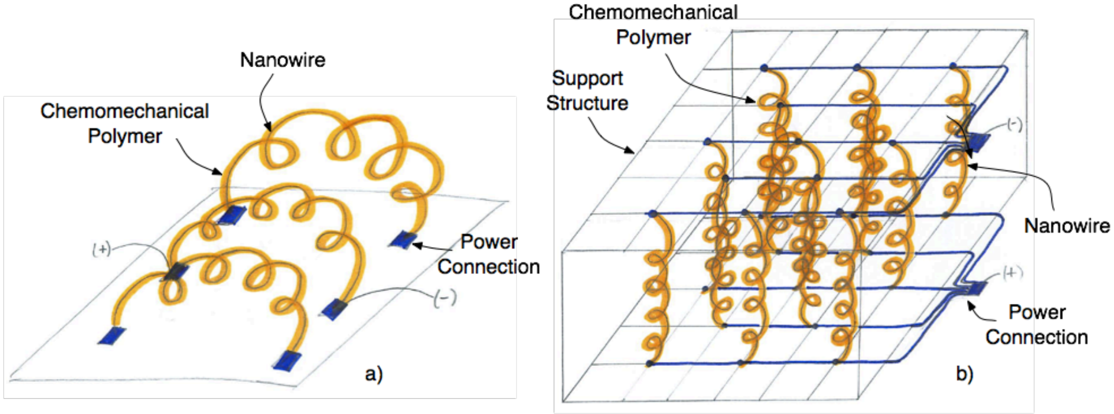

Figure 8.7. Final Second Concept Variant Inspired by Troponin and Tropomyosin.

8.3 Summary

This chapter presented a case study following one route of the problem-driven approach provided by the systematic biologically-inspired design method of Chapter 7. Following this approach, several biological systems were reviewed and four were investigated in detail, which led to the design of an innovative chemical sensor. All three thought processes introduced in Chapter 6 were utilized in this case study. It was shown how the concept synthesis patterns can be used to generate biologically-inspired concepts. Considering prior knowledge, design experience, biological solution inspiration and manufacturability considerations resulted in concepts that are not immediately obvious to a non-expert in sensor design. Connections formed that lead from guard cells, the silk protein, troponin and tropomyosin and the strategy of change shape to multiple chemical sensor designs were presented. Through constantly revisiting the needs, a solution was found to the problem. In this case, three of the four designs did not meet all the needs. However, the design that did meet all the needs, in its first iteration was not feasible. Four iterations of the chemical sensor concept resulted in a design that could allow a signal to be transduced. Pursuing this concept could offer a solution to the areas of environmental sensing, breath analysis for diseases and point-of-care testing.

Traditional sensor schemes involve few sensing devices and require a significant amount of computing power to handle the data created. Nature demonstrates robust sensing with minimal processing. It has been shown that the designer using the systematic biologically-inspired design method does not need expert knowledge, but rather broad knowledge of many fields. The biological knowledge base was a key factor in designing the sensing layer, while the engineering knowledge base was a key factor in designing the sensing element. Both assisted with making the leap to the innovative design. The link between nanowire and insect chemoreceptor may be obvious, however, the link between troponin and tropomyosin and cantilever with a bi-metallic strip is less obvious. Although query strategies must be used from time to time, the knowledge contained in the repository and biological corpus supplements the designer’s knowledge and causes one to consider solutions from different viewpoints. Using a knowledge base increases the chance for a designer to develop an innovative design. This case study proves it is possible.

CHAPTER 9 - SOLUTION-DRIVEN CASE STUDY

9.1 Overview

This chapter will demonstrate how the solution-driven approach of the systematic biologically-inspired design method was used to develop an innovative concept. The majority of trees in Corvallis, Oregon are covered with an organism called lichen. Seeing this biological system on a daily basis leads to a curiosity of how it functions, survives, and protects itself. These curiosities fueled the design process. Following the five steps of the systematic design method lead to a solar thermal collection device. The following sections will walk the reader through the thought processes, model iterations and connections formed that lead to the leaps from lichen to solar thermal collection device.

9.2 Following Curiosity

The majority of trees in Corvallis, Oregon are covered with what appears, at first glance to someone not familiar with lichen, to be a light green bushy moss. Seeing this biological system (Figure 9.1) on a daily basis leads to the first curiosity of what is it? Once it was discovered that the biological system is called lichen and is a symbiosis of two organisms, more curiosities were born. How does lichen function? How does lichen survive? Why is it a symbiosis? How does lichen protect itself? Following the systematic biologically-inspired design method these questions are answered. These curiosities satisfy the first step.

Figure 9.1. Photo of Lichen.

9.2.1 Decompose

To decompose a black box and biological functional model of lichen and satisfy Step 2, the modeling methodology of Chapter 5 is employed. The modeling process begins with gathering information. Lichen is a symbiotic organism comprised of a fungus (mycobiont) and an organism capable of producing food by photosynthesis (photobiont), typically a green algae or cyanobacterium (Ahmadjian 1993; Brodo et al. 2001; Nash 2008). Lichens grow in almost every climate and thrive where other organisms refuse to live, such as harsh climates or in areas of limited resources, which can include bare rock, desert sand, cleared soil, dead wood, animal bones, rusty metal, and living bark (Brodo et al. 2001). A lichen can survive such conditions because of the symbiosis—the mycoboint protects the photobiont physically from predators and too much sunlight in return for carbohydrates to live (Ahmadjian 1993; Brodo et al. 2001; Nash 2008; McCune 2010a). In addition to sunlight, lichen also need water and nutrients to sustain life and perform photosynthesis. Nutrients consist of elemental chemicals (e.g., oxygen, carbon, nitrogen) and minerals that are derived from the atmosphere, taken up from a substrate, and transported to lichen by rain water or droplets from the surrounding environment. The photobiont communicates with the mycobiont to receive more or less sunlight, water and nutrients to fuel the photosynthesis, while the mycobiont communicates to the photobiont when more carbohydrates need to be produced (McCune 2010a). For lichen to form, mycobiont and photobiont must encounter each other on a stable surface. Once the mycobiont secures itself around the photobiont, fully enclosing the photobiont, a surface is no longer required. Lichens can take on different appearances based on their growth form. The major difference between the growth forms is the location of the cortex and whether it is centralized or spread out (Nash 2008). Functionally speaking, all growth forms of the lichen are similar in principle with differing morphology.

