

# An Engineering-to-Biology Thesaurus To Promote Better Collaboration, Creativity and Discovery

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## Abstract

Biological inspiration for engineering design has occurred through a variety of techniques such as database searches, keyword and antonym searches, knowledge of biology, observations of nature and other “aha” moments. This research aims to alleviate the knowledge gap problem by providing a link between engineering and biology with a thesaurus. The biologically connotative terms that comprise the thesaurus were collected utilizing an organized verb-noun search; collocated words were extracted from texts based on a functional search word. This thesaurus should enable the engineering and biology communities to better collaborate, create and discover.

## Keywords:

Engineering design, Function, Analogical reasoning

## 1 INTRODUCTION

The natural world provides numerous cases for analogy and inspiration in engineering design. From simple cases such as hook and latch attachments to articulated-wing flying vehicles, nature provides many sources for ideas. Methods such as design by analogy and functional modeling exist to enhance creativity in the engineering design process by focusing on function rather than form or component. Biological organisms and phenomena, which are in essence living engineered systems, provide insight into sustainable and adaptable design. The evolution of natural designs offers engineers billions of years of valuable experience, which we feel can inspire engineering innovation. 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. A fundamental problem to effectively execute biomimetic designs is that the effort and time required to become a competent engineering designer creates significant obstacles to becoming sufficiently knowledgeable about biological organisms and phenomena (the converse can also be said). In an effort to bridge the gap between the engineering and biological domains, the creation of a partial thesaurus that will contain biologically connotative words related to engineering function and flow terms, is envisioned. This approach should enable the search for biomimetic solutions to engineering functions and aid with comprehension of biological material.

The purpose of a thesaurus is to represent information in a classified form to group related concepts. The engineering-to-biology thesaurus proposed here has a unique structure and classification; it is merged with the reconciled Functional Basis [1] as a set of correspondent terms. Thus, the classification is predetermined according to that of the authors' model; however, it remains the intermediary between the biology and engineering domains. A tool such as the engineering-to-biology thesaurus increases the interaction between the users and the knowledge resource [2].

In the following sections several points will be discussed:

(1) the nomenclature of function based design; (2) the related work and research efforts (3); the model for designing the thesaurus structure; (4) the method used to populate the thesaurus; (5) the implications such a thesaurus has on the engineering and biology communities; and (6) two example applications of the engineering-to-biology thesaurus.

## 2 NOMENCLATURE

Terms used throughout this paper that are specific to this research are described in this section.

*Biologically connotative term* – a word that will appear in a biological text and not an engineering text.

*Biological phenomena* – a biological fact or situation that is observed to exist or happen.

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

*Flow* – refers to the type of material, signal or energy that travels through a system or a device.

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

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

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

## 3 BACKGROUND AND RELATED WORK

### 3.1 Function based design

Design specifications and requirements 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 [3]. Since the introduction of function structures, numerous functional modeling techniques, product decomposition techniques and function taxonomies have been proposed [4-7].

The original list of five general functions and three types of flows developed by Pahl and Beitz [3] were further evolved by Stone, *et al.* into a well-defined modeling language comprised of function and flow sets with definitions and examples, entitled the Functional Basis [8]. Hirtz, *et al.* later reconciled the Functional Basis and NIST developed taxonomy into its most current set of terms [1]. The reconciled Functional Basis is utilized for developing hierarchical functional models, which describe the core functionality of products and processes in domain independent function and flow terms. Branching from the Functional Basis efforts is the lexical-analysis-based approach to function based design by Fantoni *et al.* [9]. By utilizing synonyms and antonyms of desired functions and exploring changes in flow, this method claims to convert each problem into an opportunity.

A functional reasoning method developed by Zhang *et al.* is the Behavior-driven Function-Environment-Structure (B-FES) modeling framework, which assigns function to behavior before function to physical structures [10]. This framework provides an opportunity to explore a wide variety of solutions based on behavior, without constraint set by function. Function/means tree is a hierarchical function based design method, which demonstrates the causal relationship between function and means at different levels [11]. Xu *et al.* utilize hierarchical function structures to create a non-numeric key element vector, of which, functional design knowledge is extracted for use with automated design synthesis [12]. Multi-objective optimization functions apply design constraints to extracted knowledge to produce design solutions.

