

DETC2010/DTM-28233

AN ENGINEERING-TO-BIOLOGY THESAURUS FOR ENGINEERING DESIGN

Jacquelyn K. S. Nagel, Robert B. Stone
Oregon State University
Corvallis, OR, USA

Daniel A. McAdams
Texas A&M University
College Station, TX, USA

ABSTRACT

Engineering design is considered a creative field that involves many activities with the end goal of a new product that fulfills a purpose. Utilization of systematic methods or tools that aid in the design process is recognized as standard practice in industry and academia. The tools are used for a number of design activities (i.e., idea generation, concept generation, inspiration searches, functional modeling) and can span across engineering disciplines, the sciences (i.e., biology, chemistry) or a non-engineering domain (i.e., medicine), with an overall focus of encouraging creative engineering designs. Engineers, however, have struggled with utilizing the vast amount of biological information available from the natural world around them. Often it is because there is a knowledge gap or terminology is difficult, and the time needed to learn and understand the biology is not feasible. This paper presents an engineering-to-biology thesaurus, which we propose affords engineers, with limited biological background, a tool for leveraging nature's ingenuity during many steps of the design process. Additionally, the tool could also increase the probability of designing biologically-inspired engineering solutions. Biological terms in the thesaurus are correlated to the engineering domain through pairing with a synonymous function or flow term of the Functional Basis lexicon, which supports functional modeling and abstract representation of any functioning system. The second version of the thesaurus presented in this paper represents an integration of three independent research efforts, which include research from Oregon State University, the University of Toronto, and the Indian Institute of Science, and their industrial partners. The overall approach for term integration and the final results are presented. Applications to the areas of design inspiration, comprehension of biological information, functional modeling, creative design and concept generation are discussed. An example of comprehension and functional modeling are presented.

INTRODUCTION

Utilizing biological information during the engineering design process has taken many forms. Inspiration for solving or finding direct solutions to engineering problems have been obtained through chance observances [1-4], functional keyword searches [5-7], systematic reverse engineering [8, 9], use of function-structure-behavior terms to search a database [10, 11], TRIZ [12], analogical reasoning [13-15], and functional representation through functional models [16-19]. Although each method has a different procedure, they all share one thing in common; the promising biological system or phenomena must be abstracted to capture the functional principle. However, the functional principle is not the only biological aspect that can be mimicked. Morphology (shape), behavior (strategy), material, manufacturing process or any combination of these can be imitated. For instance, principle and morphology of a biological system can be imitated to improve an existing product [20]. A typical strain gauge has interdigitated electrodes, is rectangular and can only sense strain in one direction. The campaniform sensillum or flexible exocuticle that many insects possess inspired a novel redesign of the traditional strain gauge, directly based on morphology, that can sense strain in all directions (360°) [21]. Consider a circular or elliptical hole in a rigid material; it acts as a stress concentrator when pressure is applied. An elliptical opening in the insect's cuticle, which is covered by a thin membrane layer, senses deformation because of the stress concentration [22, 23]. The opening causes mechanical coupling and global amplification to occur, and acts as a biological strain gauge.

The novel strain gauge is just one example of a successful biologically-inspired, engineering design [24-27], however, choosing the biological system or phenomena to imitate is often left up to the designer, of whom typically has limited biological knowledge. Scenarios that involve the designer making educated decisions about how to utilize biological knowledge provided the impetus for developing an engineering design tool that eases the burden on the designer. In 2007, Nagel *et al.*

developed a set of signal flow grammars to provide templates that aid in the manual and automatic assembly of functional models [28]. Nodes are utilized to clearly establish the location of system boundaries and the required input and output flows in a functional model. While a grammar is informative when modeling an unfamiliar system or process, such as a biological system, the very nature of a grammar prevents it from being all-inclusive. A grammar of biological functions did not seem feasible, thus, an engineering design tool that categorizes biological information based on function, material, signal and energy was created. The resultant tool is a thesaurus of biological terms for use with the Functional Basis [29] as a set of correspondent terms, which is named the engineering-to-biology thesaurus. This work is not a biological ontology that allows automated information processing or inference. Rather, it is a means to map terminology between two dissimilar domains for the identification of synonyms. The thesaurus serves as a versatile design tool that affords design engineers, with a limited biological background, a means for developing connections between nature and engineering.

Lindemann and Gramann acknowledge the difficulties of utilizing biological principles in engineering design in the following statement, “The first difficulty was to find some of the huge number of possibilities within biology you might look at. The main reason is the lack of the specific knowledge especially concerning the terminology. This problem is time consuming and in addition one has to understand the principle of all the different phenomena” [9]. The engineering-to-biology thesaurus aims to circumvent these and other difficulties by providing a list of synonymous biological terms to the generalized engineering terms of the Functional Basis modeling lexicon. The thesaurus has the potential to serve as a key tool in future biomimetic design activities:

- Promotion of knowledge transfer from the biological to engineering domain;
- mapping of biological terminology to engineering function and flow terminology;
- facilitation of biological information in engineering designs without having an extensive background in biological knowledge;
- promotion of creativity in engineering design; and
- assistance during an inspiration search.

In the following sections of this paper several points will be discussed: (1) background research in engineering lexicons and taxonomies related to biologically-inspired design; (2) research efforts related to this work; (3) model for designing the thesaurus structure; (4) approach taken to integrate functional terms from related efforts; and (5) the applications this thesaurus has in engineering design.

BACKGROUND

This research explores the structure and purpose of an engineering design thesaurus and how it enhances an existing design lexicon. Researchers at many universities are working on the knowledge transfer problem between the engineering

and biological domains by developing function or function-behavior-structure based design languages. The design language research efforts of Oregon State University, the Indian Institute of Science and the University of Toronto are the three that comprise the second version of the engineering-to-biology thesaurus. Their research efforts are explained in the following paragraphs.

