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EXPLORING THE USE OF CATEGORY AND SCALE TO SCOPE A BIOLOGICAL FUNCTIONAL MODEL

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ABSTRACT

The natural world provides numerous cases for analogy and inspiration in engineering design. Biological organisms, phenomena and strategies, herein referred to as biological systems, are, in essence, living engineered systems. These living systems provide insight into sustainable and adaptable design and offer engineers billions of years of valuable experience, which can be used to inspire engineering innovation. This research presents a general method for functionally representing biological systems through systematic design techniques, affording conceptualization of biologically-inspired, engineering designs. Functional representation and abstraction techniques are utilized to translate biological systems into 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. Functional modeling is typically driven by customer needs or product re-designs; however, these cannot be applied to biological systems. Thus, we propose the use of biological category and scale to guide the design process. 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, where as, 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. In our case, the engineering design method is function-based design. 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. General guidelines for modeling biological systems at varying scales and categories are given, along with two modeling examples.

1 INTRODUCTION

Observation of nature has influenced the many disciplines of engineering in some way. In recent years, plants and insects have significantly impacted engineering designs [1-4]. Biological systems offer exemplary methods such as flight, imaging, sensing, adaptation to the environment, and locomotion. From these, engineers have learned and created novel technologies. This field of research into biologically-inspired design, also termed biomimicry [5], has seen many successes. For example, biomimetic robots mimic the look and functionality of an insect, and on a larger scale achieves feats that typical robots could not. Thus, changing the expectations of future robotic systems. The same can be said for unmanned air vehicles that copy the articulated wings of insects [6] and birds, or the motion detection systems modeled after the compound vision systems of many insects [7, 8].

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 are critical because they allow a designer to draw parallels between domains. For example, when Koryo Miura observed that plant leaves unfold in two directions at once, Miura designed a novel folding technique (Miura-ori) for erecting solar panel arrays in space that requires little storage room and provides maximized surface area [9]. Miura-ori has also been applied to maps and Japanese drink cans resulting in maps that are easier to collapse and cans that are stronger but use 30% less material.

Abstraction plays a major role in the early stages of engineering design and is a valuable tool during the conceptual design phase [10-13]. Abstractions allow one to capture the essence of a product, process, or component within a succinct phrase or diagram. Finding an appropriate abstraction is a fundamental hurdle to the use of biology as a reliable source of inspiration in engineering design. This research proposes using functional modeling to abstract biological systems in a repeatable and systematic manner that can be paired with existing function-based, engineering design tools. Functional modeling has the advantage of providing an abstraction of the object achieving the function, which is not always clear in a biological system. Functional representation of biological information has the potential to provide several advantages for engineering design:

- Systematic approach for establishing and representing functionality;
- information captured at multiple levels of fidelity;
- identification of characteristics that can be mimicked by engineering means;
- identification of analogies between the engineering and biological domains;
- creativity in concept generation; and
- archival and transmittal of information.

The hallmark of this approach is the translation of useful information from an unfamiliar context into a generalized context that is easier to comprehend through abstractions. Using an engineering design modeling lexicon, biological information is captured and abstracted into a context that engineering designers are familiar with. 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. The resultant models can then be used with function-based design tools, such as concept generation techniques. Overall, biological functional models afford designers a systematic approach to designing biologically-inspired solutions.

This research advances functional modeling of biological systems for engineering design activities. Specific contributions include a general method for functionally representing biological systems, assisting the designer with managing biological information, and abstracting biological information. Background information on the chosen modeling lexicon and biological design is provided in Section 2. Section 3 discusses the methodology of modeling a biological system and focuses on how to scope a biological functional model through the choice of biological category and scale. The two examples of lichen and insect chemoreception are used to demonstrate the biological functional modeling methodology in Section 4. Section 5 offers a discussion of the modeling methodology results, a summary of the key points for biological functional modeling, limitations and strengths of the method and how all of the pieces fit together in the larger design context to assist with biologically-inspired, engineering design. The paper ends with conclusions (Section 6) and future work (Section 7).

2 BACKGROUND

Functional representation through functional modeling has a long history of use in systematic design methods [12]. Furthermore, functional modeling is often considered a fundamental step in the engineering design process [11-18]. Stone et al. [19] created a well-defined modeling language comprised of function and flow sets with definitions and examples, entitled the Functional Basis. Hirtz et al. [20] later reconciled the Functional Basis, into its current set of terms, with research efforts from the National Institute of Standards and Technology (NIST), two universities, and their industrial partners. In the Functional Basis lexicon, a function represents an action or transformation (verb) being carried out, and a flow represents the type (noun), material, signal or energy, passing through the functions of the system. There exist eight classes of functions and three classes of flows, both having an increase in specification at the secondary and tertiary levels. Both functions and flows have a set of correspondent terms that aid the designer in choosing correct Functional Basis terms. The complete function and flow lexicon can be found in [20].