To scope a functional model of an engineered system a design question must be posed. The same holds true for biological systems, and more importantly, it provides a starting point from which to begin researching the biological system of interest past basic information. Consider the following design question for the lichen: How do the mycobiont (fungus) and photobiont (photosynthetic organism) interact to survive as the symbiotic organism, lichen? Table 9.1 captures the biological flows that have been identified for lichen and the Functional Basis translations that are salient to understanding the lichen symbiosis and aid in answering the posed design question.

Understanding how the mycobiont and photoboint work in symbiosis to survive requires knowledge of the principal functionalities of the two organisms that comprise the lichen, and how they each contribute to the symbiosis. To define the biological category used during functional modeling

Table 9.1. Relationship between lichen flows (Ahmadjian 1993; Brodo et al. 2001; Nash 2008) and the Functional Basis (Hirtz et al. 2002).

Biological Information	**Functional Basis Flows**
Fungus (*mycobiont*)	Liquid-solid mixture material
Green Algae or Cyanobacterium (*Photobiont*)	Liquid-solid mixture material
The photobiont uses *sun light* to perform photosynthesis	Electromagnetic energy
Nutrients	Solid material
Water	Liquid material
Symbiosis	Liquid-solid mixture material
Photosynthesis creates *carbohydrate sugars*	Chemical energy
Photobiont *communicates* with mycobiont to receive more/less sun light, nutrients and water	Control signal
Predators	Material
Mycobiont creates a *poisonous coating* to prevent predators from eating lichen	Solid-solid mixture material

requires investigation of physiology, morphology, behavior and strategy of the biological system. Realizing that the mycobiont and photobiont are both organisms initially points to the physiology category. However, since survival is posed in the design question, it could also be argued that this includes the behavior category. To further narrow in on which category is of interest, it is necessary to return to the design question. While survival is discussed, it is in the context of interaction between the mycobiont and the photobiont. There is not discussion of possible external stimuli such as harsh climates or areas of limited resources. Further research into the symbiosis of the two organisms reveals that lichen employs resource sharing in exchange for protection. These are elements that fall within the vital functionality of the organism. Therefore, we will consider that the boundary set for the lichen functional model is the category of physiology.

Lichen physiology was demonstrated at multiple biological scales and the answer to the posed design question can be best captured with a mixed scale functional model. Modeling lichen at the organism scale would convey that two materials are secured together in the lexicon of the Functional Basis. This result, however, does not fully answer the posed design question as we do not know how the two organisms interact. Thus, we must mix the scales to include the organ level to fully understand the interaction between the mycobiont and the photobiont. Examining lichen at the organ scale reveals that the photosynthetic organism performs photosynthesis in return for sunlight, environmental and predator protection. Photosynthesis performed by the photobiont produces carbohydrate sugars. These carbohydrates are made available for both organisms; their consumption by the mycobiont provides for sunlight, environmental and predator protection, and their consumption by the photobiont allows the photosynthesis process to continue. The intake and transfer of sunlight, water and nutrients by the mycobiont and its conversion to carbohydrates by the photobiont, answers half of the posed design question. The other half relates to the mycobiont. The mycobiont, or fungus, forms around the photobiont offering protection from excess sunlight, harsh environmental conditions and from predators. This filtering of light, sharing of water and nutrients and the production of chemicals to repel predators must be added with the intake, transfer and conversion of sunlight mentioned above to completely answer the posed question. To direct the biomimetic concept using the organ scale alone would result in a design that acts more as a component than a product, whereas the organism scale would act, at least at a high level, as a product. Looking at a more detailed scale such as molecular would focus on the chemical reactions of the Calvin Cycle (Campbell and Reece 2003) occurring during photosynthesis to produce the carbohydrate sugars; while this might be interesting from an analogical standpoint, this detail is outside of the scope of the posed design question. Thus, a mixed scale model comprised of organism (photobiont and mycobiont) and organ (carbohydrate production and predator deterrence) biological scales is considered for lichen.

Realizing that lichen only exists when there is a symbiosis conjures up the basic instinctual actions of sustaining and protecting life, thus the black box model of the system is described as provision (i.e., to accumulate or provide a material or energy flow (Hirtz et al. 2002)). As input flows, the mycobiont and the photobiont are both brought into the black box. These two organisms are represented as liquid-solid mixture materials due to their aqueous composition. The water, nutrients and sunlight necessary for survival are also brought into the model; inside the black box, lichen is formed. The primary flows include the photobiont, mycobiont, water, nutrients and predators as materials, and sunlight as the energy of the systems. This black box model is provided in Figure 9.2.

Investigating the lichen functionality, the flows required, and the biological system category and scales resulted in a well-defined scope. The lichen biological functional model, shown in Figure 9.4, is decomposed from the black box model of Figure 9.2 and an organism only scale model of lichen in Figure 9.3. To arrive that the mixed scale model, time was taken to initially understand and model lichen as a single system. In Figure 9.3, the mycobiont and photobiont portions of the lichen are both imported into the system. They are guided together where the mycobiont secures the photobiont. The mycobiont surrounds the entire photobiont to provide protection to the entire organism. The predator flow is also decomposed to capture the key biological action of *protection*. The predators chain begins with the predator imported. It is then prevented; a bold material flow and a thin energy flow enter the prevent block to represent the toxins excreted by the mycobiont. The predators export the system after the failed attack. Also captured by the second level granularity model is a high-level representation for *sustainability*. Energy/ material mix is imported into the system and regulated by the mycobiont. The high level representation is chosen as regulate as the engineering-to-biology thesaurus maps *sustain* to the engineering function of regulate. Communication between the photobiont and mycobiont helps to regulate the flow of these nutrients to the photobiont, which is creating the sugars for survival. The energy created by the photobiont—termed chemical—is directed not only back to the photobiont for its survival, but also to the mycobiont for its survival.

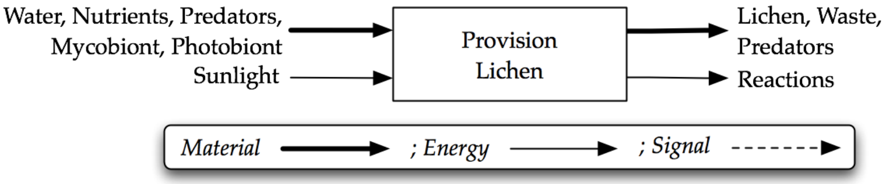

Figure 9.2. Lichen Black Box Model.