### 3.2 Creativity in design

Creativity in engineering design is considered to have two distinct forms, novelty and usefulness. Thompson and Lordan explain this dichotomy as '[n]ovelty may take the form of something completely new or it may be a combination of existing ideas or products. For something to be creative it must satisfy a need, it must serve a purpose and it must make a positive contribution' [13]. According to Cross, the generation of creative thoughts, either satisfactory or not, can be described with four generalized models: analogy, combination, first principles, and emergence [14]. In regards to utilizing biological designs, research has shown that the use of analogy has been the most successful method in engineering design. Mak *et al.* [15] and Chakrabarti *et al.* [16] both demonstrate that creative, engineered solutions were inspired by their biological analogs, at varying levels of abstraction.

Several design-by-analogy methods have been developed and go beyond the formal design methods that just include analogies and metaphors within the design process. McAdams *et al.* takes a unique approach to design-by-analogy by utilizing a design repository of prior

engineering solutions that includes information about product functionality [17]. A quantitative measure based on functional similarity is presented and validated through case studies. Also following a model based approach is the analogical design research by Bhatta *et al.* They explore analogies using two types of models: case specific, Structure-Behavior-Function models of physical devices and case independent, Behavior Function models of physical principles [18]. Hey *et al.* found that while 'metaphors and analogies in design ... can enhance creativity and innovation' tools and methods that assist in the search process for suitable analogies are lacking [19]. To increase the likelihood of generating a design solution Hey *et al.* suggest reframing or creating multiple representations of the design problem. Through re-representation, multiple linguistic representations are created for key word searches in various databases, which result in a larger set of analogous solutions [19].

Goel reiterates the important application of analogies in his statement '[a]nalogical reasoning appears to play a key role in creative design' [20]. Although Goel was researching AI and concept generation software, he and all the aforementioned researchers have shown that the desirable consequence from analogical reasoning is creativity in design.

### 3.3 University of Toronto research effort

Researchers at the University of Toronto have recently worked to provide designers with biologically meaningful words that correspond to the Functional Basis functions. They analyzed the functions in the secondary, tertiary and correspondent levels to develop groups of words that were similar according to WordNet [21]. Biologically meaningful words were identified through a methodology developed by Chiu *et al.* [22] using bridge verbs - verbs that were modified by a frequently occurring noun - categorizing bridge verbs and screening match results. Four cases for identification are discussed and examples presented: synonymous pair, implicitly synonymous pair, biologically specific form and mutually entailed pair [21]. Based on semantic relationships, the engineering function terms of the Functional Basis were used to systematically generate a list of biologically significant and connotative keywords. A short list is shown in Table 1.

## 4 ENGINEERING-TO-BIOLOGY THESAURUS

The engineering-to-biology thesaurus presented in this paper was developed to enhance the reconciled Functional Basis by Hirtz *et al.* [1]. The structure of the thesaurus was molded to fit the knowledge and purpose of the authors; synonyms and related concepts to the Functional Basis are grouped at class, secondary and tertiary levels. In the paragraphs below, the thesaurus model and population method are explained followed by implications of an engineering-to-biology thesaurus.

### 4.1 Thesaurus model

Studies have shown that user feedback in the form of questions is the most important source for analyzing information needs [23]. In the authors' experience, correlating biological terms to the Functional Basis functions was not an issue. The authors' had the most difficulty understanding biological terms that were

Functional Basis term	Convert	Mix	Transport	Store	Stabilize	Collect
Biologically meaningful term	Decompose	Exchange	Circulate	Deposit	Bind	Concentrate

Table 1: Short list of biologically connotative function words.

considered flow type (material, signal and energy) when utilizing biological organisms or phenomena for idea generation or design inspiration. Guessing if a biological material is liquid, solid or a mixture by its name generally resulted in a wrong choice, which made the biological concept perplexing. Similarly, needing a reference to look up biological terms each time a potential organism or phenomenon was found made the research tedious, and disrupted thought patterns leading to decreased efficiency. Thus, flow correspondent terms were chosen for the first draft of the engineering-to-biology thesaurus, which can be seen in Table 2.