With biologically-inspired, or biomimetic, 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 biomimetic design. Biomimetic design "offers enormous potential for inspiring new capabilities for exciting future technologies" [21] and encourages engineering innovation [21, 22]. Research in biologically-inspired design theory has led to focused searching for representation methods, inspiration facilitators, information transfer, and concept generation techniques.

Focused searching for biological inspiration has been achieved through keyword searches of a biological corpus and software that interacts with a pre-populated database. Chiu and Shu have developed a method for identifying relevant biological analogies by searching a biological corpus using functional keywords [23-25]. The engineering domain keywords are expanded using WordNet to create a set of natural-language keywords to yield better search results. Stemming from this approach, Stroble et al. developed an algorithm to search a biological corpus first by function and then by flow [26]. The algorithm begins with Functional Basis functions, but has been modified to use the function terms from the biological domain [27].

Representation of biological systems for engineering design has taken many avenues. Chakrabarti et al. developed a software package entitled Idea-Inspire that uses a database of natural and complex artificial mechanical systems categorized by a verb-noun-adjective set that captures the principle of the system [28]. Each database entry is further classified under seven behavioral constructs. These comprise the SAPPhiRE model of causality [29]. Vincent et al. has explored the use of TRIZ (Theory of Inventive Problem Solving) to abstract and categorize biological systems by the generalized engineering problems that can be solved by biology [30]. Wilson and Rosen explored reverse engineering of biological systems for knowledge transfer [31]. 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 [32]. 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 [33]. This paper was merely an exploration on the feasibility of modeling biological organisms with functional models, and as such, it stops short of providing an approach that may be used for repeatable functional model generation. In a similar vein, Stroble et al. investigated functional modeling of natural sensing for the use of conceptual biomimetic sensor design [34]. Functional models of how an organism detects, 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.

Conveying biological information in an engineering context has lead to methods of aesthetic design, material design and determination of biologically meaningful terms. Wen et al. have developed the Product Design from Nature method that assists designers with inspiration based on biological geometric features [35]. Vincent has performed extensive research in the area of biological materials and has identified the major categories of natural materials and explains how engineers can potentially benefit from each [36]. Cheong et al. have worked to provide designers with biologically meaningful words that correspond to the Functional Basis functions based on semantic relationships [23]. Synonyms, troponyms and hypernyms of functions were identified.

Concept generation techniques for biology-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 [28, 32, 37]. Vincent et al. uses the engineering contradictions of TRIZ to develop concepts [30]. Helms et al. developed two processes for biologically inspired design that involve defining the biological solution, extraction of the biological principle and application of the biological principle [38]. Both diagrammatic and textual descriptions are used in the design processes. Mak and Shu studied the use of biological phenomena descriptions for idea generation [39]. Participants were provided with support for analogical mapping. A variety of concepts were developed.

3 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 [40]. Each part or piece in an overall biological system has an intended function. Function, therefore, may be utilized as the link to connect the biological and engineering domains for the identification of engineering design inspiration.

Functional modeling is a useful tool for capturing the essence of a product, process, or component with a diagram. Physically decomposing a product, process or component for re-design 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. To achieve a similar well-defined scope for a biological functional model we propose the use of biological categories and scales because, for obvious reasons, the same design rules to not apply to biological systems. The following sub-sections explain biological term mapping, category, scale, and the functional modeling methodology.

3.1 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 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 in Section 3.4, a reference should be identified and the designer begins learning 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 facilitate biological functional modeling, an engineering-to-biology thesaurus [41, 42] mapping biological terms to the Functional Basis functions and flows is employed. The engineering-to-biology thesaurus maps terminology between the two dissimilar domains for the identification of synonyms.

Our approach to modeling biology with the Functional Basis aims to accurately reflect the material, energy or signal 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 a biological system *biological energy* would not be descriptive enough for engineering designers to relate to or create connections between the domains. Thus, equivalent engineering energies are encouraged for modeling identified biological flows to accurately describe a biological system.