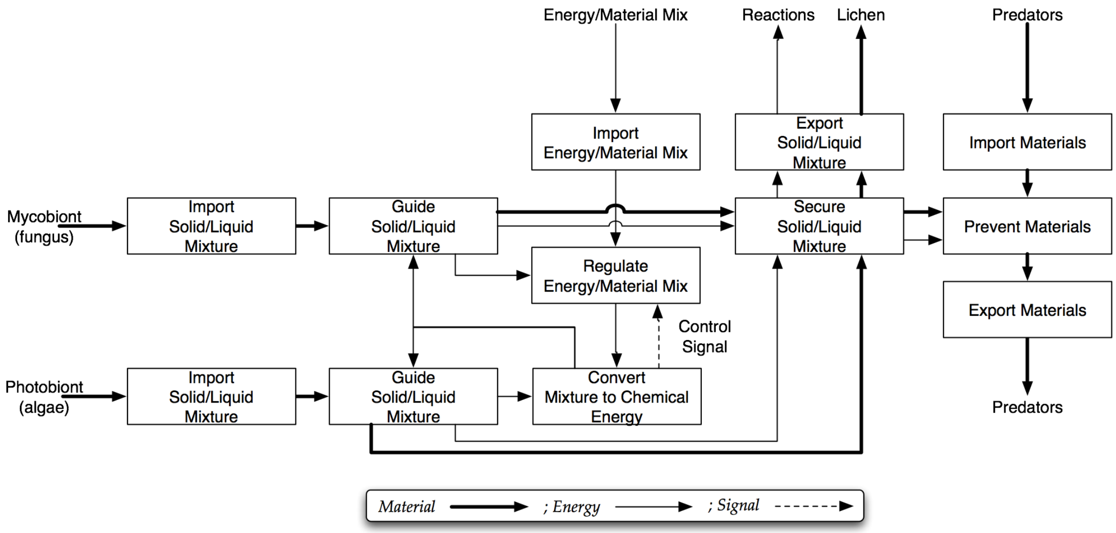

Figure 9.3. Lichen Biological Functional Model of Category Physiology and Scale Organism.

The functional model of Figure 9.4 represents two biological scales. The photobiont being *secured* by the mycobiont and the *prevention* of predators represents the organism scale portion of the mixed model. The *regulation* of water, nutrients, and sunlight, *conversion* of water, nutrients, and sunlight into chemical energy, *storage* and *supply* of chemical energy, *conversion* of chemical energy into a protective coating and *measurement* of chemical energy represent the organ scale portion of the mixed model. Functions within the striped shaded area are at the organ scale for the mycobiont and functions within the solid shaded area are at the organ scale for the photobiont. In the organ scale portion of the model sunlight is imported as electromagnetic energy. The conversion of sunlight, water and nutrients into chemical energy is fueled by previously stored chemical energy, which is supplied to both the photobiont, to power further carbohydrate production, and the the mycobiont, to allow protection.

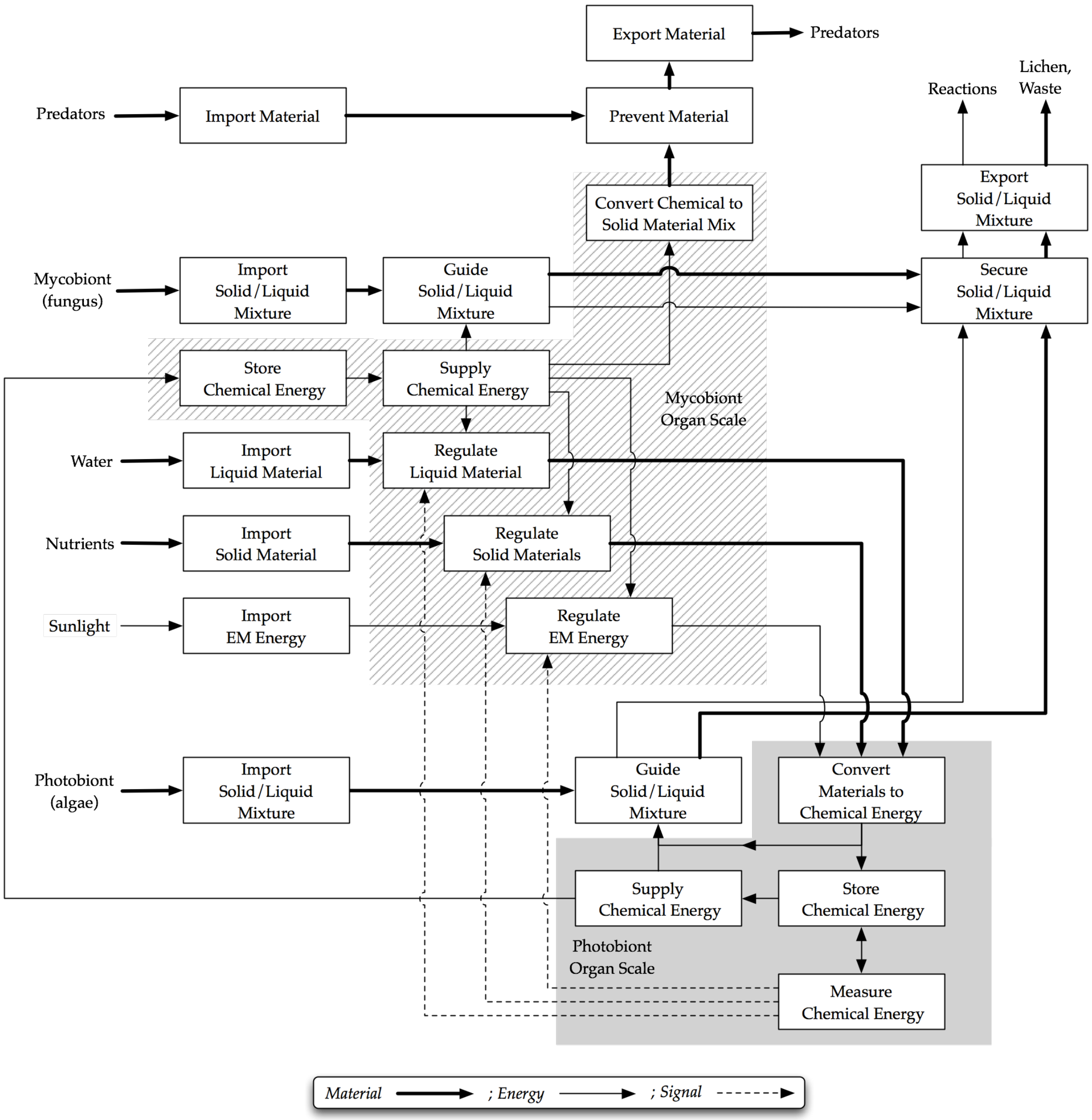

Figure 9.4. Lichen Biological Functional Model of Category Physiology and Mixed Scales Organism and Organ.

