Function-Based Biology Inspired Concept Generation

J.K. Stroble Nagel[1], R.B. Stone[1] and D.A. McAdams[2]
[1]*Oregon State University;* [2]*Texas A&M University*
USA

1. Introduction

Animals, plants, bacteria and other forms of life that have been in existence for millions of years have continuously competed to best utilize the resources within their environment. Natural designs are simple, functional, and remarkably elegant. Thus, nature provides exemplary blueprints for innovative designs. Engineering design is an activity that involves meeting needs, creating function and providing the prerequisites for the physical realization of solution ideas (Pahl & Beitz 1996; Otto & Wood 2001; Ulrich & Eppinger 2004). Engineering, as a whole, is about solving technical problems by applying scientific and engineering knowledge (Pahl & Beitz 1996; Dowlen & Atherton 2005). Traditionally, the scientific knowledge of engineering is thought of as chemistry or physics, however, biology is a great source for innovative design inspiration. By examining the structure, function, growth, origin, evolution, and distribution of living entities, biology contributes a whole different set of tools and ideas that a design engineer wouldn't otherwise have.

Biology has greatly influenced engineering. The intriguing and awesome achievements of the natural world have inspired engineering breakthroughs that many take for granted, such as airplanes, pacemakers and velcro. One cannot simply dismiss engineering breakthroughs utilizing biological organisms or phenomena as chance occurrences. Several researchers were aware of this trend in the early 20th century (Schmitt 1969; Nachtigall 1989), but it was not until later that century that the formalized field of Biomimetics or Biomimicry came about. Biomimetics is devoted to studying nature's best ideas to solve human problems through mimicry of the natural designs and processes (Benyus 1997). It is evident that mimicking biological designs or using them for inspiration leads to leaps in innovation (e.g., Flapping wing micro air vehicles, self-cooling buildings, self-cleaning glass, antibiotics that repel bacteria without creating resistance).

This research focuses on making the novel designs of the natural world accessible to engineering designers through functionally representing biological systems with systematic design techniques. Functional models are the chosen method of representation, which provide a designer a system level abstraction, core functionality and individual functionalities present within the biological system. Therefore, the functional models translate the natural designs into an engineering context, which is useful for the conceptualization of biology inspired engineering designs. The biological system information is presented to engineering designers with varying biological knowledge, but a common understanding of engineering design methods. This chapter will demonstrate that creative and novel engineering designs result from mimicking what is found in the natural world.

Although most biology inspired designs, as mentioned previously, are mechanical, structural or material, this research focuses on how biological organisms sense external stimuli for the use of novel sensor conceptualization. Sequences of chemical reactions and cellular signals during natural sensing are investigated and ported over to the engineering domain using the Functional Basis lexicon (Hirtz et al. 2002) and functional models. In the following sections, related work of biology in design, natural sensing from the biological perspective, a general methodology for functionally modeling biological systems, two conceptualization approaches and two examples are covered. The discussion and conclusion sections explain how all of the pieces fit together in the larger design context to assist with biology inspired, engineering design. For the sake of philosophical argument, it is assumed that all the biological organisms and systems in this study have intended functionality, as demonstrated through functional models.

2. Related Work

Initial problem solving by inspiration from nature may have happened by chance or through dedicated study of a specific biological organism such as a gecko. However, more recently engineering design researchers have created methods for transferring biological phenomenon to the engineering domain. Their goal is to create generalized biomimetic methods, knowledge, and tools such that biomimicry can be broadly practiced in engineering design. A short list of prominent research in biologically inspired products, theories, and design processes is: (Brebbia et al. 2002; Brebbia & Collins 2004; Chakrabarti et al. 2005; Bar-Cohen 2006; Brebbia & Technology 2006; Vincent et al. 2006; Chiu & Shu 2007).

Research utilizing biological system information with systematic design techniques has recently demonstrated analogy identification, imitation and design inspiration. The work of Nagel et al. (2008) 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. Rather than start with a design need, biological systems were modeled first as a black box and functional model, and from those biological system models, functionally analogous, engineered systems were identified. Analogies between the biological and engineered systems are demonstrated through a combined morphological matrix pairing functionalities and solutions. Shu et. al (2007) explored combining functional modeling and biomimetic design to facilitate automated concept generation. Three biological strategies were extracted from natural-language descriptions of biological phenomena and functionally modeled. The single phenomenon of abscission was shown to provide solutions for different engineering problems. Additional insight was provided to an engineering designer for use during the concept generation phase than with biomimetic design alone.

In a similar vein, Stroble et. al (2008) investigated functional modeling of natural sensing for the use of conceptual biomimetic sensor design. Functional models of how an organism within the Animalia or Plantae Biological Kingdoms takes in, translates and reacts to a stimulus were created at multiple biological levels. These models were entered into a design repository for archival and for use with existing automated concept generation techniques (Bryant et al. 2005; Bohm et al. 2008). Wilson and Rosen (2007) explored reverse engineering of biological systems for knowledge transfer. Their approach is comprised of seven steps that result in idea generation. Like other biomimetic engineering design methods, the biological system must be functionally abstracted or decomposed into physical and functional parts. A behavioral model and truth table depicting system functionality allows the designer to describe the biological system with domain-independent terms to allow for the transfer of general design principles.

The research presented in this chapter advances functional modeling of biological systems with the Functional Basis (Hirtz et al. 2002) and offers a general method for functionally representing biological systems through systematic design techniques. Traditionally, systematic design techniques have been utilized for the design of mechanical or electro-mechanical products. This treatment of engineering design theory tests the boundaries of systematic techniques to develop electrical products.

3. Background

This section provides terms used throughout this chapter that are specific to this research, and abbreviated background information about systematic design methods and biological sensing at the Kingdom level. The following sections are provided to educate the reader and support the motivation for this research.