3.2 Defining Mimicry Categories

Mimicking a biological system for the creation of biologically-inspired technology has occurred through several mechanisms. Although each method has a different procedure, they all share one thing in common; the promising biological system must be abstracted to capture the essence of the system. In most cases, it is the functional principle that is abstracted. This research investigates biologically-inspired design through functional modeling.

Functional modeling is typically driven by customer needs or the re-design of an existing product. However, these needs and constraints that are transformed into engineering requirements, as one would use in the typical engineering design process, cannot be applied to biological systems. A biological system, as considered here, is any biological organism, phenomenon or strategy observed to exist. 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. Therefore, we propose the use of biological categories (and scales) to guide the design process.

Three of the four biological categories are derived from the three outlets biological organisms have for coping with a changing environment: physiology, morphology and behavior [43, 44]. 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. The fourth category is derived from identifying 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. The four biological categories that assist with setting one boundary for biological functional models are defined as [43-46]:

- 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.

These mimicry categories aid the designer with defining a boundary when developing a functional model for use with design activities, but also stimulate the designer to consider the biological system from a particular viewpoint. Without customer needs and constraints to guide the initial design process a designer could become overwhelmed by the unfamiliar, and possibly immense quantity of, biological information. Unless the biological system is well known and easily understood, it is easy to overstep the scope of a biological functional model. Therefore, utilization of biological category is one approach to assist with putting the information into the right perspective. The designer must take cues from the literature or biologist as to what information represents the category of interest. In addition to answering a design question related to the biological system, the biological functional model must also comply with a chosen biological scale.

3.3 Identifying Biological Scales

The second approach to assisting with putting biological information into the right perspective is through the use of biological scale. 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 more difficult. 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 scale(s) 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 modeling is employed. Biological computational models range 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 [47]. This scale can be utilized for functional representation of biological systems, allowing engineers to clearly define a second boundary for the biological functional 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 [48]. Advantageous starting points are the cellular, organ, organism, and behavior biological scales, which are readily defined in biological literature.

When generating a biological functional model, the biological scale is often constrained to a single scale (i.e., the model contains only elements from the organ scale). 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. Just as for category, the designer must take cues from the literature or biologist as to what information represents the scale(s) of interest. It is important when developing mixed, biological scale models, to remember that any concepts derived from analogies between natural and engineered systems will also be of mixed scale. A mixed scale model is demonstrated by the lichen example in Section 4.1.

3.4 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 essence of the system.
   - Take notes that capture the essence of the 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" [49].)
   - 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 design question the functional model aims to answer.
   - The design question is the first boundary set for scoping the biological functional model.
   - 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 modeling language within the bounds set by the design question, category and scale.
   - Use the engineering-to-biology thesaurus to choose the most suitable functions and flows 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 [50], 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 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 [43].)

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 open future biomimetic design opportunities.

4 EXAMPLES

To demonstrate how a designer would utilize the general biological modeling methodology, two examples are provided in this section. Section 4.1 reviews lichen at a mixed biological scale and category of function. Section 4.2 reviews olfactory chemoreception of insects at a scale of cellular and category of function. Each step of the methodology and the results are presented.

4.1 Lichen Example

Consider lichen as a biological system to illustrate the general biological modeling methodology. A lichen is a composite of a fungus (mycobiont) and an organism capable of producing food by photosynthesis (photobiont), typically a green algae or cyanobacterium [51-53]. Lichens grow where other organisms refuse to live, such as harsh climates or in areas of limited resources, which include bare rock, desert sand, cleared soil, dead wood, animal bones, rusty metal, and living bark [52]. Lichen can survive such conditions because of the symbiosis—the mycoboint protects the photobiont in return for carbohydrates (food) to live [51-53]. All that is needed is a stable surface for the lichen to adhere. 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 [53]. All growth forms, functionally speaking, of the lichen are similar in principle with differing morphology. Multiple biological flows were encountered while researching the essence of lichen. The flows of interest were mapped to the engineering flows of the Functional Basis and are provided in Table 1.

Table 1. Relationship between lichen flows [51-53] and the Functional Basis [20]

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
Symbiosis	Mixture material
Substrate	Solid material
Lichen on *substrate*	Mixture material
Photosynthesis creates *carbohydrate sugars*	Chemical energy

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 the lichen has been defined: How does the fungus use a photosynthetic organism (photobiont) to survive as the symbiosis, lichen?