The water, nutrients and sunlight enter the striped shaded area (also labeled mycobiont organ scale) where they are regulated by communication from the photobiont. The mycobiont allows the regulated energy rich nutrients to pass through and enter the solid shaded area (also labeled photbiont organ scale) where a conversion creates carbohydrate sugars—modeled as chemical energy. Chemical energy—sugar—is one of the biological correspondent terms of the engineering-to-biology thesaurus for chemical energy. The photobiont stores a small portion of the carbohydrate sugars for reserve, uses a portion immediately to continue fueling the conversion process, and passes the remainder to the mycobiont. The mycobiont also creates a store of carbohydrate sugars; they are supplied as necessary for its survival. Store is used to represent the conservation of carbohydrate sugars for future consumption based on the biological correspondent term of conserve, but also the definition of the term store which is, "to accumulate a flow" (Hirtz et al. 2002). Supply is used to represent the use of stored carbohydrate sugars for consumption based on the thesaurus biological correspondent term of feed, but also the definition of the term supply which is, "to provide a flow from storage" (Hirtz et al. 2002).

The model in Figure 9.4 also investigates the basic instinctual action of protection at a deeper level of abstraction. Included at the mycobiont organ scale is the creation of the toxins that protect the lichen from predators. The mycobiont, which is the outer organism of lichen, excretes a coating that crystallizes on its surface to repel lurking predators. This coating can give off a smell, taste foul and can be toxic; this is dependent on the species of lichen (Nash 2008).

The biological functional model was validated through two discussions with a lichenologist, and comparison to existing model abstractions in biological texts and known flows. During the first meeting with the lichenologist of the Oregon State University Plant Pathology and Botany Department, an initial lichen functional model was presented (McCune 2010a). This initial meeting consisted of, first, both the researchers and the biologist arriving at common understanding of the nomenclature required to (1) describe a biological system as an engineered system and (2) describe a biological system to an engineer.

As a common understanding was reached, the lichenologist was able to explain how the initial model in Figure 9.5 misrepresents the lichen. The first problem was with the surface; it is now understood that lichen do not require a rigid surface to live. The second problem was with the symbiosis. The initial model in Figure 9.5 models the symbiosis more as a parasitic relationship where the mycobiont uses the photobiont for food in a one-way arrangement. The lichenologist explained how, our initial representation, while being correct based on the initial literature review used to generate the model, fails to capture the most recent advances and understanding in the field (Nash 2008), and that the symbiosis is a two-way arrangement where the mycobiont offers protection (both from predators and from excess sun light) to the photobiont. Following the discussion of the shortcomings of the model, the dialog focused on how the model could be improved. Figures 9.2, 9.3 and 9.4 represent the new models, created following the initial discussion with the lichenologist. These models were verified and approved during the second meeting (McCune 2010b). This validation further supports the suitability of the mixed scale and chosen category used to guide the generation of the functional model for answering the posed question.

It is important to note, that this initial model, was based on literature that the lichenologist considered outdated, and that many aspects of biology simply are not yet understood. So, similarly to performing a study of an engineering system, it is important to have the most current sources of information to guide the modeling process to ensure that the model represents the most current understanding of the strategy, behavior, physiology and morphology of the biological system in question.

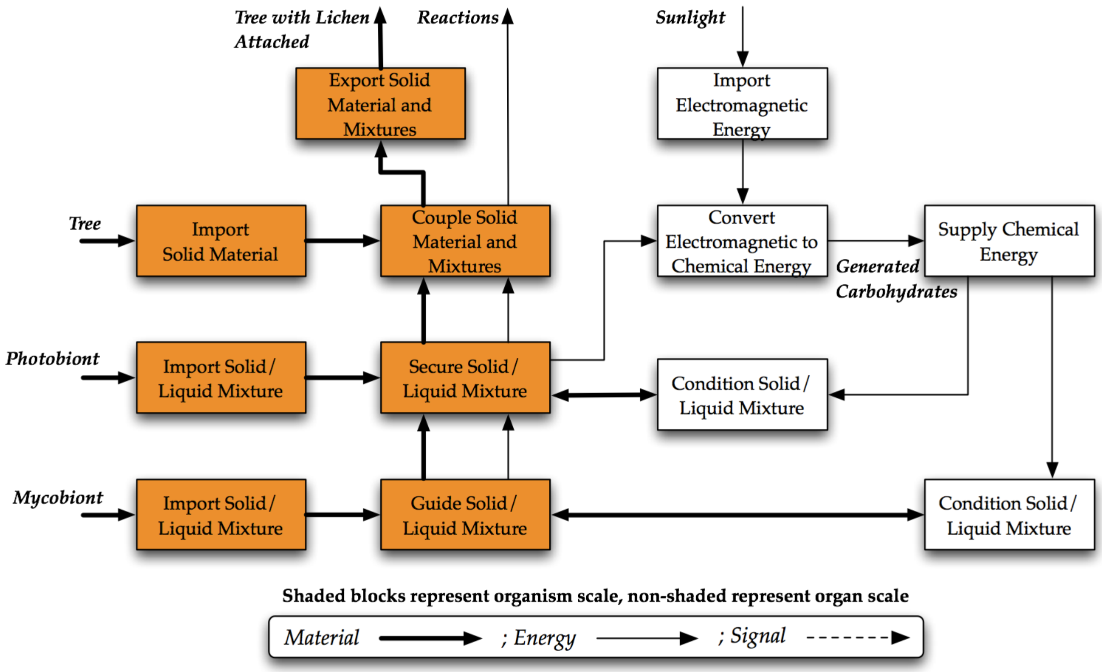

Figure 9.5. First Pass Lichen Biological Functional Model of Category Physiology and Mixed Scales Organism and Organ.

9.2.2 Query

Following Step 3 of the design methodology, the biological functional model of Figure 9.4 is used to query an engineering knowledge base. The Design Repository housed at Oregon State University is the engineering knowledge base for this case study. The tools used to access the knowledge base are the automated morphological matrix tool and the concept generator software, MEMIC, as described in Chapter 6. The biological functional model is first created in the FunctionCAD software, and is then exported as an adjacency matrix (a 2D matrix capturing the topology of the functional model) to MEMIC. MEMIC returned engineering components for half of the lichen function/flow pairs; for the remaining half of the function flow pairs, MEMIC returned an incompatibility error meaning that engineering systems were not known to solve the function-flow pairs in the same order as they occur in the biological system. To find solutions for these remaining functions the Design Repository was queried with the automated morphological matrix tool. The chosen engineered solutions have been substituted for each function/flow pair in the biological functional model and is provided in Figure 9.6. Components marked with an asterisk were not found directly from queries to the Design Repository. To identify these remaining components, functions were queried minus their flows or with a flow at the primary level using the Design Repository.