## 4.2 Population Method

Population of the engineering-to-biology thesaurus was achieved through functional word searches of a biological textbook that covers a broad range of topics, described as an organized verb-noun search. Chosen words were determined by their macrorelevancy, which is identified by frequency of use [2]. Functional Basis functions (verbs) were utilized for searching the biological textbook to extract biologically connotative words (nouns) that an engineering designer interested in function based design might encounter. Variations of the stem function word were not considered during the searches. For example, detect is the stem function word and the variations of this verb: detection, detects, detected, and detecting were not included in search results. The nouns that were collocated, within the sentence, to the search word were counted and sorted by frequency and all nouns that appeared more than two times were considered macrorelevant. Each macrorelevant term was researched to determine if it was of signal, material or energy type in the new Oxford American dictionary [24] and Henderson's dictionary of biological terms [25] before being placed. Placement of terms in the thesaurus was at the discretion of the authors and trite, domain independent terms were dismissed from the engineering-to-biology thesaurus.

Key challenges to this approach for populating the thesaurus were the time required to search each function term to generate a noun listing and understanding the definition provided in the dictionary of biological terms. Several biological dictionary entries referenced other biological terms that were unclear or unknown, which required referencing more than one definition to determine the material, energy or signal type of the term in question. This

## 4.3 Implications on Biological and Engineering Communities

The engineering-to-biology thesaurus was generated with the intention of promoting collaboration between the biology and engineering domains, resulting in discovery of creative, novel ideas. The following paragraphs describe plausible applications of the presented thesaurus. However, with few boundaries in the field of design, this thesaurus could be employed in ways the authors' have not considered.

### *Comprehension*

The engineering-to-biology thesaurus has the potential to aid engineering designers with the comprehension of biological contexts by substituting Functional Basis terms for commonly used biological words. Lopez-Huertas wrote that a thesaurus "...is thought of as a way of easing communication between texts and users in order to increase the interaction in information retrieval, and thus facilitate information transfer" [2]. Achieving efficient information retrieval through a thesaurus allows an engineering designer to cross into the biological domain to gain functional knowledge, without becoming overwhelmed by biological organisms and phenomena.

### *Searching for biological inspiration*

Searching a natural-language corpus for biological inspiration based on engineering functionality or using engineering terms typically produces results that are mixed. Hits that contain the search words often use them out of context or in a different sense than the designer intended. By utilizing the biologically connotative flow terms with desired functionality, search results improve and become more focused on biological systems.

### *Functional modeling of biological systems*

The engineering-to-biology thesaurus provides direction when choosing the best suited flow term to objectively model a biological system. Functional modeling of biological systems allows representation of solutions to specific engineering functions and direct knowledge discovery of the similarities and differences between biological and engineered systems as viewed from a functional perspective. The creation of engineered systems that implement strategies or principles of their biological counterparts without reproducing physical biological entities is another benefit to biological functional models.

### *Collaboration, creation, discovery*

Terms contained within the engineering-to-biology thesaurus can be utilized to discover biological analogs to existing engineered systems and visa versa. Analogical reasoning often requires an interdisciplinary team to ensure the analogy is properly represented, whatever the mix of domains. Exploration of biomimetic designs prompt collaboration between biology and engineering researchers.

## 5 EXAMPLE APPLICATION

In this section, two examples utilizing the engineering-to-biology thesaurus are presented. A simple translation of the phenomenon abscission is presented first to demonstrate how this thesaurus can aid with comprehension. Second, a comprehensive example is given regarding the method of sensing within bacteria; signal transduction occurs to alert the bacteria of stimuli via a two-component regulatory system [26].

### 5.1 Simple Translation

A text excerpt describing abscission is presented in its original form and in a "translated" form using the term relationships established through the engineering-to-biology thesaurus. The phenomenon of abscission is taken from the biology textbook *Life, The science of biology* [27].

*'In many species, leaves senesce (deteriorate because of aging) and fall at the end of the growing season, shortly before the onset of the severe conditions of winter. Leaf fall (abscission) is regulated by an interplay of the hormones ethylene and auxin. Finally, the entire plant senesces and dies.*

*The effect of auxin on the detachment of old leaves from stems is quite different from root initiation. This process, called abscission, is the cause of autumn leaf fall. Leaves consist of a blade and a petiole that attaches the blade to the stem. Abscission results from the breakdown of a specific part of the petiole, the abscission zone. If the blade of a leaf is cut off, the petiole falls from the plant more rapidly than if the leaf had remained intact. If the cut surface is treated with an auxin solution, however, the petiole remains attached to the plant, often longer than an intact leaf would have. The time of abscission of leaves in nature appears to be determined in part by a decrease in the movement of auxin, produced in the blade, through the petiole.'*