The flows of Table 1 aid in answering the design question posed about the lichen functionality, however, they do not make explicit the category or scale of the biological information. Understanding how the mycobiont and photobiont 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. Defining the biological category to satisfy Step 4 requires investigation of possible biological conditions. Realizing that the mycobiont and photobiont are both organisms cues the category of organism. Could the category of strategy be correct for this case? The symbiosis does allow survival in harsh conditions. However, the functional model would also need to include harsh climate or limited resource conditions, and demonstrate the change in carbohydrate production and dormancy, respectively. It is these external environmental conditions that would result in an internal change of the lichen. The symbiosis of the two organisms involves resource sharing to allow the lichen to exist; it is not a behavior of the system. Therefore, consider that one boundary of the lichen 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 lichen was found at multiple biological scales. Modeling lichen at the organism scale would convey that two materials are coupled to another material in the lexicon of the Functional Basis. This result is not descriptive enough to utilize for concept generation. Examining lichen at the organ scale, where photosynthesis takes place, reveals that one of the organisms produces carbohydrates through photosynthesis for consumption by both organisms in return for protection. This finding is more interesting than the coupling of two organisms alone. The lichen exhibits many fungal filament networks to sustain life that branch and then fuse together when they meet to form a mesh of hair-like threads. The top surface is normally a layer of tightly packed hyphae called a 'cortex'. Majority of the lichen contributes to the body, which is known as the thallus. This information is at the tissue scale, indicated by the terms hyphae and thallus; however this information is too focused on morphology to be of use for function-based, concept generation. 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 a high level, as a product. Thus, a mixed model comprised of the *organism* (photobiont and mycobiont) and *organ* (photosynthesis) biological scales is defined for Step 5. Realizing that lichen only exists when there is a symbiosis, which aids in survival, the black box model of the system is described as provision (i.e., to accumulate or provide a material or energy flow [15]). The primary flows include the tree, the photobiont and the mycobiont as materials and sunlight as the energy. This black box model is provided in Figure 1.

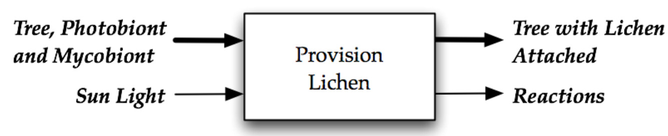

Figure 1. Black Box Representation of Lichen

Investigating the lichen 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 2, is decomposed from the black box model (Figure 1). The functional model represents two biological scales. The photobiont being *secured* by the mycobiont and *coupled* to the tree represents the organism scale portion of the mixed model. The production of chemical energy represents the organ scale portion of the mixed model. In the organ portion of the model, sunlight is *imported* as electromagnetic energy, *converted* to the chemical energy and *supplied* to both the photobiont, to fuel further photosynthesis, and the mycobiont, to further allow *coupling*.

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 the lichen symbiosis and how the symbiosis allows survival. At mixed biological scales, the functional model of the lichen represents the two organisms joining together and attaching to a solid surface. One organism provides protection, while the other organism generates carbohydrates. The carbohydrates are shared between both organisms. By capturing protection,