Sensors exist within the engineering knowledge base, however, they measure electromagnetic or electrical energy. By changing the flow of chemical energy to just energy, the query returned engineering solutions. In this case, the concept is not far along enough to determine if measurement will be of electrical, chemical or perhaps some other energy. Thus, the generic component of sensor was chosen to solve that function. Regulation of electromagnetic energy by a lens was found by following a similar query strategy as for the measure function. This time the function was changed to a higher level as searching by regulate energy resulted in too many solutions. Also, the solutions spanned fifteen types of energy, exponentially increasing the solution space. Iterating each match for a possible solution would be too time consuming. Searching by control magnitude electromagnetic energy resulted in only a few matches, of which, lens was one of them. This strategy not only saved time and effort, but narrowed the solutions to only one energy. The third function/flow pair that required an extra query step with the morphological matrix tool is the convert chemical energy to solid mixture material, the protective coating the lichen produces. Carbohydrate sugars that the lichen creates can also be considered a material and when querying the Design Repository by convert material to material, staying very high-level, the condenser was found to solve that function.

9.2.3 Make Connections

To develop an engineered solution from the components shown in Figure 9.6 a designer must make connections, but also keep in mind the scales that were chose for the functional model. While the model represents the symbiosis, it also contains two separate organisms to perform photosynthesis, securing and protection that comprise the symbiosis. The engineering component model of Figure 9.6 shows that connections drawn at the organism scale will involve the reservoir, housing, lens, cover and tubing, while the pump, valve, film, battery and sensors components are drawn at the organ scale. Knowing that the concept of converting sunlight into useable energy has been emulated in solar panels, the connection between photobiont to film to solar panel is established. Solar panels need rigidity and support, but when those are striped away, the part that actually converts light into electricity is a thick film. This knowledge assists with the connection between photobiont

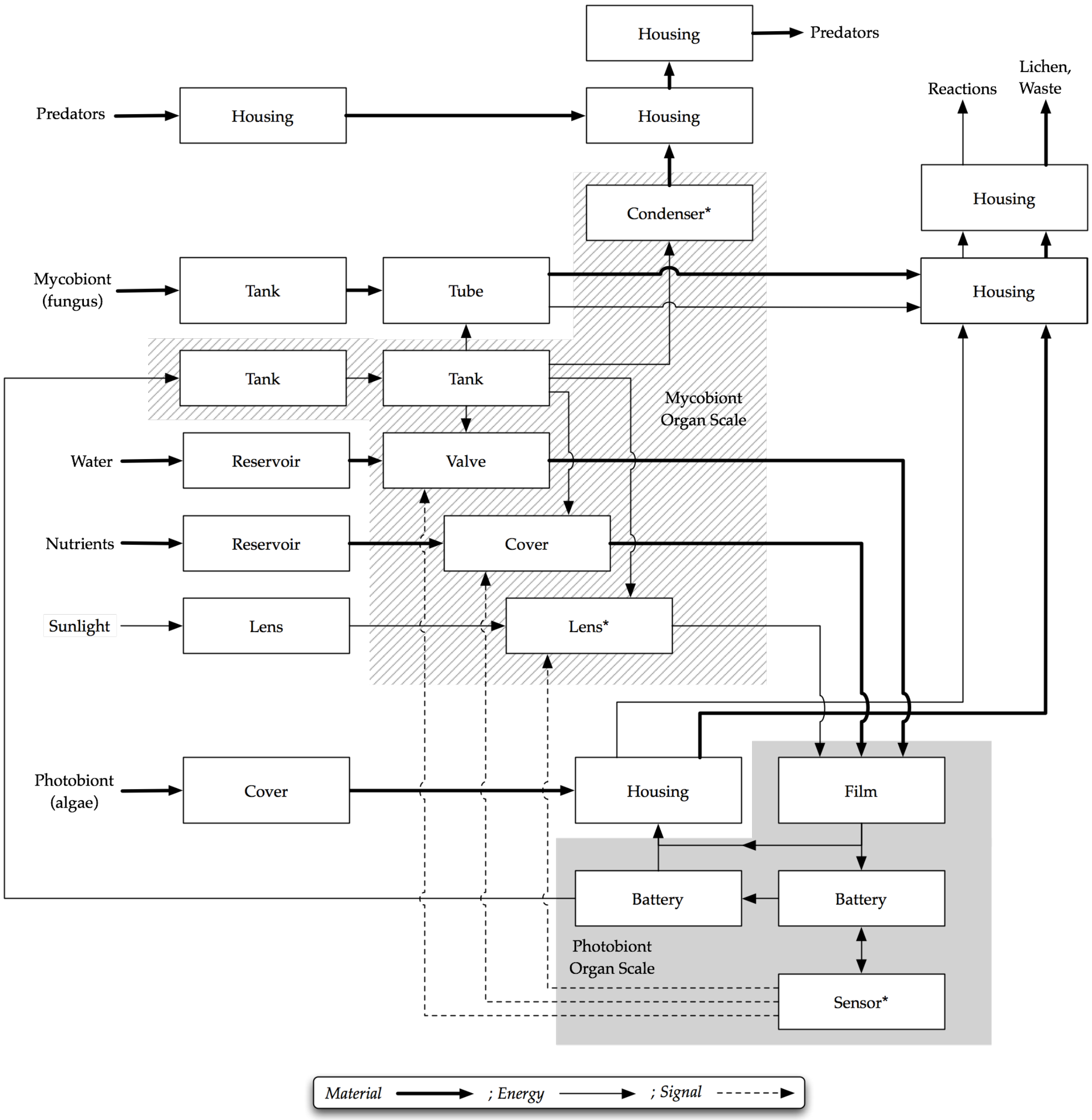

Figure 9.6. Lichen Biological Functional Model of Category Physiology and Mixed Scales Organism and Organ with Engineering Components.

and solar panel. Although the solar panel does not convert liquids or solids to useable energy, the aim is not to directly copy the natural system, but to facilitate connections between the domains. Continuing with the function/flow pairs that represent the photobiont organ scale the functions concerning storage and supply of chemical energy are also suitable for the storage and supply of electrical energy. Now that electrical energy has been decided, the senor should be chosen to monitor electrical energy and not chemical energy.