3.1 Nomenclature

- Biomimicry - a design discipline devoted to the study and imitation of nature's methods, mechanisms, and processes to solve human problems. Also referred to as biology inspired design.
- Biological organism – a biological life form that is observed to exist.
- Biological system – any biological situation, organism, organism sub-system or portion of an organism that is observed to exist or happen (e.g., Bacteria, sensing, insect compound vision, DNA, and human heart).
- Functional Basis - a well-defined modeling language comprised of function and flow sets at the class, secondary, tertiary levels and correspondent terms.
- Functional model - 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.
- Flow – refers to the material, signal or energy that travels through the sub-functions of a system.
- Function – refers to an action being carried out on a flow to transform it from an input state to a desired output state.

3.2 Systematic Design Methods

Design requirements and specifications set by a customer, internal or external, influence the product design process by providing material, economic and aesthetic constraints on the final design. In efforts to achieve the customer's needs without compromising function or form, function based design methodologies have been researched, developed and evolved over the years. Most notable is the systematic approach of Pahl and Beitz (1996). Since the introduction of function structures, numerous functional modeling techniques, product decomposition techniques and function taxonomies have been proposed (Pahl & Beitz 1996; Stone & Wood 2000; Otto & Wood 2001; Ulrich & Eppinger 2004). The original list of five general functions and three types of flows developed by Pahl and Beitz (1984) were further evolved by Stone and Wood (2000) into a well-defined modeling language entitled the Functional Basis. The Functional Basis is comprised of function and flow sets, with definitions, correspondent terms and examples. Hirtz, et al. (2002) later reconciled the Functional Basis and NIST developed modeling taxonomy into its most current set of terms. The reconciled Functional Basis provides designers with sets of domain independent terms for developing consistent, hierarchical functional models, which describe the core functionality of products and systems.

3.3 Natural Sensing

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 detecting the stimulus, which mimics, directly or analogically, 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 nature's elegance in engineering design. This section covers fundamental knowledge of the biological processes involved during natural sensing at multiple biological levels - termed scales, in the Animalia and Plantea Kingdoms.

Natural sensing occurs by stimuli interacting with a biological system, 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 are of most interest to the engineering community for mimicry, are grouped into the class known as extroreceptors (Sperelakis 1998). The three classes of receptors are (Aidley 1998; Sperelakis 1998):

- Proprioceptors – Internal – vestibular, muscular, etc.
- Interoceptors – Internal without conscious perception – blood pressure, oxygen tension, etc
- Extroreceptors – External – chemoreceptors, electroreceptors, mechanorecptors, magnetoreceptors, photoreceptors, and thermorecpetors.

Proprioceptors and interoceptors are excellent biological sensing areas to study for developing medical assistive technologies, however, they are not investigated in this research. The receptors of interest are within the six families under the class of extroreceptors. 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 that result in chemical cellular signals (Spudich & Satir 1991). For more detailed information about natural sensing than provided in the following subsections and how it could be utilized for engineering design, consult Barth et al. (2003) and Stroble et al. (2009).

3.3.1 Animalia Kingdom

Biological organisms of the Animalia Kingdom are multi-cellular, eukaryotic organisms capable of cognitive tasks (Campbell & 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 - the external stimuli energy triggers a cascade of messengers which control ion channels.

Transduction in this Kingdom is a quick process that happens within 10μs - 200ms per stimulus (Aidley 1998). During transduction, a sequence of four events occur as shown in Table 1, which are uniform across the six receptor families (Sperelakis 1998). 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 navigational tasks.

3.3.2 Plantae Kingdom

The Plantae Kingdom simply refers to multi-cellular, eukaryotic organisms that obtain nutrition by photosynthesis (Campbell & Reece 2003). Transduction in this Kingdom 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 - the external stimuli energy triggers a cascade of messengers which control ion channels (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 as shown in Table 1, which are uniform across the six receptor families (Sperelakis 1998).

Photo, mechano, chemo, magneto and thermoreceptors, in that order, are the dominant receptors in organisms of the Plantae Kingdom. 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 & Satir 1991).

Transduction Sequence	Animalia Kingdom	Plantae Kingdom
Detection	Protein binding and signal propagation about receptor cell	Protein binding and signal propagation about receptor cell
Amplification	Cascade of intracellular chemical signals	Cascade of intracellular chemical signals
Discrimination	Modulation of chemical signals into an electrical code sent to the nervous system	N/A
Adaptation	Over time, a prolonged stimulus has less of an effect	Change in turgor pressure or chloroplast orientation

Table 1. Transduction sequence for two biological Kingdoms

4. Modeling Biology

Representing the world in terms of its function (i.e., what the world does) as opposed to its form (i.e., what comprises the world) is commonly used to abstract problems in engineering design. Functional representation enables a thorough understanding of the requirements while decreasing the tendency of designers to fixate on some particular physical solution for a problem. When viewed functionally, biological systems operate in much the same way that engineered systems operate (French 1994). Each part or piece in an overall biological system has an intended function. Function, therefore, may be utilized as the link to connect natural and engineering domains to identify analogies. Functional representation of biological systems has the potential to provide several advantages for engineering design:

- Systematic approach for establishing and representing functionality;
- functionality, morphology 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.

4.1 Mapping Biology to Function

Representing biological functionally using the lexicon of the Functional Basis allows biological solutions to be stored in an engineering design repository and utilized for concept generation. These biological solutions can then be recalled and adapted to engineered systems. However, modeling biological systems is not as straightforward as modeling engineered systems. One cannot easily take apart a biological system, examine the parts and associate function as one would an engineered system. Rather, the designer must rely on biological literature or biologists for detailed information about the desired system. To facilitate biological functional modeling, an engineering-to-biology thesaurus (Stroble et al. 2009) mapping biological correspondent terms to the Functional Basis is employed.