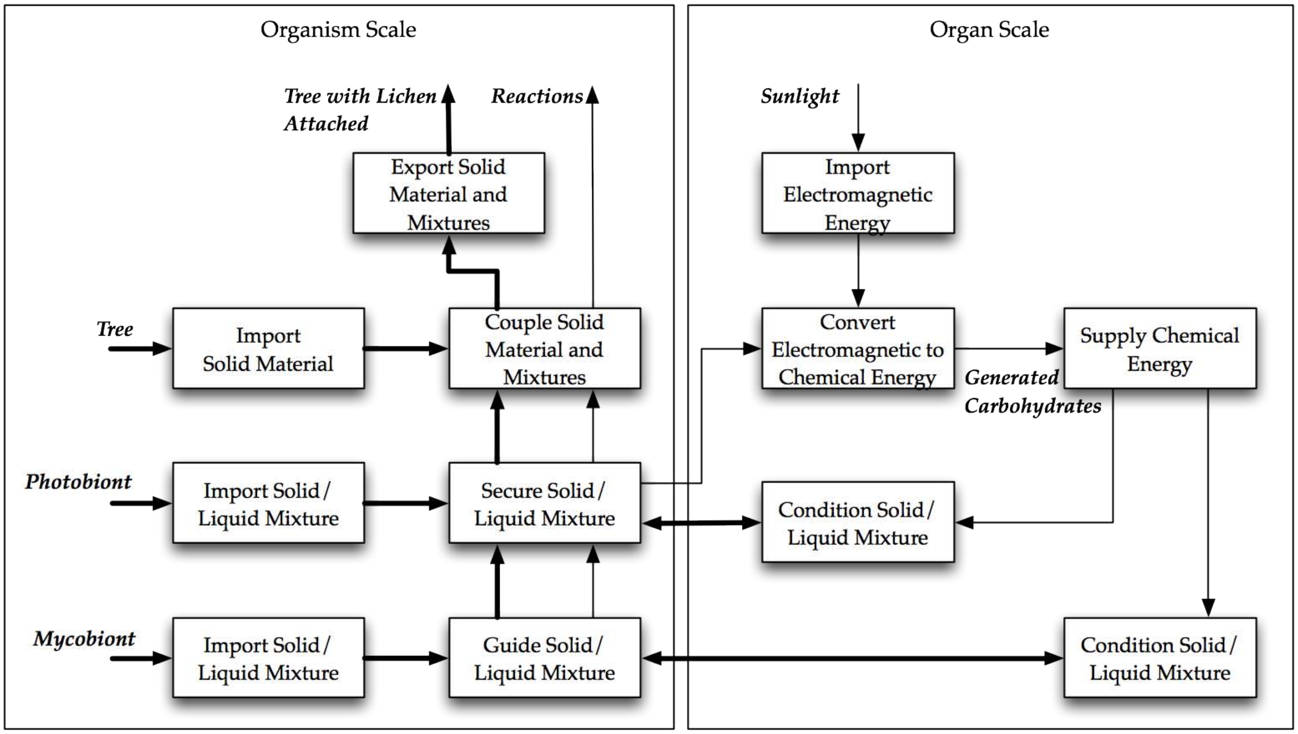

Figure 2. Lichen Functional Model

energy creation and distribution, the functional model can be abstracted to—one organism offers protection and one organism offers sustenance in order for both to survive on a solid surface. At the black box level the lichen is modeled as having the function of provision. Accumulating or providing a material or energy is a natural occurrence in the symbiosis formed by lichen.

It is evident that both abstractions are similar and both answer how the fungus uses a photosynthetic organism (photobiont) to survive as a symbiosis. 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 photobiont generates carbohydrates from sunlight or how the carbohydrates are taken by the mycobiont for survival, but rather, the functional model had simply directed the sunlight into and out of the lichen without describing photosynthesis conversion, then the functional model would not have correlated to the question posed, the black box or to the functional model. Thus, the biological functional model would need to be revised. Furthermore, had the flow of sunlight flow been omitted from the black box, it would have not been included in the subsequent functional models resulting, again, in a failure to answer the posed design question. This validation further supports the mixed scale biological functional model for satisfying the design question.

4.2 Insect Olfactory Chemoreception Example

Consider 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) [54]. For this example we will focus on insect olfaction, specifically the ability of the antennae.

Antennae are made of a chitin-protein complex referred to as cuticle, which are porous, and covered in a waxy layer to prevent desiccation [55]. 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 [55-58]. 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 [55-57]. 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 [55-57]. The odor binding protein is responsible and required for receptor site activation and deactivation [58]. 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 [55-58]. 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. The flows of interest were mapped to the engineering flows of the Functional Basis and are provided in Table 2.

Table 2. Relationship between chemoreception flows [55-57] and the Functional Basis [20]

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

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 has been defined: How does an insect interact, interpret and respond to an olfactory stimulus?

The flows of Table 2 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 [55, 57, 58]. 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 [55, 57, 58]. 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" [49], 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 [59], 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 [59]. Although the second messengers and odorants are molecules, they are necessary for the cellular level 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 [15]). 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 3.

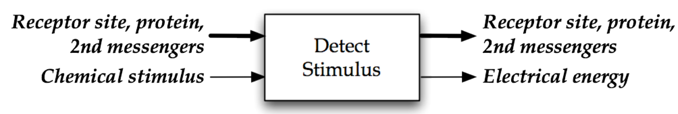

Figure 3. Black Box Representation of Insect Olfactory Chemoreception

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 4, is decomposed from the black box model of Figure 3. The functional model represents the biological category of *function* 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 binding 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.