Examining the engineering components that represent the mycobiont organ scale reveals that most deal with liquids. The component relationships stand out, but do not immediately connect with an engineering system other than a tank of liquid with a valve and a cover. For the mycobiont, the though process must be expanded to achieve a meaningful connection. Recalling the morphology of lichen signifies that it could be helpful to consider that the imported liquid, solid and electromagnetic energy must first pass through the mycobiont. This viewpoint assists with the connection between mycobiont and two lenses and immersion lithography. The electromagnetic flow chain has two lenses in a row, which brings to mine immersion lithography. Immersion lithography is further confirmed as a connection to the mycobiont as the second lens is grouped with the components that deal with liquids. A connection between mycobiont and immersion lithography is established.

9.2.4 Create Concepts

With the connections established, it is up to the designer to now create a concept that utilizes the connections. For the lichen two connections were established, one with the photobiont and one with the mycobiont. When considering the engineering components in a similar structural relationship as lichen, the leap made is to an innovative solar thermal collection device. This is a symbiotic product where one device, the thermal collection portion, contains and protects a separate second device, the solar collection portion. A sketch of the conceptual design is given in Figure 9.7. The innovative device consists of a solar panel surrounded by a reservoir. The reservoir is filled with a liquid material that acts both as a thermal collection medium, a filter and as a lens directing solar energy to the panel. A pump cycles liquid from the reservoir into an exchange tank where thermal energy can be added or removed from the water keeping the surrounding liquid temperature optimal for the solar panel. Excess thermal energy removed from the liquid can be used to supplement a domestic hot water heating system. A battery stores electrical energy created by the solar panel; this power could be used to supplement a domestic power system but is also required to run the pumping system.

This concept has several components that are similar to existing solar thermal collection devices, which leads the feasibility of this concept. What makes it innovative is the configuration of the engineering components. Current devices do not use liquid as a lens to concentrate light, rather, a glass cover of the correct thickness is used. Drawing thermal energy away from a solar panel is a known method for increasing the efficiency of solar panels (Duffie and Beckman 1991). Lamson and Baur developed a solar thermal electric panel (STEP) system that performs heat exchange on the back side of the solar panel (Lamson and Baur 2008). The STEP system has an exchange tank, pumps, valves and sensors to monitor when the water needs to be cycled for maximum efficiency. The major difference between this concept and the STEP system is the placement of the liquid used for heat exchange, which was inspired by lichen. A prototype needs to be created to judge the reliability and manufacturability of the design. However, the concept is validated as it is similar to an existing design. Additionally, this case study further validates the systematic design method of Chapter 7.

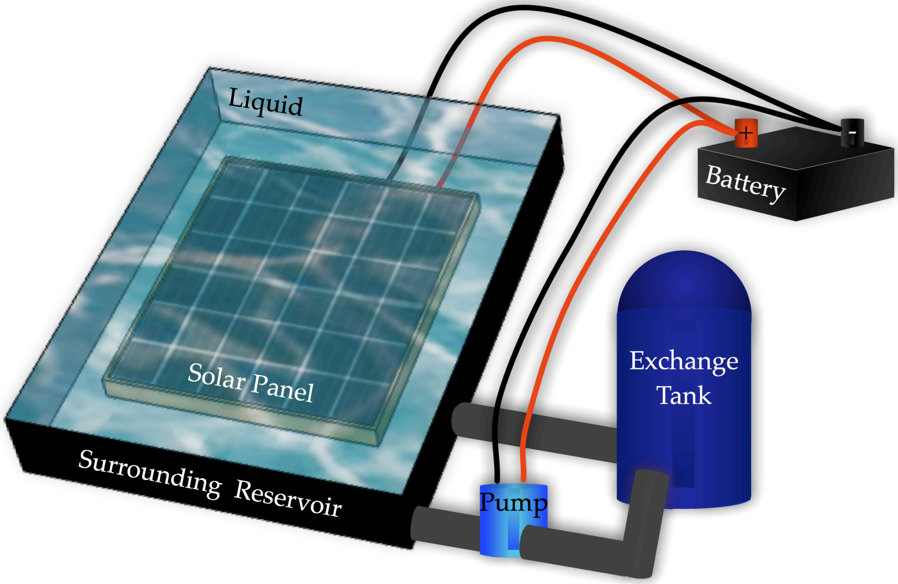

Figure 9.7. Conceptual Design Inspired by Lichen Model.

9.3 Summary

This chapter presented a case study following the solution-driven approach provided by the systematic biologically-inspired design method of Chapter 7. Following this approach, the biological system of lichen was investigated, which led to the design of an innovative solar thermal collection device. Thought processes, model iterations and connections formed that lead from lichen to solar thermal collection device were presented. As mentioned in Chapter 7, this solution can be fit to a problem or archived for future design reuse. In this case, an innovative solar thermal collection device is timely as alternative and renewable energy are hot topics right now. Pursuing this concept could offer a solution to some of the problems in our world today.

Not being an expert in the field of solar and thermal collection devices makes this discovery even more exciting. Once again, it has been shown that the designer using the systematic biologically-inspired design method does not need expert knowledge, but rather broad knowledge of many fields. The engineering knowledge base, the Design Repository, was a key factor in making the leap to the innovative design. The link between solar panel and photobiont are obvious, however, the link between mycobiont and immersion lithography is not. The same can be said for the supporting components of tank, pump, reservoir, housing, battery and cover. Although query strategies must be used from time to time, the knowledge contained in the repository supplements the designer's knowledge and causes one to consider solutions from different viewpoints. Using a knowledge base increases the chance for a designer to develop an innovative design. A biological functional model captures nature's approach to design from which a designer can learn or utilize to develop innovative designs. This case study proves it is possible.

CHAPTER 10 - CONCLUSIONS AND FUTURE WORK

10.1 Overview

A large part of the research that comprises this dissertation is exploratory. Creating a “sturdy” bridge between two dissimilar domains that will encourage designers to cross back and forth between the domains is an immense challenge. This dissertation sets the foundation for the function-based design bridge between engineering and biology. As more progress is made the bridge will move towards completion. This exploratory research shows promise and, like most bodies of research, is not complete. However, it does prove the stated hypothesis and meet the listed objectives. The greater impact to the field of engineering design and biomimicry is summarized in the conclusions section. Additional avenues for continued research to improve the tools and techniques of the framework, the design methodology and biomimetic sensors are covered in the future work section.