<b>Class (Primary)</b>	<b>Secondary</b>	<b>Tertiary</b>	<b>Biological Correspondents</b>	
<b>Material</b>	Human		Being, body	
	Gas		Oxygen, nitrogen, chlorine	
	Liquid		Acid, chemical, water, concentration, solute, cytokinin, pyruvate, fluid, nicotine, auxin, opium, glycerol, carotenoid, plasma, repressor	
	Solid	Object		body, substrate, microfilament, microtubules, structure, DNA, motor, fiber, chain, matter, nucleus, organ, tissue, muscle, ligand, cilia, gtp, flagella, RNA, tRNA, mRNA, tube, vein, heart, plant, ribosome, seed, apoplast, endotherm, ectotherm, stem, kidney, egg, ovaries, leaves, embryo, bacteria, gene, oncogene, cryptochromes, urea, chloroplasts, carbon, glucagons, adipose, angiosperm, meristems, mineral, stoma, shoot, capillary, receptors, hair, bone, tendon, neuron, photoreceptors, mechanoreceptors, host, chromosome, algae, petiole, promoter, phyla, lysosome, introns, exon, archaea, allele, cone, strand, centriole, spore, euryarchaeota, sporangia, zygote, sulfur, ctenophore, lipoproteins, stp, nephron, hyphae, plasmodesma, angiosperms, conifer, plasmid, xylem, pigment, sperm, hippocampus, somite, parathormone
			Particulate	
			Composite	Molecule, enzyme, virus, phloem, ribozyme, prokaryote, macromolecule, polymerase, nucleotide, polypeptide, organelle, symplast, mesophyll, brood, codon, messenger
	Mixture	Gas-gas		Air, dioxide
		Liquid-liquid		Solution, poison, slime, blood, urine, cytoplasm, peptide, hormone, melatonin, thyroxine, calcitonin, thyrotropin, estrogen, somatostatin, cortisol, glucagons, adrenocorticotropic, testosterone
		Solid-solid		Adenosine, glial, glomerulus, blastula, monosaccharides, membrane mulch, phosphate, gibberellin, plastids
		Solid-Liquid		Lipids, glutamic acid, synapse, peptidoglycan, cell, centrosomes, phytochrome, retina, insulin, protein, hemoglobin
		Liquid-Gas		
		Solid-Gas		
		Solid-Liquid-Gas		
		Colloidal		
	<b>Signal</b>	Status		Change, variation, lateral, allosteric, swelling, catalyzes, translation, exposed, active, separated, cycle, form, reaction, redox, deficiency, saturated, diffusion, broken, vicariant, hybridization, orientation, resting, cues, magnetic, volume, under, organized, fruiting, fatty, anaphase, metaphase, conjugation, osmolarity, senescence
			Auditory	Sound
			Olfactory	Smell
Tactile			Cold, pain	
Taste			Gustation	
Visual		Length, shortened, long, dark, full, double		
Control			Place, inhibit, release, excretory, development, match, inducer, digest, integrate, translation, transduction, equilibrium, grown, splicing, capture, distributed, prophase, phosphorylation	
		Analog	Flowering, center, synthesis, binding, photosynthesis	
	Discrete	Flower, translocation		
<b>Energy</b>	Human			
	Acoustic		Echolocation, waves	
	Biological		Blood, glucose, gibberellins	
	Chemical		Calorie, metabolism, glucose, glycogen, ligand, nutrient, starch, fuel, sugar, mitochondria, synthesis, o, lipids	
	Electrical		Electron, potential, q, feedback, charge, fields	
	Electromagnetic	Optical		Light, infrared
		Solar		Light, sun, ultraviolet
	Hydraulic		Pressure, osmosis, osmoregulation	
	Magnetic		Gravity, fields, waves	
	Mechanical			Muscle, pressure, tension, removing, stretch, depress
		Rotational Translational		
	Pneumatic		Pressure	
Radioactive/ Nuclear				
Thermal		Temperature, heat, infrared		
Overall increasing degree of specification →				

Table 2: Engineering-to-biology thesaurus.