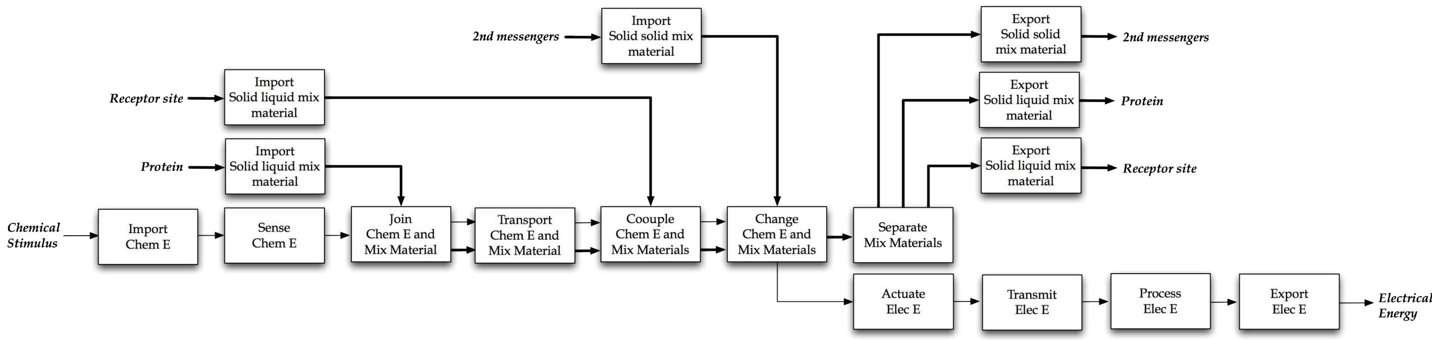

Figure 4. Chemoreception Functional Model

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 DISCUSSION

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 domain and biology and find inspiration for the development of novel, engineering solutions. Functional decomposition works for identifying connections between biological and engineering systems as it creates a common approach for system decomposition. Functional modeling holds the potential to provide a translator between these domains, and lead to function-based, concept generation activities.

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.

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.

Although this research approach assists with the translation of biological information from a non-engineering context into a generalized, engineering context through functional models, the major limitation is that the designer must be able to think abstractly. Meaning the designer using the method presented in this paper must be able to think abstractly, about both biological and engineered systems. Assisting with abstracting biological information systematically is the Functional Basis, a functional modeling lexicon, which has sets of engineering and biological correspondent terms. With the use of the design tools mentioned in this paper, biological information is captured and abstracted into a context that engineering designers are familiar with. This research supports the early stages of design or what are known as the "fuzzy" front end. In general, the modeling of biological systems will likely be conducted as part of an effort to populate a knowledge basis with biological information that a broader set of designers may use. The systematic approach to modeling biological systems, however, does make it accessible to any designer.

6 CONCLUSIONS

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. To facilitate biologically-inspired design, a general method for functionally representing biological systems through systematic design techniques is presented and illustrated through two 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 methods. 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 systems in this study have intended functionality.

Two examples utilizing the general biological modeling methodology were presented. The lichen was modeled at a mixed biological scale (organism and organ) and the category of physiology. 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 was provided for both examples regarding the choices of category and scale. It was shown how a designer with little biological knowledge could take cues from the biological literature when developing a functional model.

To facilitate the future development of biological system functional models, 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 process and be open to consider biological systems from different viewpoints, which might prompt the designer to discover novel and innovative ideas. Though biological systems provide a wealth of elegant and ingenious approaches to problem solving, there are challenges that prevent designers from leveraging the full insight of the biological domain. 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 analogs to be discovered with cues taken from each level. The biological domain provides many opportunities for inspiration, and this research assists with identifying analogies between what is found in the natural world and engineered systems.

7 FUTURE WORK

Further work will include using the general biological functional modeling methodology to populate a knowledge basis, investigation of concept generation approaches that utilize biological information, as well as, performing large-scale design studies with students in engineering design courses or professionals that are familiar with functional modeling. We expect the studies will identify weaknesses of the method that need improvement. The resulting biological functional model information would integrate easily with the Oregon State University Design Repository [60] and would afford automated biomimetic concept generation.

Function-based automated concept generation could be extended in two ways with the addition of biological information. Biological functional models could be used to explore analogous engineering components and systems, or biological entries in a design repository could lead to biologically-inspired designs that began from the typical approach based on customer needs. Automated concept generator software such as MEMIC [61, 62] or the automated morphological matrix tool [63] that interface with the Design Repository would allow quick access to relevant biological organisms, strategies or phenomena that solve engineering problems.

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) [64] could allow for the creation of more accurate functional models through the inclusion of environment and process representations. Overall, we wish to continue modeling biological systems to improve the usefulness of this methodology and facilitate future biologically-inspired, conceptual designs.

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