Our approach to modeling biology with the Functional Basis aims to accurately reflect the material, signal, or energy flows carrying out biological system functions. For example, the Functional Basis flow set lists fifteen different forms of energy, of which biological energy is included. However, since labeling all forms of energy that flow through an organism *biological energy* would not be descriptive enough for engineering designers to relate, create and utilize analogies, therefore equivalent engineering energies are identified to accurately describe functionality of a biological system.

Consider again natural sensing as the biological system to illustrate the mapping of biological terminology to the Functional Basis. Chemoreception of the Animalia Kingdom will be the focus. Mapping terms is one of the early steps leading to a biological functional model; however, a designer first needs to clearly define the research goal. 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 system. Consider the following question for natural sensing: How does a biological organism of the Animalia Kingdom take in, interpret and react to an external chemical stimulus? Table 2 lists the flows that aid in answering the research question and how they can be represented using the Functional Basis.

Biological Information	Functional Basis Flow
Protein	Solid liquid mixture material
Receptor cell	Solid liquid mixture material
2nd Messenger	Solid solid mixture material
Chemical stimulus	Chemical energy
Signal propagation about receptor cell	Chemical energy
Cascade of *intracellular chemical signals*	Chemical energy
Modulation of *chemical signals* into an electrical code	Electrical energy

Table 2. Relationship between sensing and Functional Basis terms (Hirtz et al. 2002)

4.2 Defining Mimicry Categories

Mimicking a biological system for the creation of biology inspired technology happens in multiple ways. Traditionally, biomimetic designs have tended to mimic the observable aspects of biological systems, such as how the system gathers or transports food and liquid, without considering mimicry boundaries. It was observed, however, that functional analogies occurring from a strategic or process perspective tend to be less obvious and require more detailed information about the biological system (Nagel et al. 2008). To aid with identifying potential mimicry aspects of a biological system a set of mimicry categories is established, which are: function (principle), morphology, strategy (behavior), manufacture, or any combination of these. The definitions of the mimicry categories with regards to biological systems are:

- Function: the fundamental principle, quality or attribute of a biological system.
- Morphology: the form of a living system, and the associations amongst an system's structures.
- Strategy: the reaction of a biological system in response to a particular situation or stimulus; its behavior.
- Manufacture: the production of something by a biological system.

These mimicry categories aid the designer with defining a boundary when developing a functional model. It is very easy to overstep the scope of the functional model when modeling a biological system. In addition to answering a research question related to the biological system, the biological functional model must also comply with a chosen biological scale (described in Section 4.3).

Reconsider natural sensing and the research question posed in Section 4.1. Understanding how an organism of the Animalia Kingdom takes in and interprets an external chemical stimulus requires knowledge of the principal functionalities of cellular communication, transduction and the primary energy an organism creates during transduction. One could argue that this also includes the category of strategy because the question considers the reaction to an external stimulus. However, the functional model would also need to include states for reactions of fear, surprise, neutral and no reaction. Natural sensing involves transduction of a stimulus and cellular communication, which always results in a cellular reaction; it is not the behavior of the system that is in question. Once the energy is released from the system (e.g., propulsion or movement) a behavior can be observed. Therefore, consider that the functional model boundary set for natural sensing of a chemical stimulus is the category of *function*.

4.3 Identifying Biological Scales

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. Comparison of biological terms to Functional Basis terms at deeper, more defined levels is time consuming as each part of a biological system has a unique way of interacting with the world around it, thus terminology becomes a problem. Any desired functional model level can be achieved with enough effort and resources; however the questions become, where can inspiration be most readily achieved, and what scales must be modeled to best capture this biological information to achieve inspiration?

To define the level of biological information required for a functional model, the biological scale utilized in multi-scale biological computational models is employed. A biological computational model ranges from atomic level to population, and has the following order: atomic, molecular, molecular complexes, sub-cellular, cellular, multi-cell systems, tissue, organ, multi-organ systems, organism, population and behavior (White et al. 2009). This scale can be utilized for functional representation of biological systems, allowing engineers to clearly define the level of a biological model. Although the biological scale can be viewed as a constraint on the model, it is also a creative analogical reasoning challenge. Analogies from the same biological system can be derived at more than one scale. This has been demonstrated by (Shu et al. 2007). Advantageous starting points are the cellular, organ and organism biological scales, which are readily defined in biological literature.

When generating a biological functional model, the biological scale is often constrained to a single level (i.e., the model contains only elements from the organ level). Generating models constrained by 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. It is important when modeling mixed, biological scale models, to remember that any final concepts derived from analogies between natural and engineered systems will also be of mixed scale. This concept of mixed model analogies was demonstrated by the lichen example in (Nagel et al. 2010), which inspired symbiotic electronic devices.

Biological models at a very low level (i.e., molecular, sub-cellular) are not always helpful because they can provide too much detail, which results in a number of engineering components that do not work together. The converse can be said about biological models at a very high level (i.e., organism). A high level functional model may not be descriptive enough for concept generation, or may not convey the innovative principle of the biological system. However, the functional model level of fidelity is at the discretion of the designer. It is important when developing functional representations of biological systems to not mix information at one scale with information at another, unless a mixed model desired (the same could be said for an engineering system).

The functional model of Animalia chemoreception can best be captured with a model at the cellular biological scale, due to the cellular communication aspect of natural sensing. Modeling at the organ level would convey that a stimulus is converted and a reaction is the result. This result is not descriptive enough to utilize for concept generation of novel sensor technology. However, before a functional model is created, a black box representation is developed to abstract the system in question. Realizing that sensing occurs by transduction, which involves interpretation of a stimulus, the black box model of the system is described as detect (i.e., to discover information about a flow) (Hirtz et al. 2002). The flows, identified in Section 4.1 include the chemical stimulus and the electrical response as the energies, and multiple mixture materials. This black box model is provided in Figure 1.