10.2 Conclusions

Biological systems operate in much the same way that engineered systems operate. Each part or organ in the overall system has defined physiology, morphology and behavior that can be studied. Physiology, morphology, behavior and strategy offer engineers a starting viewpoint for understanding interesting biological systems. From a design perspective, function is an advantageous viewpoint as it allows the problem to be broken down into smaller, easily solved portions and reduces fixation on a particular solution before alternatives have been explored. Function, then, provides a common ground between the domains, which is the foundation of this research. Following a methodical design approach from the viewpoint of functionality, it is possible to identify biological systems that solve engineering functions for conceptual engineering design. The approach is formalized in the systematic biologically-inspired design methodology of Chapter 7. Direct benefits from following the biologically-inspired design approach are the ability for engineers with a limited background in biology to interface with biological information, transform the biological information into an engineering context, formulate connections between the domains and perform biologically-inspired design.

Recall the stated objectives of this dissertation:

1. Identify relevant biological systems that solve a desired function.
2. Translate relevant biological information from a biological context into an engineering context.
3. Formalize a functional representation method that captures the biological functionality such that it can best be exploited by designers.
4. Investigate approaches to function-based concept generation utilizing biological information.
5. Formalize an overall method for systematic biologically-inspired, engineering design.
6. Apply the systematic method to demonstrate the design of an innovative product.

Every objective is met in this work. Objective 1 is met through the organized search strategy presented in Chapter 3. Objective 2 is met with the engineering-to-biology thesaurus presented in Chapter 4. The third objective is met through the biological functional modeling methodology presented in

Chapter 5. The fourth objective is met by the two conceptual design approaches of Chapter 6. Objective 5 is met through the systematic design methodology presented in Chapter 6. The final objective is addressed through the case studies of Chapters 8 and 9.

The formalized design methodology is the first function-based, systematic approach to biologically-inspired design. In the process of formulating the overall systematic design methodology, a framework of tools and techniques to support the method is developed. The individual parts of the framework offer assistance with the specific engineering design objectives of identify, translate, represent and conceptualize. In the larger design context, they coalesce to assist with systematic biologically-inspired design. The framework offers organization in the knowledge transfer process, thus addressing a major gap of biomimicry methods. Implications of the framework are beyond that of the biologically-inspired design method to the very core of biologically-inspired design. Together, the framework and systematic design method reduce the disconnect between biology and engineering and set the foundation for bridging the two domains.

The *key contributions* of this research extend beyond biological and biomimetic data archival in a design repository for future design reuse. The framework and systematic design method make fundamental contributions to engineering design theory. The organized search tool contributes by allowing an engineering designer to query a biological knowledge base with familiar keywords–engineering terms. The search strategy is designed specifically to work with non-engineering subject domain specific information. By searching with familiar keywords, the resultant matches can immediately be analyzed from the analogical reasoning mindset. Meaning connections can be formed between the abstracted problem to be solved and biological systems that perform the searched keyword. The solution space is augmented with solutions a designer normally would not have, thereby increasing the probability of an innovative design. Through integration with the engineering-to-biology thesaurus, a more accurate and detailed listing of biological systems is made available to a designer.

The engineering-to-biology thesaurus enables the mapping of synonymous biological and engineering terms. Rather than encompass all engineering terminology, the confined set of generalized engineering terms of the Functional Basis was chosen as an initial starting point. Using the Functional Basis as the thesaurus model allows translation of biological information into a more generalized context. Translated information is an abstraction of the true information, which can be used for a variety of design activities. Thus, the thesaurus contributes by encouraging collaboration between biologists and engineers and discovery of biologically-inspired engineering solutions. A key application is functional modeling of biological systems.

Biological functional models abstractly represent key biological information in an engineering context. Thus, the biological information is accessible to engineering designers with varying biological knowledge, but a common understanding of engineering design methods and lexicons. This research contributes a method for functionally representing biological systems with the Functional Basis. This method enables representation of multiple biological scales within a category, thus promoting multiple levels of abstractions and connections to engineering from a single biological system. The resultant models can be used with function-based design tools (e.g., an automated concept generator) or archived for future design reuse (i.e., design repository).

Concept generation methods and tools help stimulate designer creativity and encourage exploration of the solution space beyond an individual designer's knowledge and experience. Two techniques, problem-driven and solution-driven, assist concept generation with biological information. Where one approach follows traditional systematic design the other encourages exploration of curiosities. Systematic exploration of engineering analogs to biological systems is a key contribution of this work. Thus, adding systematic exploration to chance biological observation and inspiration.

The systematic design methodology for developing biologically-inspired solutions represents a new holistic design approach that integrates with existing design tools and methods. This method contributes by offering designers guidance for identifying opportunities for biologically-inspired design based on functional representations of biological systems. Validation of the method was demonstrated through application of the method to conceptual engineering design problems and exploration of curiosities. Case studies resulted in both concepts that embody existing technologies and innovative designs.

With regards to sensor design, this research challenged traditional engineering design theory and methodology which has been reserved for mechanical and electro-mechanical designs to also include purely electrical designs (e.g., sensors). Not only are sensor designs feasible, but the designs were also generated by a non-expert. Furthermore, this research motivates further exploration of biological sensing mechanisms.

The research within this dissertation has an immediate and *broad impact*. A novel impact of this work is the creation of the engineering-to-biology thesaurus. The thesaurus is a first of its kind and is envisioned to enable the engineering and biology communities to better collaborate, create, and discover. Furthermore, it facilitates many aspects of the systematic biologically-inspired design methodology. The systematic biologically-inspired design methodology enables engineers with a limited biological background to begin biomimetic design activities. The systematic design method also prompts a designer to consider a biological system from multiple viewpoints, which could inspire innovative ideas for multiple branches of engineering (i.e., electrical, mechanical, chemical, materials) from one biological system, that would otherwise be overlooked. Designers are supported by the framework from initial idea through concept generation. A key aspect of this work that gives it a broad impact is the immediate integration of the results with the Design Repository housed at Oregon State University that is available on the web. This Design Repository, though still in prototype form, has been used by undergraduate design classes at Oregon State University to assist in concept generation. Students will be exposed to biology as a source of ideas for engineered solutions. Both the biological systems of inspiration and the biomimetic solutions will be immediately available to students and the world as the research is performed.

The work here represents a significant contribution to the field of engineering design theory. It is a substantial contribution, and it sets the stage for future work in the biologically-inspired design area.

10.3 Future Work

The systematic design of biologically-inspired engineering solutions proves the hypothesis of this dissertation. However, in doing so it also uncovers areas where further work is needed. Brief discussions of those avenues for future work are provided in the following sections.