Oregon State University Research Effort

The formal idea of a standard set of engineering function and flow terms for systematically creating function structures was originally proposed by Pahl and Beitz [30]. A function represents an operation performed on a flow of material, signal or energy. Numerous researchers further evolved this set of generally valid functions and flows. Hundal proposed a further refined set of function and flow classes in [31]; however, flows were excluded. Little *et al.* developed a set of function and flow terms, which classified both functions and flows at class and basic levels [32]. Szykman *et al.* created a standardized taxonomy of function and flow terms, separated into classes down to the fourth level, for the purpose of computer-based design [33]. Separately, but at the same time, Stone and Wood developed a well-defined standardized modeling lexicon comprised of defined function and flow sets with definitions and examples, entitled the Functional Basis [34]. Hirtz, *et al.* later reconciled the efforts by Stone and Szykman to form the current version of the Functional Basis [29]. Within the Functional Basis there exist eight classes of functions and three classes of flows, both having an increase in specification at the secondary and tertiary levels. There are 21 secondary and 24 tertiary functions, accompanied by correspondent terms to aid the designer in choosing the correct function. Similarly, there are 20 secondary and 22 tertiary flows accompanied by correspondent terms. In 2009, Stroble *et al.* [35] further expanded the Functional Basis to include a set of biological flow correspondent terms, which comprised the first version of the engineering-to-biology thesaurus. Adding biological function correspondent terms was identified as the next step and is achieved by integration of multiple research efforts.

Indian Institute of Science Research Effort

Chakrabarti *et al.* developed a software package entitled Idea-Inspire that allows one to search a database with a function-behavior-structure set, which is simply a verb-noun-adjective set [10, 36]. Their database is comprised of natural and artificial complex mechanical systems. Each entry’s motion or process is described functionally by behavioral language in the form of a function-behavior-structure model. When using Idea-Inspire, the user abstracts a desired solution action by choosing terms that describe the function, behavior and structure from a pre-defined list of terms. The Idea-Inspire software yields seven behavioral constructs following the SAPPhIRE model – state change, action, parts, phenomenon, input, organ, and effect – for each search result that adequately fit the chosen function-behavior-structure set [37, 38]. SAPPhIRE explains the causality of natural and engineered

systems [37, 38]. The aim of the software is to inspire ideas rather than solve the problem directly, as the name implies.

University of Toronto Research Effort

Researchers at the University of Toronto have worked to provide designers with biologically meaningful words that correspond to engineering functions. Hacco and Shu developed a method for biomimetic conceptual design [39], which was later refined by Chiu and Shu for searching biological literature using functional keywords for design inspiration [5, 6]. The keywords used in the search strategy are cross-referenced with Wordnet to define a set of natural-language keywords for yielding better results during the search. Typically, searches are based on multiple keywords. Later in 2008, Cheong *et al.* used the search strategy in conjunction with the terms of the Functional Basis to identify biologically meaningful words [40]. The Functional Basis functions in the secondary, tertiary and correspondent levels were analyzed to develop groups of words that were similar according to WordNet. Four cases for identification are discussed and examples presented: synonymous pair, implicitly synonymous pair, biologically specific form and mutually entailed pair [40]. Based on semantic relationships, the engineering function terms of the Functional Basis were used to systematically generate a list of biologically significant and connotative function keywords.

ENGINEERING-TO-BIOLOGY THESAURUS

The engineering-to-biology thesaurus was developed to encourage collaboration between biologists and engineers, and discovery and creation of biologically-inspired engineering solutions. 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 this section, the thesaurus model, population methods of the biological flows and functions, particular details about the thesaurus, and validation are explained. The engineering-to-biology thesaurus provided in Appendix A is the second version and is not a comprehensive list of all biological terms. However, this work-in-progress is slowly and steadily bridging the gap between the two domains. Biological correspondent terms to the Functional Basis functions and flows are shown in place of the original engineering correspondent terms.

Thesaurus model

The purpose of a thesaurus is to represent information in a classified form to group synonyms and related concepts. A thesaurus of the English language has classes and categories with an index of terms directing the user to the correct instance (i.e., noun, verb, adjective) of the term under examination. The engineering-to-biology thesaurus proposed here has a unique structure and classification; it is merged with the reconciled Functional Basis as a set of correspondent terms. It does not include an index nor does it include adjectives. Only verbs and nouns that are synonymous to terms of the Functional Basis are considered. The Functional Basis class level terms, however,

do emulate the classes of a traditional thesaurus. Furthermore, the secondary and tertiary level Functional Basis terms emulate the categories of a traditional thesaurus. Biological terms that fit in the function and flow sets, and correspond to multiple functions or flows, are repeated and italicized to designate the special case. Thus, the classification is predetermined according to that of the 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 [41] by presenting the information as a look-up table. This simple format fosters one to make associations between the engineering and biological lexicons, thus, strengthening the designer's ability to utilize biological information.

Biological Functions

The majority of biological information is written in such a way that correlating biological verbs to Functional Basis functions is relatively straightforward. However, there are always exceptions. Well-known functional terms that appear in a biological text may not have the meaning an engineer would typically know. For instance, the term *bleaching* outside of the biological domain means to clean, sterilize or whiten, as most know. Rather, the biological meaning refers to the process of separation between the retina and opsin in vertebrate eyes and causes the retinal molecule to lose its photosensitivity [42]. It is these types of exceptions that OSU researchers were cognizant of when compiling the set of biological correspondent function terms for the engineering-to-biology thesaurus. Keyword searches of a biological textbook using the automated information retrieval tool [43] were performed to gather a list of collocated verbs that occur within the same sentence as the search word. To signify which function terms are utilized in both domains, the Functional Basis term is repeated in the biological correspondent list. It should be noted that some of the biological function correspondent terms are nouns that name a process corresponding to a Functional Basis function. Identified biological functions were cross referenced in the Oxford American dictionary [44], Henderson's dictionary of biological terms [45] and the Oxford Dictionary of Biology [46] before placement in the thesaurus, which was at the discretion of the authors. All other function terms were obtained from research performed at the Indian Institute of Science and University of Toronto, which are made explicit in the next section.