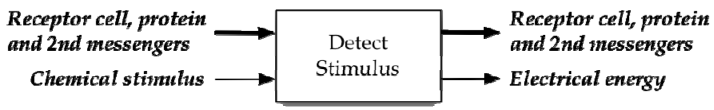

Fig. 1. Black box model of natural sensing

4.4 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 formalized. The methodology offers a designer direction when creating a biological functional model and provides empirical guidelines to improve model accuracy. The methodology is as follows:

1. Identify a good reference (e.g., biology text book) for the biological system of interest.
2. Read the overview of the biological system to understand the core functionality of the system.

- Make note of materials, energies and signals utilized while reading about the biological system. Refer to the engineering-to-biology thesaurus for guidance on how biological flows relate to flows found in engineered systems.

3. Define the research question the functional model aims to answer.
4. Define the category of the functional model.
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 modeling language.
   - 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 modeling language within the bounds set by the research question, biological category and 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).
   - Utilize a software program that allows quick rearrangement of blocks to make this process quicker (i.e. FunctionCAD (Nagel et al. 2009), Omni Group's OmniGraffle, and Microsoft's Visio).
7. Double-check and/or validate (e.g., have a biologist review model hierarchies) the functional model against the research question, biological category and scale, 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 & Reece 2003).

In this section, the chemical sensing example developed through Sections 4.1-4.3 is continued. Previously, Steps 1 through 5 were developed by investigating the sensing functions, the flows required, the biological system scale and category. Now following Step 6, the functional model, shown in Figure 2, is decomposed from the black box (Figure 1). The functional principles of cellular communication and transduction, which perform the natural sensing sequence of perceive, transduce and respond are depicted within Figure 2. Perceive and respond are represented as sense and actuate, respectively. The functions of detect, change, process and condition are what comprise transduce, the organ level function of convert. As one can see, the number of material and energy interactions at the cellular level can become complex. For comparison, the organ level functional model of chemical sensing is provided in Figure 3.

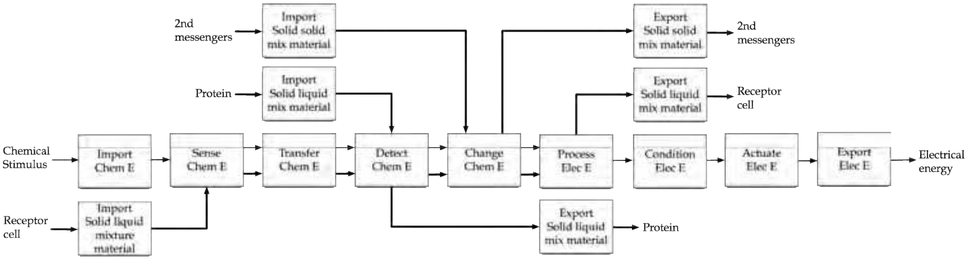

Fig. 2. Functional model of chemical sensing at the cellular scale

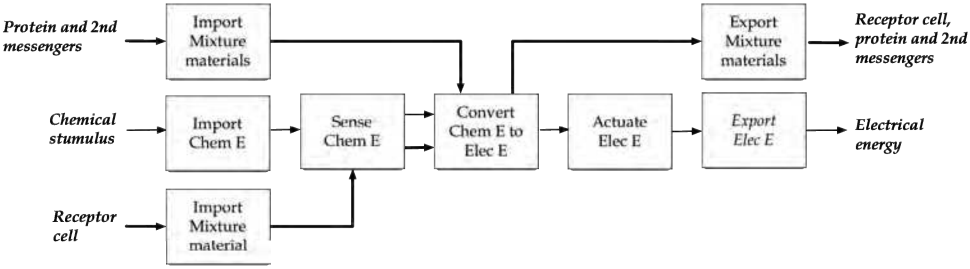

Fig. 3. Functional model of chemical sensing at the organ scale

The detailed biological events occurring during chemoreception, recognition of a taste or smell, by an organism of the Animalia Kingdom are provided in Table 3. Table 3 demonstrates in list format the Functional Basis terms that should be used for creating functional models at a sub-cellular scale for chemical sensing; also allowing one to comprehend the similarities between the two domains. The final action of the sensing sequence, respond, is described in the model as the function actuate. This term is preferred to describe response at a general level because the resultant electrical energy from sensing, once processed and conditioned, will be directed to the portion of the system that elicits the response. However, at a deeper level the exact response can be chosen. Possible function term choices are: regulate, change, guide, indicate, stop, position or inhibit.

A biologist of the Biology department at Missouri University of Science and Technology validated the biological functional models of chemoreception and the information in Table 3. However, a brief analysis of existing model abstractions and known flows, and the model's ability to answer to the designated research question is performed. The functionality in question is how chemoreception occurs within an organism of the Animalia Kingdom. By capturing perceive, transduce and respond, the functional model can be abstracted to—a chemical stimulus enters the organism boundary, which is translated by the receptor cells and changed into an electrical energy to trigger a response. At the black box level the chemical sense is modeled as having the function of detect. To discover information about a flow (stimulus) is a natural occurrence during chemical sensing. It is evident that both abstractions support the initial research question, thereby supporting the validity of the model. 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 (Section 4.1) have been satisfied. It is therefore concluded that the biological functional model is valid.