The translated version of the text exert utilizing the term relationships of the engineering-to-biology thesaurus:

*In the fall season, leaves of plants indicate a status signal to humans shortly before the onset of severe winter conditions. Leaf fall referred to as abscission is regulated by the interplay of liquid material and liquid-liquid mixture materials internal to the plant. The effect of the liquid material auxin on the detachment of old leaves from stems is quite different from root initiation. Leaves which are material-solid-objects utilize a material-solid-object called a petiole, which attaches the blade to the stem (also a material-solid-object). The abscission zone is where the material-solid-object petiole detaches from the material-solid-object stem. Separation is the main function of this phenomenon. Separation can be deterred with the material-liquid auxin, which is created in the blade of the leaf. The time of the status signal offered by plants, death or all leaves abscise, appears to be determined in part by a decrease in a particular material-liquid flowing through plant leaves*

The translation process as demonstrated above was performed manually by reading the text excerpt describing abscission and identifying possible terms for translation. Translation of concepts occurs by substituting unclear biological terms with corresponding engineering terms, one sentence at a time. The two paragraphs from *Life, The science of biology* [27] was shortened to one, concise paragraph clearly presenting the concept of abscission as events between materials. This tool allows the designer the freedom to choose which of the possible terms for translation are indeed translated, thus suiting the needs for engineers who are at the novice to advanced levels in biological topics.

Analyzing the biological phenomena with engineering terms allows engineers to look at the phenomena of abscission as the separation of solid materials due to liquid materials, disregarding specifics. By not confining the design space, the designer captures the underlying principle of the biological phenomena, which increases the interaction in information retrieval and facilitates information transfer between the domains.

## 5.2 Functional Modeling and Analogical Reasoning

In effort to demonstrate the versatility of the engineering-to-biology thesaurus a comprehensive example exploring the use of signal transduction in engineering design is considered next. A majority of biomimetic designs have been modeled after physical biological phenomena that can be observed, meaning direct imitations of biology, and are represented in mechanical, civil and architectural designs [28-30]. Direct mimicry has also lead to two biomimetic designs based on the fly. A elementary motion detector chip based on the physiology of the common house fly was developed, which includes a photoreceptor circuit integrating each ommatidia of the compound eye and signal processing circuit to simulate the wide field motion sensitive neurons found in flies [31]. Second, artificial compound eyes developed by polymeric synthesis self-align to transmit light to a CMOS sensor array [32]. Mimicking unseen phenomena, such as activity on the cellular level, is more difficult as biological terminology becomes narrow and requires more knowledge of the subject. This example is a qualitative measure of the engineering-to-biology thesaurus.

The topic of signal transduction in prokaryotes explains how bacteria sense their environment for survival. Bacteria respond to nutrients, synthesizing proteins involved in uptake and metabolism, and non-nutrient signals both physical and chemical [26]. Signaling pathways in bacteria consist of modular units called transmitters (sensor proteins) and receivers (response