Functional terms from the Indian Institute of Science were collected from the Idea-Inspire software. Every natural system entered into the software's database was indexed using the pre-determined list of verbs, nouns and adjectives. Analyzing the list of verbs by cluster [37] revealed scientific terms applicable to biological systems grouped with engineering terms exactly matching those of the Functional Basis. Utilizing multiple dictionaries as in the OSU analysis, the verbs of Idea-Inspire were paired with Functional Basis functions.

Functional terms from the University of Toronto were collected from the work by Cheong *et al.* whom identified

biologically meaningful words to those of the Functional Basis [40]. Because background work was already performed on the semantic relationships of the biologically meaningful words, further investigation was not performed. Rather, the terms were directly added to the thesaurus.

Biological Flows

In the authors' experience, understanding biological terms that were considered flows (material, signal and energy) when utilizing biological systems or phenomena for idea generation or design inspiration posed the most difficulty. Determining if a biological material is liquid, solid or a mixture by its name typically requires domain knowledge that most engineers do not have, which cause biological concepts to be perplexing. Similarly, needing a reference to look up biological terms each time a potential organism or phenomenon was found made the research tedious, and disrupted thought patterns leading to decreased efficiency.

Identification of engineering-to-biology thesaurus flow terms, for the first thesaurus version, was achieved through functional word searches of a biological textbook [35]. Functional Basis functions (verbs) were utilized for searching the biological textbook to extract biological words (nouns) that an engineering designer interested in function based design might encounter. 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 [44] and Henderson's dictionary of biological terms [45] before being placed. Placement of terms in the engineering-to-biology thesaurus was at the discretion of the authors. The flow terms of the first thesaurus version were carried over to the second version.

Thesaurus Particulars

Key challenges to the approach for populating the thesaurus described in this research were the time required to search each term to generate a listing of collocated terms and understand the definition provided in the dictionary of biological terms. To determine the material, energy or signal type of the flow term in question, generally multiple biological dictionary entries were referenced. Considering biological processes that perform a specific function within the system revealed many macrorelevant terms that would have been overlooked if only verbs were analyzed.

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

special case of those terms. This treatment is similar to the repeated words of the engineering correspondent terms.

Validation

The addition of functional terms and nouns that name biological processes similar to engineering functions to the thesaurus requires a validity check of the current listing by a biologist. Validation of the thesaurus terms was performed by a professor of Zoology at Oregon State University. Term placement analysis is the first step in the validation process. Dr. Brownell reviewed both sets of biological corresponding terms and offered his insight. Biological terms that were incorrectly placed in the thesaurus were moved to better map the terminology to the engineering domain or were removed due to ambiguity per his suggestion. We believe term placement analysis by Dr. Brownell is adequate validation to facilitate all potential applications of the thesaurus, just as the reconciled Functional Basis is adequate for use with a variety of design activities. Application validation, the second step, will occur through future design studies.

INTEGRATION OF DESIGN LANGUAGES

Compiling multiple research efforts focused on language driven inspiration of innovative engineering designs strengthens the advantages of each effort. The terms utilized for Idea-Inspire must be broad enough to capture the principles of both biological and engineered systems, whereas, the carefully chosen terms of the Functional Basis were initially meant for engineered systems only. The biologically meaningful words discovered by semantic relationships utilized for creative design exercises, demonstrate functional terms that yield good results when searching a biological text for inspiration. Integration of these two research efforts with the OSU effort ensures the success of future design activities. Previously tested and successful terms of Table 1 and the broad scoping, yet easily overlooked, terms of Table 2 are included in the engineering-to-biology thesaurus of Appendix A.

It is interesting to note that Table 2 does not include any terms for the function of convert because transform (the correspondent for convert) and change are considered as the same cluster for the Idea-Inspire software. Additionally, some of the biological correspondents in Table 2 are identical to the original Functional Basis set of correspondent terms. These terms were repeated to signify that the term is used in both domains. Table 1 is shorter, but offers on average more correspondent terms per Functional Basis term due to the rigorous method of determining biologically meaningful terms. Moreover, Table 1 offers a fascinating observation about the sustainability of natural systems—multiple terms have multiple functions. Consider *connect*, it could mean bringing two objects together or it could refer to stabilizing support. Also consider *bind*, this term could refer to stability, liking or exporting. Both research efforts provide substantial contributions to the engineering-to-biology thesaurus.

Table 3 lists the OSU contribution of biological function correspondent terms for the second version of the engineering-

Table 1. University of Toronto Functional Terms [42]

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

to-biology thesaurus. All but four of the Functional Basis function terms have identified biological correspondents.

APPLICATIONS

The engineering-to-biology thesaurus was developed with the intention of promoting collaboration between the biology and engineering domains, resulting in discovery of creative, novel ideas. The following subsections describe plausible applications of the presented thesaurus, which are summarized in Figure 1. However, with few boundaries in the field of design, this thesaurus could be employed in ways the authors' have not considered.

Searching for biological inspiration

Searching a natural-language corpus, such as a textbook, for biological inspiration based on engineering functionality or using engineering terms typically produces results that are mixed. Results containing the search word often use the search word out of context, not at all or in a different sense than the designer intended. By utilizing the biological correspondent terms of the thesaurus when searching for a specific function or flow that solves the engineering problem, search results improve [47] and become more focused on the desired biological systems or phenomena.

Table 2. Indian Institute of Science Functional Terms [38]

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

Comprehension

Lopez-Huertas wrote that a thesaurus "...is thought of as a way of easing communication between texts and users in order to increase the interaction in information retrieval, and thus facilitate information transfer" [43]. The engineering-to-biology thesaurus has the potential to aid engineering designers with the comprehension of biological contexts and facilitate information transfer in two ways; (1) direct translation of biological text into engineering "speak" and (2) abstraction of a biological system or phenomena in engineering terms.