Biological Term		Engineering Term	
Action	*Description of events the action is comprised of....*	Functional Basis Term	
Perceive	Chemical stimulus occurs	Sense	Import
	First signal propagation about receptor cell		Sense
	Second signal propagation about receptor cell		Transfer
Detect	Receptor cell transforms external stimulus into a biological stimulus of the same type	Detect	Detect
Amplify	Fluctuation of second messengers for a chemical cascade	Change	Increment, Decrement
	Ion channels open or close for Na+ or K+		Actuate
	Cell membrane depolarizes		Change
Discriminate	Change electrical signal into a frequency	Process	Change
	Send frequency to brain		Transmit
	Recognize chemical stimulus		Process
Adapt	Adapt to prolonged chemical stimulus	Condition	Condition
Respond	Electrical energy produced by the chemical reaction, it is based on the stimulus	Actuate	Actuate, regulate, stop, etc.
	Reaction is now external		Export

Table 3. Animalia chemoreception biological and engineering terms

5. Concept Generation

Function-based automated concept generation may be extended in three ways with the addition of biological information. The typical approach would generate functional models based on customer needs. Then automated concept generator software, such as MEMIC (Bryant et al. 2005), would be used with the Design Repository (2009) to identify potential solutions for each component. This approach, as well as the three extensions that can lead to biological inspiration, are illustrated with Figure 4. The three new approaches utilize either biological information stored in the Design Repository or biological information modeled functionally to focus queries on analogous engineered solutions. The first approach, shown as a dashed line in Figure 4, uses a functional model developed from a biological system (discussed in Section 4) to discover corresponding engineering components to mimic the functionality of the biological system. The second approach, shown as a solid line in Figure 4, uses a conceptual functional model developed from customer needs and constraints to discover which biological components currently stored in a design repository inspire functional solutions to fill engineering requirements. The third approach represents a hybrid of the two prior approaches. In this third hybrid approach, shown as a double line in Figure 4, a biological system is modeled functionally and is used to discover other analogous biological systems priorly stored in a design repository. These analogous biological systems can then be used by the designer to inspire novel engineered solutions for each function. In this chapter the first two approaches (shown as either a dashed or solid line in Figure 4) are discussed further.

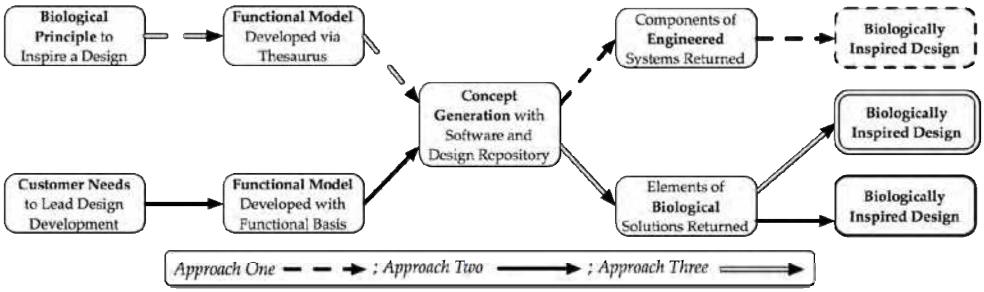

Fig. 4. Summary of concept generation approaches

The two approaches to biologically inspired design discussed in the following subsections utilize a design repository and automated concept generation software; for this research the examples access the Design Repository housed at Oregon State University (2009), the automated morphological matrix tool (Bohm et al. 2008) and the concept generator software, MEMIC (Bryant et al. 2005). The Design Repository at Oregon State currently houses descriptive product information such as functionality, component physical parameters, manufacturing processes, failure, and component connectivity for over 113 consumer products and 18 biological phenomena amounting to over 5,600 physical artifacts. Both the automated morphological matrix tool and MEMIC access the Design Repository to return potential solutions for each function in a system. Where the 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 designer for concept generation. Functional models created with the software FunctionCAD (Nagel et al. 2009) can be exported directly to MEMIC to speed up the concept generation process. All design tools mentioned in this chapter can be found at the Design Engineering Lab's website:
www.designengineeringlab.org.

5.1 Approach One

Concept generation approach one is a new proposal for concept generation of innovative products that utilizes functional models based on systems of interest, rather than deriving a product directly from customer needs. This particular method is useful for product redesign and improvement. By taking a product originally derived from customer needs and identifying features that need improvement, to meet the customer expectations, the designer can take inspiration from another system—in this case biology—to discover product innovations. A designer could utilize approach one to explore the possibilities that other systems offer.

For this approach to work, the system of interest is a biological organism or strategy. A functional model of the biological system is first created. The functional model is then used to query the Design Repository for potential engineered solutions to each function using MEMIC and/or the automated morphological matrix tool. The input is processed, and a set of engineering components is returned for each function-flow pair in the functional model of the biological system. The designer must choose from the resulting component suggestions to develop a complete conceptual design. This methodology is formalized below:

1. Generate a functional model of the biological system to be mimicked following the procedure outlined in Section 4.
2. Utilize an automated concept generator to query a design repository for potential solutions for each function in the functional model of the biological system.
3. Review the engineering components returned by the automated concept generator that fulfill the same functionalities as the functions in the biological system.
4. Choose conceptual design variants from the automated concept generator.
5. Continue with the conceptual design process and/or proceed to detailed design.

This approach is limited by the data available in the design repository being queried for analogies; when data is available, analogies are easily discovered between biological and engineered systems. The solutions returned, however, often do not fit together as they would in a traditional engineered system and require a large amount of insight from the designer to be able to draw analogies leading to an engineered system. This approach therefore lends itself more toward innovate design problems where novel solutions tend to dominate.

Consider again the chemoreception example utilized through Section 4 where the Animalia chemical sense was used to demonstrate the generation of a functional model of a biological system. Chemoreception will be used to explore engineering possibilities with concept generation approach one. In the previous section, Step 1 of this approach is completed; the functional model of chemoreception is provided in Figure 2. To query the Design Repository with the MEMIC software for Step 2, the biological model of Figure 2 was created in FunctionCAD and 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 function/flow pairs; for the remaining half of the function flow pairs, MEMIC returned an incompatibility error meaning that engineering systems in the Design Repository were not known to solve function-flow pairs in the same order as the biological system. To find solutions for these remaining functions, the Design Repository was queried with the morphological matrix tool, and available solutions were chosen from the resultant morphological matrix. Not all of the function/flow pairs have solutions. However, the chosen engineered solutions have been substituted for each function in the functional model of the biological system and is provided in Figure 5.