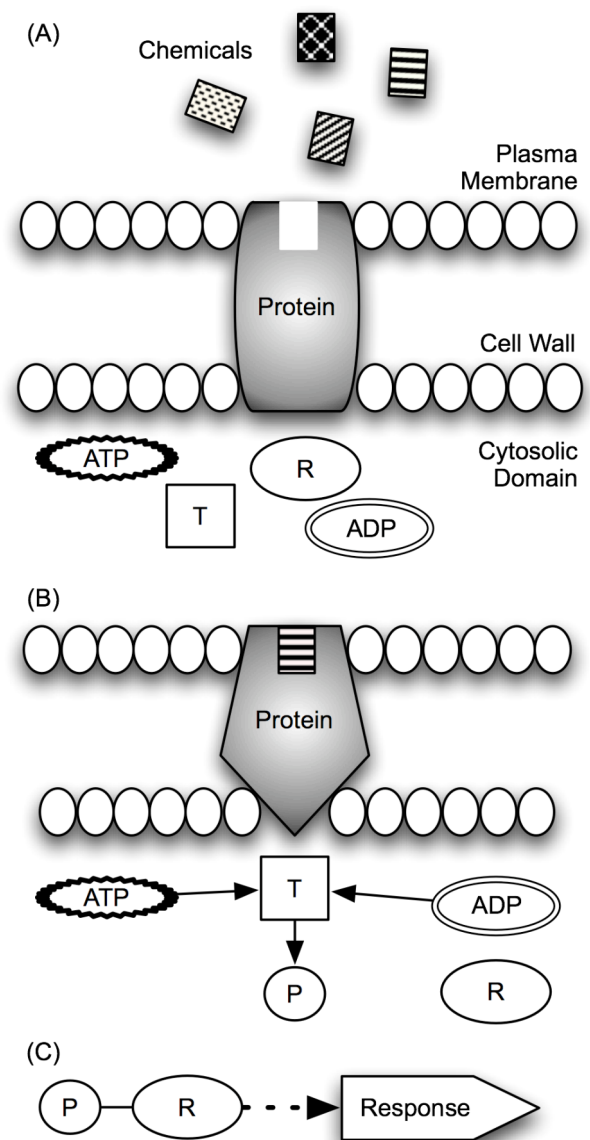


Figure 1: Method of sensing extracellular signals with TCRS in bacteria.

regulator proteins), which comprise the two-component regulatory system (TCRS). Example bacterial processes that are controlled by TCRS are chemotaxis, sporulation and osmoregulation.

Tiaz and Zeiger explain bacteria employ TCRS to sense extracellular signals as the following. 'Bacteria sense chemicals in the environment by means of a small family of cell surface receptors, each involved in the response to a defined group of chemicals (hereafter referred to as ligands). A protein in the plasma membrane of bacteria binds directly to a ligand, or binds to a soluble protein that has already attached to the ligand, in the periplasmic space between the plasma membrane and the cell wall. Upon binding, the membrane protein undergoes a conformational change that is propagated across the membrane to the cytosolic domain of the receptor protein. This conformational change initiates the signaling pathway that leads to the response.' - [26]

Figure 1 provides a visual representation of the sensing process; (A) Defining cellular boundaries and substances present in bacteria; (B) Conformational change sends a signal to cytosolic domain triggering the transmitter to release protein phosphate; (C) phosphate binds to the receiver initiating the output response.



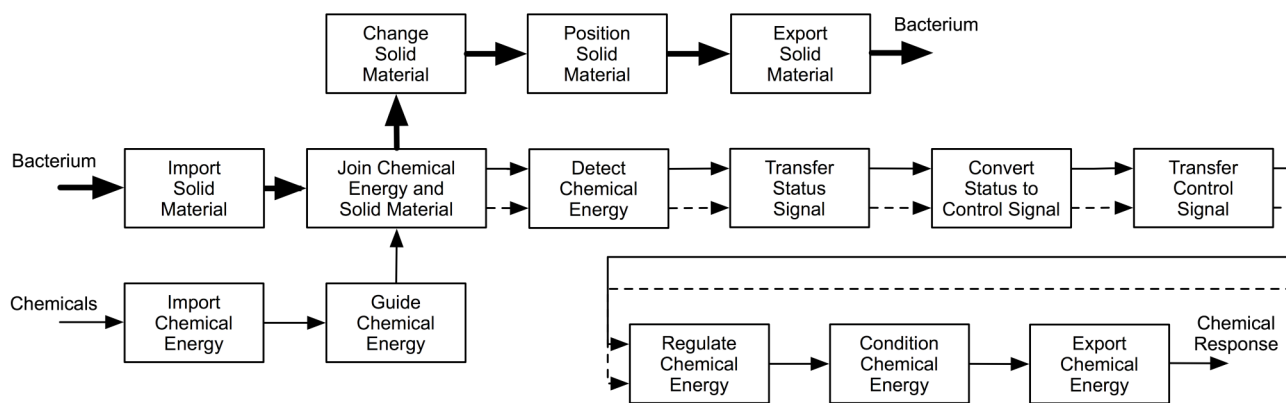


Figure 2: Functional Model of TCRS.

To utilize TCRS with function-based design, a functional model of the method shown in Figure 1 is given in Figure 2. Ligands are found in the thesaurus under material-solid-object and energy-chemical. In the case of TCRS, ligands are utilized as chemical signals, thus chemical energy was the chosen flow. Bacterium, the singular form of bacteria, is listed as a material-solid-object in the thesaurus because a prokaryote cell does not have a well defined nucleus. Binding of ligand to the protein is captured with the *join chemical energy and solid material* function flow pair. After coupling, detection of the stimulus signal occurs, which is propagated to the cytosolic domain, releasing protein phosphate. A signal pathway is now established, which regulates the chemical energy within the bacterium to produce a response. The two components of TCRS are transmitter and receiver proteins, however, from a functional standpoint chemical energy is needed to couple with and change the bacterium material to elicit a response. This abstraction of TCRS can now be utilized for analogical reasoning.