Direct translation can be achieved by substituting biological words that appear in the thesaurus with their corresponding Functional Basis terms. Essentially, this will rewrite the biological information in engineering "speak" and increase the likelihood of a designer making connections between the two sets of information and gaining inspiration as a result. Many design methods rely on abstractions and

Table 3. Oregon State University Functional Terms

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

describing an abstracted biological principle in engineering terms is advantageous. Not only does it increase the likelihood of a designer understanding the biological principle, but also it lends itself to formulating connections between the biological and engineering domains and easy comparison to other abstractions. Efficient information retrieval through the engineering-to-biology thesaurus allows an engineering designer to cross into the biological domain and gain functional knowledge without becoming overwhelmed by unfamiliar biological systems and phenomena.

Functional modeling of biological systems

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

Concept Generation

Concept generation, manual or computational, aims to generate several conceptual design variants. During this process engineers draw on their prior knowledge, search design catalogs, use a knowledge basis and in some cases search patents [48-51]. Biology is another resource available to engineers for design inspiration. Designers can use the terms of the thesaurus to understand how nature *removes* for example. From the biological correspondent terms one could relate the terminology to prior knowledge or develop an analogy that leads to design inspiration. Considering biological systems and phenomena through generalized engineering terms allow connections to be made between the domains, which facilitates knowledge transfer. Therefore, biological information can be used in function-based engineering design methods.

A computational method that has been pursued is the population of a biomimetic design repository, which enables the storage of biological knowledge indexed by engineering function. Storing the biological information based on the function the biological system or phenomena solves allows quick access to principle solutions. There are a total of 30 biological entries in the OSU Design Repository¹, 13 are phenomena and 17 are systems (organisms) for this purpose. The OSU Design Repository facilitates computational concept generation and comparison of biological and engineered components. The designer chooses from resulting computational concept generator suggestions, engineered and biological, to develop a complete conceptual design.

¹ www.designengineeringlab.org

Collaboration, creation, discovery

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

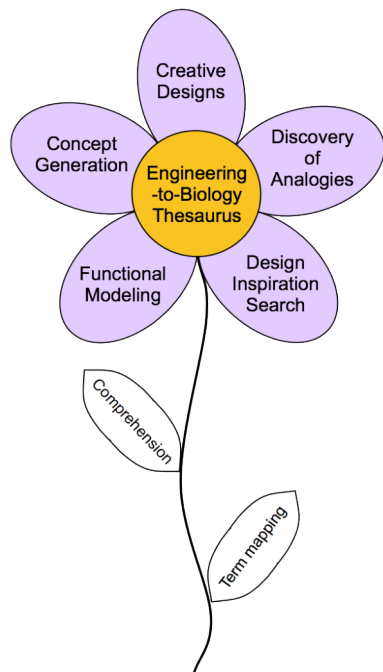


Figure 1. Engineering-to-Biology Thesaurus Applications

APPLICATION EXAMPLE

In effort to demonstrate the versatility of the engineering-to-biology thesaurus a comprehensive example exploring sensing, or signal transduction, in bacteria is considered. This example demonstrates the engineering-to-biology thesaurus applications of comprehension and functional modeling. The majority of biomimetic designs have been modeled after physical biological phenomena that can be observed, or experienced first hand as mimicking unseen phenomena, such as activity at the cellular level, is more difficult. Biological terminology often becomes narrow and requires more knowledge of the subject. The following example serves as a qualitative measure of the engineering-to-biology thesaurus to show that this tool can assist with translating narrow biological terminology into generalized engineering terms without requiring the designer to learn deep biological knowledge. A simple translation of what is the two component regulatory system, the mechanism of sensing within bacteria, is presented to demonstrate comprehension. From the translated biological information a functional model is derived.

The topic of signal transduction in prokaryotes explains how bacteria sense their environment for survival. Signal transduction occurs to alert the bacteria of stimuli via a two-component regulatory system (TCRS) [52, 53]. Bacteria respond to nutrients, synthesizing proteins involved in uptake and metabolism, and non-nutrient signals both physical and chemical [52, 53]. Signaling pathways in bacteria consist of modular units called transmitters (sensor proteins) and receivers (response regulator proteins), which comprise the TCRS. Example bacterial processes that are controlled by TCRS are chemotaxis, sporulation and osmoregulation [52].

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." - [52]

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

Figure 2 provides a visual representation of the TCRS sensing process; (A) Defining cellular boundaries and substances present in bacteria; (B) Conformational change sends a signal to cytosolic domain triggering the transmitter to release protein phosphate; (C) phosphate binds to the receiver initiating the output response. Abbreviations: T-Transmitter, R-Receiver, ATP-Adenosine triphosphate, ADP-Adenosine diphosphate, P-Phosphate. ATP and ADP are required to initiate communications between the transmitter and receiver proteins and phosphate is required to activate the receiver to produce a response [52, 53].

Ligands are found in the thesaurus under *material-solid-object* and *chemical energy*. In the case of TCRS, ligands are utilized as chemical signals, thus *chemical energy* was the chosen flow. Protein, an organic compound made of amino acids arranged in a linear chain and folded into a globular form [46], is synonymous with *material-solid-liquid-mix*, as is cell. Bind was found under multiple classifications. Join was

chosen to represent binding of chemical energy and a solid-liquid material. Binding causes *detection* of the stimulus signal. Detection causes a *status signal* to be *transferred* to the cytosolic domain, which causes the release of protein phosphate. Communication is now initiated. Phosphate, which under goes phosphorylation, acts as a *control signal* that is *transferred* to the receiver protein to *regulate and condition* the *chemical energy* within the bacterium to produce a response. The two components of TCRS are transmitter and receiver proteins, however, from a functional standpoint chemical energy is needed to join with and change the bacterium material to elicit a response. The textual and diagrammatic abstractions of TCRS can now be utilized for developing connections between biology and engineering. A functional model of TCRS in bacteria is shown in Figure 3.