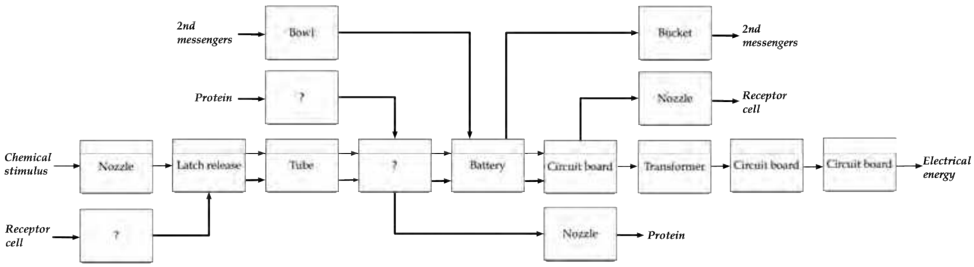

Fig. 5. Animalia chemoreception model with engineering components

It is not surprising that the biological functional model of chemical sensing did not return a complete set of engineering components that solve the biological functions. However, the blank spaces give the designer freedom to innovate or leverage knowledge from any source when developing the concept. Of the engineering components given in Figure 5, many of the import and export functions suggested a nozzle as a solution, which is a means to move material (of most types) from one location to another. The notion of nozzle inspires thoughts of tubes or channels, all of which could achieve the same function. Circuit board replaced three of the functions within the model and incorporation of a transformer on the circuit board is feasible, further simplifying the design. The function of sense suggested a latch release, a device that gives way in the presence of enough energy, or could be used as an automatic switch to activate the device. Detect chemical energy did not return a component such as a sensor; however, this allows the designer to innovate. Cutting edge research that interfaces with chemical energy to generate an electrical signal could be applied. Up to this point in the analysis, one could envision an analogous lab-on-chip device to chemoreception with the following characteristics: a chemical is introduced to the chip which automatically turns on the device, the chemical stimulus passes over the sensing interface and the results are sent by electronic signal to a computer or data storage device.

The battery that is suggested for the change chemical energy function/flow pair does not immediately make sense for a lab-on-chip device other than to power it. However, after given more thought, the battery could possibly be used in the following ways: clean the chemical stimulus before exiting the system (e.g., eletrodeionization), provide a second measure for the output data or enhance the sensor reading. If investigated further, this concept could lead to a novel chemical detection system that closely mimics the principle functionality of the natural sense of chemoreception.

Reconsidering the biological scale of cellular, used to scope the functional model of Figure 2, the resultant concept is a device that is manufactured at the micro/nano scale, which is roughly the same size as the natural system. The final concept is not required to mimic the biological scale, as shown by the chemoreception example, but the suggestion of physical size is just one more piece of information the designer can leverage during biomimetic inspiration. It is important to understand that the concept generation approach does not generate a complete and final concept; that is the task of the designer. The approach, however, does facilitate discovering analogies between the biology and engineering domains, so that it may be easier for the designer to make the necessary connections leading to innovative biology inspired designs. Furthermore, the experience and expertise of the designer plays a critical role in developing the final concept. In this case, the designer analyzing the automated concept generation results has a background in electrical engineering, which lead to the analogy of a lab-on-a-chip.

5.2 Approach Two

The second concept generation approach leading to biologically analogous products follows the typical method of automated concept generation outlined in (Bryant et al. 2005). First, the potential customer is interviewed to identify customer needs. The customer needs are translated into functionality for the product being designed. A black box model and 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 choose the biological solutions as inspiration to novel engineered solutions.

Entries into the design repository can be any of the biological categories or scales previously described, 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 artifact to assist a designer with overcoming any potential knowledge gap between biology and engineering, thus facilitating inspiration and analogical reasoning during the design process. The Design Repository housed at Oregon State currently is populated with biological entries, which can be returned with both the automated morphological matrix tool and with the MEMIC software. The following methodology formalizes this approach:

1. Create a conceptual functional model of the desired engineering system based on mappings of customer needs and constraints to flows (Pahl & Beitz 1996; Otto & Wood 2001; Ullman 2002; Ulrich & Eppinger 2004).
2. Utilize an automated concept generator to query potential solutions for each function in the conceptual functional model.
3. Review engineering and biological components from the potential components retrieved by the automated concept generator.
4. Explore biological components for inspiration to functionalities (i.e., view the repository entry and 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 concept generator software.
6. Continue with the conceptual design process and/or proceed to detailed design.

To illustrate concept generation approach two and to continue the chemical sensor idea, a conceptual functional model of a chemical sensing device will be the focus of the example in this section. The needs and constraints of the chemical sensing device are derived from (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 4. Figure 6 provides the conceptual functional model, which completes Step 1. The functional model is created at a system level to facilitate analogical reasoning as the majority of information in the Design Repository is at a comparable level.