Engineered systems that mimic TCRS are wireless entry devices, such as a garage door opener or an automobile key fob. The handheld switch sends electrical energy in the form of a wireless signal to join with the receiver in the solid material, once detected electrical energy is regulated to open the door with the solid material changing position. It is not required to design strictly using the flows recognized in the biological system with analogical reasoning. Rather, adhering to the biological phenomena abstraction is most important. Although this example utilizes reverse engineering to match a biological system to an existing engineered system, engineering designers can utilize, the functional model of the biological phenomena to develop conceptual designs of new products and processes.

## 6 CONCLUSIONS

The natural world provides numerous cases for analogy and inspiration in engineering design. From simple cases such as hook and latch attachments to articulated-wing flying vehicles, nature provides many sources for 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. Biologically inspired or analogical designs require that designers have knowledge of previous design solutions during engineering design activities. The learned representations are organized at different levels of abstraction that facilitate the decomposition of design solutions, and allow analogs to be discovered with cues taken from each level. We presented an engineering-to-biology thesaurus that (1)

allows designers to focus on becoming a competent engineering designer; (2) lessens the burden when utilizing knowledge from the biological domain by providing a link between engineering and biological terms; and (3) lists biologically connotative words that an engineering designer interested in function based design might encounter.

Through this research, flow type biologically connotative terms were mapped to engineering terms and placed into pre-determined classifications set by the Functional Basis structure. It was observed that the majority of biologically connotative terms can be grouped at the tertiary level, indicating the preciseness of terms in the biological domain. Several material type flow terms can be grouped as material-solid-object, material-solid-composite or material-mixture-liquid-liquid. Signal is more of a subjective flow classification as materials and energies can also act as signals, as shown with the TCRS example in section 5.2, within the biological domain. Therefore, most signal flow terms are grouped at the secondary level. The most populated secondary energy flow terms, with no surprise, was chemical energy. Many chemical substances provide energy, such as sugars or starches, which humans can relate to.

Breaking down a biological solution into smaller parts, based on functionality, allows one to liken a biological organism or phenomenon to an engineered system for ease of understanding and transfer of design knowledge. The biological correspondent terms that comprise the engineering-to-biology thesaurus were collected utilizing an organized verb-noun search that extracts collocated words from a biological text based on the stem search word alone. The first draft of the engineering-to-biology thesaurus and the method for compiling the terms were presented and discussed. Implications of the proposed thesaurus on the engineering and biology communities were explored. The thesaurus will enable the engineering and biology communities to better collaborate, create and discover through comprehension of concepts, functional decomposition and guidance for inspirational searches. Furthermore, the engineering-to-biology thesaurus is a subject domain oriented, intermediary structure, which can be updated as needs are identified.

## 7 FUTURE WORK

An immediate step towards improving the engineering-to-biology thesaurus would be reconciling the efforts performed by researchers at the University of Toronto and Missouri S&T. Including the biologically meaningful function words with the biologically connotative flow terms presented here would create a complete set of biological correspondent terms for the Functional Basis. To further

strengthen the thesaurus, the population search method presented in Section 4.2 should be repeated to include variations of the stem function word. We predict this would lead to more results as biology textbooks are written in natural-language format and a longer list of biologically connotative flow terms.

Automatic translation of biological text into modified text with correspondent engineering terms inserted is another possible approach to improving the engineering-to-biology thesaurus. By automating the term swapping process, the expected outcome is increased usage, faster recognition of design parallels and overall increased knowledge transfer between the engineering and biology domains.

Other design tools created at Missouri S&T could be updated to utilize the engineering-to-biology thesaurus presented in this paper. Specifically, an automated retrieval tool recently developed searches a user defined corpus using Functional Basis functions and subject domain oriented or Functional Basis flows. The search could be enhanced by cross referencing the user input search terms with the thesaurus and searching each possible combination of function and flow terms. The web-based repository of design information could possibly utilize the terms contained within the thesaurus to discover biological analogs to existing engineered systems. A similar type of "reverse engineering" prompted the discoveries made by Tinsley *et al.* [33], however, the web-based repository was not utilized in that research.

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