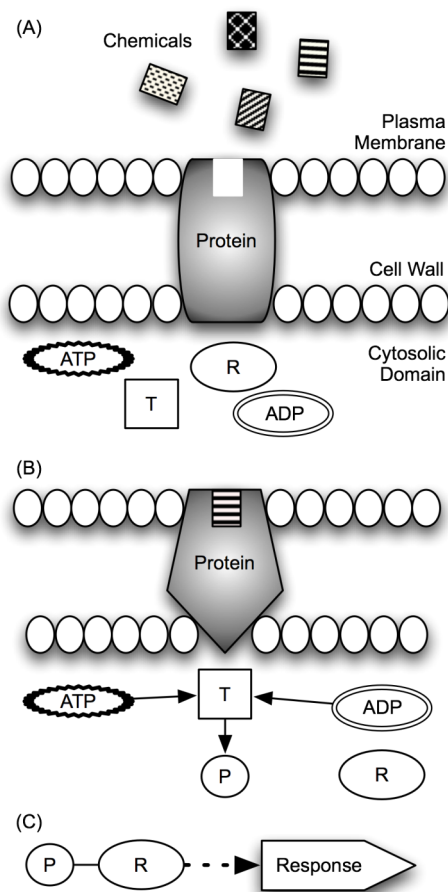


Figure 2: Method of sensing extracellular signals with TCRS in bacteria

CONCLUSIONS

The natural world provides numerous cases for inspiration in engineering design. From simple cases such as hook and latch attachments to articulated-wing aircrafts, 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 designs require that designers have knowledge of previous design solutions during engineering design activities. The learned representations from the decomposition of design solutions, engineered and biological, organized at different levels of abstraction allow connections to be discovered with cues taken from each level. This paper presented an engineering-to-biology thesaurus that (1) lessens the burden when working with knowledge from the biological domain by providing a link between engineering and biological terminology; (2) assists designers with establishing connections between the two domains to facilitate biologically-inspired designs; and (3) lists biological correspondent terms that an engineering designer interested in function-based design might encounter.

The version of the thesaurus presented in this paper represents an integration of three independent research efforts, which include research from Oregon State University, the University of Toronto, and the Indian Institute of Science, and their industrial partners. This research is a work-in-progress and is not a comprehensive list of all biological terms; however, it is among the first steps to bridging the gap between the biology and engineering domains. The overall approach for term integration and the final results are presented. Through this research, biological function and flow correspondent 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 biological flow correspondent terms are grouped at the tertiary level, whereas biological function terms are primarily grouped at the secondary level.

Implications of the proposed thesaurus on the engineering and biology communities were explored. Signal transduction in bacteria was analyzed as a comprehensive example that demonstrates the engineering-to-biology thesaurus applications of comprehension and functional modeling. Breaking down a biological solution into smaller parts, based on functionality, allows one to liken a biological system or phenomenon to an engineered system for ease of understanding and transfer of design knowledge. We believe the thesaurus will enable the engineering and biology communities to better collaborate, create and discover in the future. Furthermore, the engineering-to-biology thesaurus is a subject domain oriented, intermediary structure, which can be updated as needs are identified.

FUTURE WORK

Future work for improving the engineering-to-biology thesaurus includes examining potential terms through clustering and analyzing terms contained within the glossary of a collegiate entry-level biological textbook. While collocated terms provide an indication for macrorelevant terms, clustering analysis could be utilized to find less obvious, but equally important, biological terms for thesaurus population. Additionally, biological texts that focus on a topic of interest (i.e., insects, fungi) should be analyzed for relevant biological terms that an introductory text may not include.

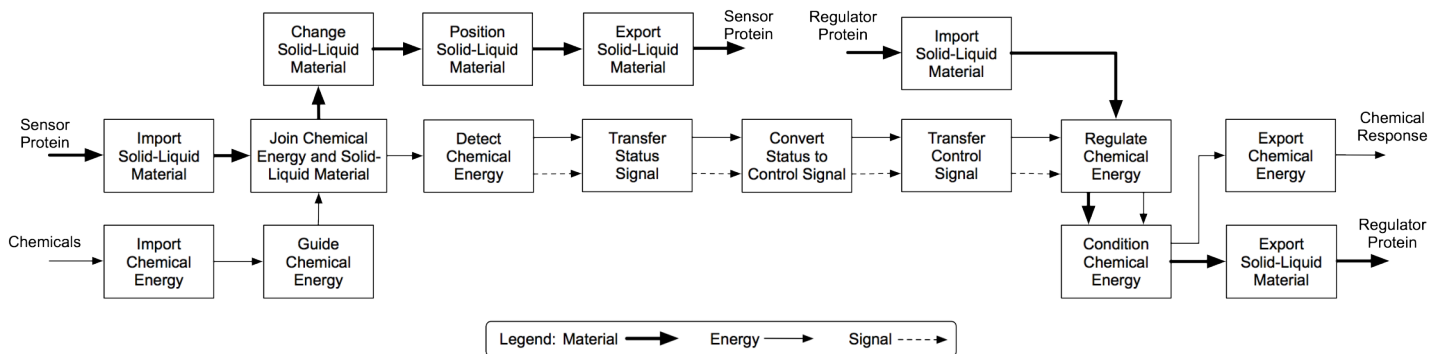


Figure 3: Functional Model of TCRS in Bacteria

Future work for the adoption of biologically-inspired engineering design involves integration of the thesaurus terms into computational concept generation software. This will enable a greater number of biological organisms, strategies and phenomena that achieve desired functionality to be found during concept generation. Thereby increasing the likelihood of biomimetic engineering solutions.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Brownell for his time and effort in the validation of the thesaurus terms. This material is based in part upon work supported by the National Science Foundation under Grant CMMI-0800596. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the NSF.

REFERENCES

[1] Bar-Cohen, Y., 2006, *Biomimetics Biologically Inspired Technologies*, CRC/Taylor&Francis, Boca Raton, FL.

[2] Hill, B., 1995, "Bionic - Element for Fixing the Aim and Finding the Solution in the Technical Problem Solving Process," Proc. IDATER 1995 Conference, Loughborough: Loughborough University. <http://hdl.handle.net/2134/1509>.