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

Table 4. Chemical sensing needs mapped to conceptual flows

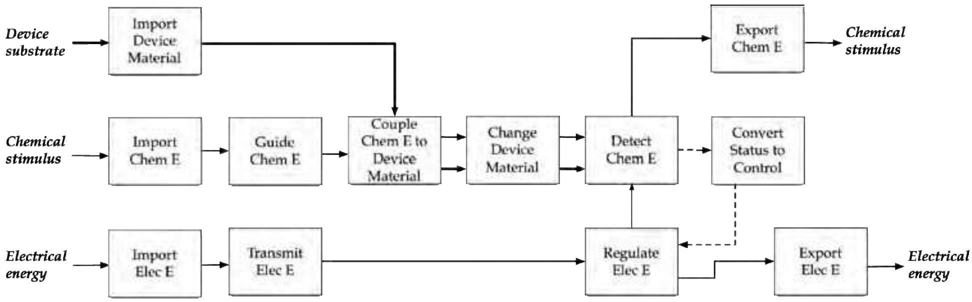

Fig. 6. Chemical sensing conceptual functional model

The chemical sensing device conceptual functional model in Figure 6 shows 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 Design Repository. Figure 6 demonstrates the indirect sensing mechanism with *couple* and *change*, sensor with *detect*, and transducer with the *convert* and *regulate* function blocks, respectively. Electrical energy is utilized to power the transducer and transfer the detection signal to the device capable of interpreting such signals, such as a computer. The boundary of the conceptual functional model includes the sensing element and the transducer.

To query the Design Repository with an automated concept generator for Step 2, the model of Figure 6 was created in FunctionCAD and exported as an adjacency matrix to MEMIC just as in Section 5.1. Again, MEMIC returned engineering components for half of the function/flow pairs; for the remaining half of the function flow pairs, the Design Repository was queried with the morphological matrix tool, and available solutions were chosen from the resultant morphological matrix. 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 as noted by the engineering components replacing the function/flow pairs in Figure 7. The functions of *change* and *detect* returned many possible components, of which, need to be analyzed before one can be chosen for the remaining two chemical sensing device conceptual functions. The five engineering components identified that *change* materials are: a heating coil, 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.

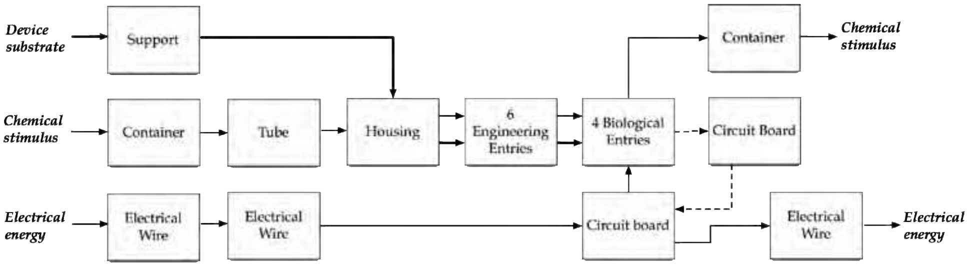

Fig. 7. Chemical sensing conceptual functional model with components

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, staple plate or filter would allow the chemical stimulus to come into contact with the device substrate, where as, the blade, punch and heating coil could change both the chemical stimulus and the device material, if used as is. 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, the returned biological components are explored for design inspiration. 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 described in Section 3.3. 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 the selection of chemicals that could interact with the sensing element. 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 leads to a sensor element surface 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. The collection of engineering and biological components presented here, inspires the conceptual design variant of a device that supports a housing containing an electrified element (not for the production of heat) acting as a barrier 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, particles (e.g., electrons) are released on the sensing element side to fill the sensor element surface cavities and generate a signal to be transduced. The filling of cavities by particles fulfills the requirement of an indirect sensing mechanism, which also supports reusability as the particles within the closed environment could return to the barrier element using a simple calibration procedure. An electronic circuit powers the sensing element, decodes the sensor signal and produces an electrical voltage or current analogous to the input. Further material property research needs to be completed before this design can be designated as feasible.

Multiple conceptual design variants for this example are possible, just as there are a number of materials applicable for the sensing element. A designer, when presented with the biological principle of natural sensing, organs of the fly, or strategies of proteins, is subsequently required to investigate the biological counterparts to each of the desired functionalities. It is through this correlation that the designer can take inspiration from the biological strategies. Again, the software does not generate a finalized concept; that is the task of the designer.

6. Discussion

Functional representation of a biological system as described in Section 4, results in a description of the biological system's functionality at a specified biological category and scale. By viewing the biological system from an engineering perspective and breaking it down into manageable parts, a designer can identify parallels between the engineering domain and biology or find inspiration for the development of novel, engineering solutions. Functional decomposition works for identifying analogies between biological and engineering systems as it creates a common approach for system decomposition. Also, with biological systems, it tends to be impractical for a designer to randomly try to match comparable engineering components to each biological component, especially for those who are biology novices. Functional modeling holds the potential to provide a translator between these domains. Concept generation techniques with function-based biological models facilitate the processes by making the task both manageable and worthwhile as demonstrated by Section 5.

When developing a functional model of a biological system, 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 research question and accurate to the system. (2) The energies associated with the biological system must be defined appropriately using analogous engineered system equivalents (e.g., Had change biological energy been used to model change chemical energy battery would not have been returned as an analogous component.) (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 question being asked of the model. (4) The choice of a low-level scale, such as molecular or sub-cellular, are not only hard to define, but often may be too detailed to lead a designer to inspiration. (5) Choosing a category serves to refine the boundary, but, like scale, it should be flexible through the concept generation process, and its consideration might prompt the designer to consider the same biological system in a new and unique way leading to new ideas. (6) Utilizing the Functional Basis aids in concept generation and should be used when developing a functional model. The flows, however, should be represented as their biological correspondents when validating the functional model of a biological system.

With concept generation approach one, a functional model is first generated of a biological system. This biological system is then used to seed inspiration for innovative engineered systems. The biology-based functional model is used to query engineered solutions to facilitate biomimicry. This approach does not begin from the traditional starting point of customer needs, and could, thus, be considered a creativity tool to open a designer's mind to the possibility of finding analogy in nature. Research has shown that while approach one can quickly lead to biological mappings to engineered systems, these mappings do not consistently make sense in an engineering context, and if taken at face value by the designer, the mappings would often result in infeasible conceptual deigns (e.g., the sensor to battery to circuit mapping discovered in the chemoreception example presented in Section 5). To make the concept work, a leap is required from the designer to understand that the component mapping is an analogy that relates the biological system to the engineered system. The approach assists with making the leap from biology to engineering, but to arrive at the final concept, the designer is required to make the leap within the engineering domain.