10.3.1 Organized Search Tool

Future work for the organized search tool software includes the incorporation of hyperlinks in the search results from noun listing to the collection of sentences and to detailed information and images. When a long list of collocated nouns is generated it becomes tedious to scroll back and forth from the noun (flow) of interest to the collection of sentences that contain the search verb (function). Interpretation of results could be sped up with the addition of hyperlinks. Also, hyperlinks to the section or complete chapter the sentence is contained in would assist with determining if a result is truly relevant. Not only would detailed biological information be available, but images as well. Visuals can stimulate designers in a different manner than text alone.

Further work for the computational concept generation technique, version 2 of the search software, involves implementation of the algorithm and testing of the code. Also, the software interface needs to be tested to optimize the presentation of the biological text excerpts. Another possible avenue for this design tool is developing a web-based version to increase accessibility and ease of use. This version would also allow results to be saved; however, the searchable documents would be predetermined.

The organized verb-noun search algorithm was presented here utilizing information from biology; however, this retrieval tool can be used for mapping any non-engineering subject to engineering through functionality. It would be interesting to look at how law, history or even psychology maps to engineering, as the generated nouns are subject domain specific.

To broaden the solution space beyond a corpus and the writing style of a single author, the organized search tool software could be upgraded to also interface with the internet. This would allow multiple domains and disciplines to be examined for inspiration based on functional language. And would reduce the need to obtain copyright permission or a searchable copy of a corpus. However, the amount of information would likely be immense and an additional filtering algorithm would need to be added.

10.3.2 Engineering-to-Biology Thesaurus

Future work for improving the engineering-to-biology thesaurus includes examining potential terms through clustering and analyzing typical biology glossary or dictionary terms. While collocated terms provide an indication for macrorelevant terms, clustering analysis could be utilized to find less obvious, but equally important, biological terms for thesaurus population. Other sources for terms are the glossary of a collegiate entry-level biological textbook and a biology dictionary. Both sources would provide significant terms and a handy description that would assist with placement in the thesaurus. Additionally, biological corpora that focus on a topic of interest (i.e., insects, fungi) should be analyzed for relevant biological terms that an introductory text may not include.

Further work also includes adopting a hierarchy for the mapped biological terms. Many of the repeated biological flows currently in the thesaurus indicate that, depending on the aspect, the biological flow has different scales. For example, an organ is a composite of tissues and tissue is a composite of cells. While organ is mapped under multiple Functional Basis terms it may be unclear why it is under composite. Just as scale is helpful for biological functional modeling, it could also help make the terminology mappings between the domains more clear.

10.3.3 Biological Functional Modeling Method

The biological functional modeling methodology successfully demonstrated the use of functional representation and abstraction to describe biological functionality; however, the models are not hierarchal. Future investigation of hierarchal biological system representation using the Function Design Framework (FDF) (Nagel et al. 2008a) could allow for the creation of more accurate functional models through the inclusion of environment and process representations. Environment states could explain the triggers to certain behavior and process models would better capture behavior, while preserving physiological information. Also, modeling of biological category morphology needs to be investigated. Currently, morphology inspiration is extracted via images and textual descriptions rather than functional models. Black box functionality can capture the overall function of a biological system's morphology, but it falls short on capturing just morphological information.

Further work for the biological functional modeling methodology is to to populate a knowledge basis, as well as, perform large-scale design studies with students in engineering design courses and/or professionals that are familiar with functional modeling. It is expected that studies will identify weaknesses of the method that need improvement. As the method is used, the resulting biological functional model information needs to be uploaded to the Design Repository housed at Oregon State University. This would facilitate educational activities and the formulation of connections between the domains that lead to biologically-inspired solutions.

10.3.4 Systematic Design Methodology

Future work includes defining tasks for each step of the methodology, developing a set of connection examples to provide novices with a starting point as well as performing design studies. Design studies with students in engineering design courses and/or professionals that are familiar with functional modeling will identify weaknesses of the method that need improvement. In a similar vein, defining individual tasks for each step of the method could prevent common mistakes from occurring and also assist novices. Making connections between the engineering and biological domains is not always easy, therefore a collection of connection examples would assist novices with getting started with this method.

10.3.5 Biomimetic Sensors

Focusing on biomimetic sensor development offers a unique application of biological system information. Traditional sensor schemes involve few sensing devices and require a significant amount of computing power to handle the data created. Nature demonstrates robust sensing with minimal processing. The subject of natural sensing provides many exemplary designs for testing the design tools and techniques. Preliminary results have revealed sensor designs that are interesting and functional, without requiring expert-level knowledge, but rather broad knowledge of many fields. More biological sensing systems need to be investigated using the framework presented in this research to better understand how minimal processing is achieved.

10.3.6 Educational Applications

Another avenue for this research is engineering education. Future work regarding educational applications includes developing biomimicry course modules, analogical reasoning exercises, and use of the framework and systematic design method in the classroom. Course modules would showcase biologically-inspired designs and how engineering design methods are used to achieve the design. Also, analysis of a biological system from an engineering point of view would be conveyed to encourage the students to take inspiration during problem solving from domains other than engineering. Analogical reasoning exercises would challenge students to identify similarities between biology and engineering. The second version of the search tool software could be used to assist engineering students with discovering the connections between biology and engineering. Utilization of the framework and systematic design method in the classroom would encourage students to consider everything around them as potential sources of inspiration, thereby increasing overall design creativity.

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VITA

Jacquelyn Kay (Stroble) Nagel, daughter of Antoinette Yadrich and Ricky E. Stroble, was born on August 22, 1982 in Independence, Kansas. She graduated grade school and 11th in her high school class in Kansas City, Kansas. After high school, Jacquelyn attended Kansas City Kansas Community College on a Phi Theta Kappa Presidential Scholarship until 2002, graduating Magna Cum Laude with an A.S. in Pre-Engineering. Jacquelyn then transferred to the University of Missouri-Rolla to pursue a B.S. in Electrical Engineering where she graduated Magna Cum Laude. She continued on to receive her M.S. in Manufacturing Engineering form UMR in May of 2007. With a new interest in engineering design, Jacquelyn joined the Design Engineering Lab to perform doctoral research in the area of biologically-inspired design. In the summer of 2009 she transferred from UMR to OSU following her advisor and in November of 2009, she married Robert L. Nagel.

Jacquelyn has obtained five internships and co-ops during her collegiate career and has gained significant teaching experience. She taught the Electrical Engineering Factory Automation Lab for three years and one semester of the Factory Automation Lectured. Jacquelyn is also an active member of multiple honors and professional societies. Among her achievements, she received Honorable Mention for the National Eta Kappa Nu Alton B. Zerby and Carl T. Koerner Outstanding Senior ECE Student Award in 2005, for demonstrating outstanding scholastic excellence, high moral character and exemplary service to classmates, university, and community.