[3] Nachtigall, W., 1989, *Konstruktionen : Biologie Und Technik*, VDI, D, sseldorf.

[4] Nachtigall, W., 2002, *Bionik : Grundlagen Und Beispiele F,R Ingenieure Und Naturwissenschaftler*, Springer, Berlin [u.a.].

[5] Chiu, I., and Shu, L.H., 2007, "Biomimetic Design through Natural Language Analysis to Facilitate Cross-Domain Information Retrieval," *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 21(1), pp. 45-59.

[6] Chiu, I., and Shu, L.H., 2007, "Using Language as Related Stimuli for Concept Generation," *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 21(2), pp. 103-121.

[7] Vakili, V., and Shu, L.H., 2001, "Towards Biomimetic Concept Generation," Proc. 2001 ASME IDETC/CIE, Pittsburgh, Pennsylvania.

[8] Wilson, J.O., and Rosen, D., 2007, "Systematic Reverse Engineering of Biological Systems," Proc. 2007 ASME IDETC/CIE, Las Vegas, Nevada.

[9] Lindemann, U., and Gramann, J., 2004, "Engineering Design Using Biological Principles," Proc. International Design Conference - DESIGN 2004, Dubrovnik.

[10] Sarkar, P., Phaneendra, S., and Chakrabarti, A., 2008, "Developing Engineering Products Using Inspiration from Nature," *Journal of Computing and Information Science in Engineering*, 8(3), pp. 1-9.

[11] Wilson, J., Chang, P., Yim, S., and Rosen, D., 2009, "Developing a Bio-Inspired Design Repository Using Ontologies," Proc. 2009 ASME IDETC/CIE, California, USA.

[12] Vincent, J.F.V., Bogatyreva, O.A., Bogatyrev, N.R., Bowyer, A., and Pahl, A.-K., 2006, "Biomimetics: Its Practice and Theory," *Journal of the Royal Society Interface*, 3, 471-482.

[13] Tsujimoto, K., Miura, S., Tsumaya, A., Nagai, Y., Chakrabarti, A., and Taura, T., 2008, "A Method for Creative Behavioral Design Based on Analogy and Blending from Natural Things," Proc. 2008 ASME IDETC/CIE, New York.

[14] Mak, T.W., and Shu, L.H., 2004, "Abstraction of Biological Analogies for Design," *CIRPAnnals*, 531(1), 117-120.

[15] Mak, T.W., and Shu, L.H., 2008, "Using Descriptions of Biological Phenomena for Idea Generation," *Research in Engineering Design*, 19, pp. 21-28.

[16] Nagel, R., Tinsley, A., Midha, P., Mcadams, D., Stone, R., and Shu, L., 2008, "Exploring the Use of Functional Models in Biomimetic Design," *Journal of Mechanical Design*, 130(12), pp. 11-23.

[17] Stroble, J.K., Stone, R.B., and Mcadams, D.A., 2009, "Conceptualization of Biomimetic Sensors through Functional Representation of Natural Sensing Solutions," Proc. International Conference of Engineering Design, Stanford, California.

[18] Shu, L.H., Stone, R.B., Mcadams, D.A., and Greer, J.L., 2007, "Integrating Function-Based and Biomimetic Design for Automatic Concept Generation," Proc. ICED, Paris, France.

[19] Vakili, V., and Shu, L.H., 2007, "Including Functional Models of Biological Phenomena as Design Stimuli," Proc. 2007 ASME IDETC/CIE, Las Vegas, NV.