Concept generation approach number two begins more traditionally and is better suited for customer-based product design methodologies. Customer needs are first gathered. Then, the customer needs are translated to function, and function is used to direct a query for potential solutions. Instead of engineered solutions being returned, however, biology—in the form of strategies, principles, organisms, organs, etc.—is returned. At this point, approach two relies on 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 or analogy from engineering to biology. In this second approach, the engineer is not required to have any prior knowledge of biological systems; the biological information would be pre-populated in a design repository, and it is from this pre-populated data that the designer may choose to make the leap to a biology inspired design.

The approaches discussed here demonstrate the feasibility of utilizing biological information during conceptual design. However, the concept generation approaches, require work by the designer to develop at least a basic understanding of analogous biological systems. The approaches do, however, provide a starting point to guide a designer toward potential analogies reducing the biological overhead. To make this work, the conceptual system design must be heavily reliant on database content—both engineering and biological domains. Finally, it is important to understand that the approaches do not generate concepts; that is the task of the designer. They do, however, provide analogies between the domains, so that it may be easier for the designer to make the final connections leading to biology inspired designs.

7. Conclusion

Utilization of engineering design tools such as functional models and automated concept generation with biological systems allows designers to be inspired by nature such that its insight might be more readily incorporated into engineering design. To facilitate biology inspired design, a general method for functionally representing biological systems through functional-based design techniques and two approaches of concept generation utilizing biological information, engineering knowledge and automatic concept generation software are formalized, presented, and illustrated through examples. Biological organisms operate in much the same way that engineered systems operate; each part or piece in the overall system has a function, which provides a common ground between the engineering and biology domains. 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 methodologies. Biology contributes a whole different set of tools and ideas that a design engineer would not otherwise have. For the sake of philosophical argument, it was assumed that all biological organs and systems in this study have intended functionality.

The process of Animalia chemoreception was presented from the biology and engineering viewpoints and referenced throughout this chapter, allowing one to comprehend the similarities between the two domains. Each step of the general biological modeling methodology is demonstrated and the results are reviewed through the common chemoreception example. Through concept generation approach one Animalia chemoreception inspired a possible novel lab-on-a-chip device. Although the initial findings from the Design Repository did not indicate a lab-on-a-chip device, the designer leveraged prior knowledge to make the connection. Concept generation approach two identified analogies between the principles of the fly antennae sensing mechanism and engineering components. Furthermore, the approach took inspiration from biology to develop a unique concept for a chemical sensing device. The biological repository entries served as design inspiration for conceptual sensor designs by guiding the designer to a pertinent biological topic, which provides a starting point for mimicry in engineering designs.

To facilitate the development of functional models of biological systems, key points that are important for the designer to consider are summarized in the discussion. But to follow these points, the designer must remain flexible throughout the concept generation process and be open to consider biological systems from different viewpoints, which might prompt the designer to discover novel and innovative ideas. By placing the focus on function rather than form or component, the utilization of biological systems during concept generation has shown to inspire creative or novel engineering designs. The biological domain provides many opportunities for identifying analogies between what is found in the natural world and engineered systems. It is important to understand that the concept generation approaches developed do not generate concepts; that is the task of the designer. They do, however, provide a systematic method for discovering analogies between the biology and engineering domains, so that it may be easier for the designer to make the necessary connections leading to biologically inspired designs.

8. Future Research

Biological Kingdoms that are not as well known to engineers could be explored for unique functionality. The Eubacteria Kingdom consists of bacteria, which are unicellular microorganisms. Bacteria are interesting because they have several different morphologies that fulfill the same purpose. The Fungi Kingdom contains various types of fungus that are invisible to the human eye and those that are closely related to plants and animals such as mold, yeast and mushrooms. An interesting and less known Kingdom is the Protista Kingdom. It is comprised of a diverse group of microorganisms whose cells are organized into complex structures enclosed by a membrane, without specialized tissues, which are unclassifiable under any other Kingdom. The Protista Kingdom has animal, plant and fungus like organisms, of which, exhibit characteristics familiar to organisms in other Kingdoms.

Functional modeling has shown successful for transferring biological knowledge to the engineering domain by focusing on functionality. Biological processes, natural sensing as a whole and various biological phenomena and organisms have been modeled. The investigative work in this study could be extended to other specific areas of biology, such as motors or energy harvesting. Continually developing the biological correspondent terms for the Functional Basis function and flow sets would further reduce confusion when modeling biological systems.

A third hybrid approach is postulated in Figure 4, but not further discussed. In this approach, biological systems would be modeled functionally following the outlined methodology in Section 4. A database would then be queried for functional matches and analogous biological systems would be returned. With the hybrid approach, knowledge of the initial biological system modeled is required, and it is upon the designer to perform research on the analogous biological systems returned from the database. Further research will be required to identify the feasibility of such an approach to concept generation in engineering design.

Further work will include refinement of the general biological functional modeling methodology, as well as, the two conceptual design approaches. This research 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. 2008) could allow for the creation of more accurate functional models through the inclusion of environment and process representations. We wish to continue adding biological and engineered system entries in to the Design Repository to improve the usefulness of these methodologies via increased biological information and to facilitate future biology inspired conceptual designs.

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Nature's evolution has led to the introduction of highly efficient biological mechanisms. Imitating these mechanisms offers an enormous potential for the improvement of our day to day life. Ideally, by bio-inspiration we can get a better view of nature's capability while studying its models and adapting it for our benefit. This book takes us into the interesting world of biomimetics and describes various arenas where the technology is applied. The 25 chapters covered in this book disclose recent advances and new ideas in promoting the mechanism and applications of biomimetics.