- [20] Stroble, J.K., Stone, R.B., and Watkins, S.E., 2009, "Biology Inspired Sensor Design," IEEE Potentials, 28(6), pp. 19-24.
- [21] Wicaksono, D.H.B., Pandraud, G., Craciun, G., Vincent, J.F.V., and French, P.J., 2004, "Fabrication and Initial Characterisation Results of a Micromachined Biomimetic Strain Sensor Inspired from the Campaniform Sensillum of Insects," Proc. IEEE Sensors 2004, 2, pp. 542-545.
- [22] Gnatzy, W., Grunert, U., and Bender, M., 1987, "Campaniform Sensilla of Calliphora Vicina (Insecta, Diptera) I. Topography," Zoomorphology, 160(pp. 312-319).
- [23] Grunert, U., and Gnatzy, W., 1987, "Campaniform Sensilla of Calliphora Vicina (Insecta, Diptera) Ii. Typology," Zoomorphology, 106(320-328).
- [24] Stroble, J.K., Stone, R.B., and Watkins, S.E., 2009, "An Overview of Biomimetic Sensor Technology," Sensor Review, 28(2), pp. 112-119.
- [25] Brebbia, C.A., and Collins, M.W., 2004, Design and Nature Ii: Comparing Design in Nature with Science and Engineering, WIT, Southampton.
- [26] Brebbia, C.A., Sucharov, L.J., and Pascolo, P., 2002, Design and Nature: Comparing Design in Nature with Science and Engineering, WIT, Southampton; Boston.
- [27] Brebbia, C.A., 2006, Design and Nature Iii: Comparing Design in Nature with Science and Engineering, WIT, Southampton.
- [28] Nagel, R.L., Vucovich, J.P., Stone, R.B., and Mcadams, D.A., 2007, "Signal Flow Grammars from the Functional Basis," Proc. International Conference of Engineering Design, Paris, France.
- [29] Hirtz, J., Stone, R., Mcadams, D., Szykman, S., and Wood, K., 2002, "A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts," Research in Engineering Design, 13(2), pp. 65-82.
- [30] Pahl, G., and Beitz, W., 1984, Engineering Design: A Systematic Approach, Springer-Verlag, London, UK.
- [31] Hundal, M., 1990, "A Systematic Method for Developing Function Structures, Solutions and Concept Variants," Mechanism and Machine Theory, 25(3), pp. 243-256.
- [32] Little, A., Wood, K., and Mcadams, D., 1997, "Functional Analysis: A Fundamental Empirical Study for Reverse Engineering, Benchmarking and Redesign," Proc. 1997 ASME IDETC/CIE, Sacramento, CA, 97-DETC/DTM-3879.
- [33] Szykman, S., Racz, J., and Sriram, R., 1999, "The Representation of Function in Computer-Based Design," Proc. Proceedings of the ASME Design Theory and Methodology Conference, Las Vegas, NV., DETC99/DTM-8742.
- [34] Stone, R., and Wood, K., 2000, "Development of a Functional Basis for Design," Journal of Mechanical Design, 122(4), pp. 359-370.
- [35] Stroble, J.K., Stone, R.B., Mcadams, D.A., and Watkins, S.E., 2009, "An Engineering-to-Biology Thesaurus to Promote Better Collaboration, Creativity and Discovery," Proc. CIRP Design Conference 2009, Cranfield, Bedfordshire, UK, pp. 353-368.
- [36] Chakrabarti, A., Sarkar, P., Leelavathamma, B., and Nataraju, B.S., 2005, "A Functional Representation for Aiding Biomimetic and Artificial Inspiration of New Ideas," AIEDAM, 19(pp. 113-132).
- [37] Srinivasan, V., and Chakrabarti, A., 2009, "Sapphire - an Approach to Analysis and Synthesis," Proc. 3rd Symposium on Research in Product Design, CPDM, IISc, Bangalore, India.
- [38] Srinivasan, V., and Chakrabarti, A., 2009, "Sapphire – an Approach to Analysis and Synthesis," Proc. International Conference on Engineering Design, Stanford, USA.
- [39] Hacco, E., and Shu, L.H., 2002, "Biomimetic Concept Generation Applied to Design for Remanufacture," Proc. 2002 ASME IDETC/CIE, Montreal, Canada.
- [40] Cheong, H., Shu, L.H., Stone, R.B., and Mcadams, D.A., 2008, "Translating Terms of the Functional Basis into Biologically Meaningful Words," Proc. 2008 ASME IDETC/CIE, New York City, NY.
- [41] Lopez-Huertas, M.J., 1997, "Thesaurus Structure Design: A Conceptual Approach for Improved Interaction," Journal of Documentation, 53(2), pp. 139-177.
- [42] Campbell, N.A., and Reece, J.B., 2003, Biology, Pearson Benjamin Cummings, San Francisco.
- [43] Stroble, J.K., Stone, R.B., Mcadams, D.A., Goeke, M.S., and Watkins, S.E., 2009, "Automated Retrieval of Non-Engineering Domain Solutions to Engineering Problems," Proc. CIRP Design Conference 2009, Cranfield, Bedfordshire, UK, pp. 78-85.
- [44] Mckean, E., 2005, The New Oxford American Dictionary, Oxford University Press, New York.
- [45] Lawrence, E., and Holmes, S., 1989, Henderson's Dictionary of Biological Terms, Wiley, New York.
- [46] Matrin, E., and Hine, R.S., 2000, Oxford Dictionary of Biology, Oxford University Press, Oxford.
- [47] Nagel, J.K.S., and Stone, R.B., 2010, "A Computational Concept Generation Technique for Biologically-Inspired, Engineering Design," Proc. Design Computing and Cognition DCC'10, J.S. Gero, ed. University of Stuttgart, Stuttgart, Germany.
- [48] Cross, N., 2008, Engineering Design Methods : Strategies for Product Design, John Wiley & Sons, Chichester.
- [49] Otto, K.N., and Wood, K.L., 2001, Product Design: Techniques in Reverse Engineering and New Product Development, Prentice-Hall, Upper Saddle River, New Jersey.
- [50] Ulrich, K.T., and Eppinger, S.D., 2004, Product Design and Development, McGraw-Hill/Irwin, Boston.
- [51] Volland, G., 2004, Engineering by Design, Pearson Prentice Hall, Upper Saddle River, NJ.
- [52] Taiz, L., and Zeiger, E., 2006, "Chapter 14: Gene Expression and Signal Transduction," Sinauer Associates, Inc., Sunderland.
- [53] Parkinson, J.S., 1995, "Genetic Approaches for Signaling Pathways and Proteins," in Two-Component Signal Transduction, J.A. Hoch and T.J. Silhavy, eds., ASM Press, Washington, D.C.

ANNEX A

ENGINEERING-TO-BIOLOGY THESAURUS

<i>Class</i>	<i>Secondary</i>	<i>Tertiary</i>	<i>Biological Function Correspondents</i>	
Branch	Separate		Bleaching, meiosis, abscission, mitosis, segment, <i>electrophoresis</i> , dialysis, denature, free, detach, release	
		Divide	Division, prophase, metaphase, anaphase, cleave, cytokinesis	
		Remove	Deoxygenate, filtrate, liberate, expulsion, evacuate	
	Distribute		Circulate, diffusion, exchange, disperse, scatter, spread, spray	
Channel	Import		<i>Absorb</i> , attract, consume, inhale, intake	
		Export	<i>Bind</i> , block, breakdown, excrete, inactivate, repel	
	Transfer		Migrate, transfer	
		Transport	Circulate, conduct, diffuse, pump, shift, displace, fly, swim, jump, bounce	
		Transmit	<i>Communicate</i> , <i>transduce</i>	
	Guide		Orient, position, slide, tunnel	
		Translate	<i>Synthesize</i> , transcribe	
Rotate		Oscillate, spin, turn, swivel, roll		
	Allow DOF		Articulate	
Connect	Couple		Recombination, mate, build, phosphorylate, bond, <i>synthesis</i> , latch, lock, extend, link, overlap	
		Join	<i>Bind</i> , adhere, bond, fuse	
		Link	Clamp, <i>activate</i> , <i>bind</i> , project	
	Mix		Blend, <i>contract</i> , exchange, fragment	
Control Magnitude	Actuate		<i>Activate</i> , induce, trigger	
	Regulate		<i>Electrophoresis</i> , gate, organogenesis, respire, sustain, preserve, remain, stabilize, maintain, regulate	
		Increase		Hyperpolarize, <i>pinocytosis</i> , <i>grow</i> , expand, multiply, replicate
		Decrease		Compress, coil, divide, fold, shorten, <i>wrap</i>
	Change			<i>Pinocytosis</i> , <i>degrade</i> , alter, <i>bind</i> , catalyze, <i>contract</i> , hydrolysis, twist, <i>mutate</i> , radiate, charged, slip, acclimatize, alternate, fluctuate
		Decrement		Decarboxylation, <i>constrict</i>
		Shape		Elongate, <i>stretch</i> , attach, <i>spread</i>
		Condition		Osmosis, <i>constrict</i>
	Stop			Clog, extinguish, halt, interphase, seal, suspend
		Prevent		Constrain, obstruct
Inhibit			Cover, destroy, inhibit, repress, <i>surround</i>	
Convert	Convert		Polymerize, <i>synthesize</i> , burn, gluconeogenesis, metabolize, <i>grow</i> , <i>transduction</i> , fermentation, glycolysis, hydrolyze, hydrolysis, respiration, ionize, decompose, <i>degrade</i> , <i>develop</i> , <i>mutate</i> , <i>photosynthesize</i>	
Provision	Store		Conserve, <i>hold</i> , <i>convert</i> , deposit, <i>photosynthesize</i>	
		Contain	<i>Absorb</i>	
		Collect	<i>Absorb</i> , catch, breakdown, concentrate, digest, reduce	
	Supply		Feed, lactate	
Signal	Sense	Detect	Detect, locate, see, smell	
		Measure	Observe, monitor, gauge, watch	
	Indicate		Fluoresce, <i>communicate</i> , <i>react</i> , mark	
	Process		Learn	
Support			<i>Develop</i> , <i>wrap</i>	
	Stabilize		Homeostasis, cling, <i>hold</i> , <i>bind</i> , <i>connect</i>	
	Secure		<i>Surround</i> , envelope	
Overall increasing degree of specification →				

Class	Secondary	Tertiary	Biological Flow Correspondents	
Material	Human		Being, <i>body</i>	
	Gas		Oxygen, nitrogen, chlorine	
	Liquid		Acid, chemical, water, <i>blood, solution</i> , base, buffer, fluid, plasma	
	Solid	Object		Fiber, <i>body</i> , substrate, microfilament, microtubules, structure, chain, <i>organ</i> , nucleus, <i>tissue</i> , muscle, cilia, flagella, tube, vein, heart, plant, ribosome, somite, apoplast, stem, kidney, egg, ovary, leaf, embryo, bacteria, chloroplast, carbon, sperm, glucagons, adipose, angiosperm, meristems, mineral, stoma, shoot, seed, capillary, receptors, hair, bone, tendon, neuron, sporangium, photoreceptors, mechanoreceptors, chromosome, petiole, lysosome, archaea, cone, strand, centriole, spore, zygote, sulfur, lipoprotein, nephron, hyphae, plasmodesma, conifer, plasmid, plastid, xylem, pigment, sperm, hippocampus, phloem
			Particulate	Cytokinin, pyruvate, nicotine, opium, glycerol, carotenoid, , GTP, ATP, urea, <i>RNA</i> , tRNA, mRNA, <i>DNA</i> , glucagon, parathormone, cryptochromes, <i>ligand</i> , promoter, gene, exon, intron, molecule, <i>enzyme, lipid, hormone</i>
			Composite	<i>Enzyme</i> , virus, ribosome, prokaryote, macromolecule, polymerase, nucleotide, polypeptide, organelle, symplast, mesophyll, brood, codon, messenger, <i>DNA, RNA</i> , cytoplasm, <i>organ, tissue</i>
	Mixture	Gas-gas		Air
		Liquid-liquid		<i>Hormone</i> , melatonin, thyroxine, calcitonin, thyrotropin, estrogen, somatostatin, cortisol, glucagon, adrenocorticotropic, testosterone, auxin, insulin, intracellular fluid, extracellular fluid, spinal fluid, poison, urine, peptide, <i>solution</i> , steroid
		Solid-solid		Adenosine, glomerulus, blastula, monosaccharide, membrane, phosphate, ribosome, centrosomes
		Solid-Liquid		Algae, synapse, peptidoglycan, cell, glia, phytochrome, retina, protein, repressor, hemoglobin, <i>blood</i> , membrane, bacterium
	Signal	Status		Change, variation, lateral, swelling, catalyzed, translation, exposed, active, separated, cycle, formation, reaction, redox, deficient, saturated, diffusion, broken, hybridization, orientation, resting, cue, magnetic, volume, under, organized, fruiting, fatty, anaphase, metaphase, prophase, conjugation, osmolarity, senescence, signal, allele
			Auditory	Sound
Olfactory			Smell	
Tactile			Pain	
Taste			Gustation	
Visual			Length, shortened, long, dark, full, double	
Control			Place, inhibit, release, excrete, development, match, induce, digest, integrate, translation, transduction, equilibrium, grown, splice, capture, distribute, phosphorylation	
		Analog	Binding, center, synthesis, photosynthesis	
	Discrete	Flower, translocation		
Energy	Human			
	Acoustic		Echolocation, sound wave	
	Chemical		Calorie, metabolism, glucose, glycogen, <i>ligand</i> , nutrient, starch, fuel, sugar, mitochondria, <i>lipid</i> , gibberellin	
	Electrical		Electron, potential, feedback, charge, field	
	Electromagnetic	Optical		Light, infrared
		Solar		Light, sun, ultraviolet light
	Hydraulic		Pressure, osmosis, osmoregulation	
	Magnetic		Gravity, field, wave	
	Mechanical			Muscle contraction, pressure, tension, stretch, depress
		Rotational		
		Translational		
Pneumatic			Pressure	
Thermal			Temperature, heat, infrared, cold	
Overall increasing degree of specification →				