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Biologically Meaningful Keywords for Functional Terms of the Functional Basis

Biology is recognized as an excellent source of analogies and stimuli for engineering design. Previous work focused on the systematic identification of relevant biological analogies by searching for instances of functional keywords in biological information in natural-language format. This past work revealed that engineering keywords could not always be used to identify the most relevant biological analogies as the vocabularies between biology and engineering are sufficiently distinct. Therefore, a retrieval algorithm was developed to identify potential biologically meaningful keywords that are more effective in searching biological text than corresponding engineering keywords. In our current work, we applied and refined the retrieval algorithm to translate functional terms of the functional basis into biologically meaningful keywords. The functional basis is widely accepted as a standardized representation of engineering product functionality. Therefore, our keywords could serve as a thesaurus for engineers to find biological analogies relevant to their design problems. We also describe specific semantic relationships that can be used to identify biologically meaningful keywords in excerpts describing biological phenomena. These semantic relations were applied as criteria to identify the most useful biologically meaningful keywords. Through a preliminary validation experiment, we observed that different translators were able to apply the criteria to identify biologically meaningful keywords with a high degree of agreement to those identified by the authors. In addition, we describe how fourth-year undergraduate mechanical engineering students used the biologically meaningful keywords to develop concepts for their design projects. [DOI: 10.1115/1.4003249]

1 Introduction

Biomimetic design uses biological phenomena as inspiration to solve engineering problems. Humans have borrowed many ideas from biology for design. Although many examples of successful biomimetic design exist, most of them were inspired from chance observation. As such, the potential of using biological phenomena to create innovative designs may be limited by an engineer's existing or chance biological knowledge. Therefore, engineers may benefit from a systematic method that helps them access the vast amount of biological information in existence, which may lead to more novel and useful concepts.

Our approach has focused on directly searching biological information that is already available in natural-language format, e.g., texts, papers, etc. However, past work revealed that this approach may be limited by differences in lexicons, or vocabularies, between the domains of engineering and biology, i.e., words widely used in engineering might be used in different meanings or uncommonly in biology and vice versa [1]. Hon and Zeiner [2] supported that product design information retrieval is challenging because different words could describe the same functions. Chiu and Shu [3] therefore developed an algorithm to identify potential biologically meaningful keywords that can locate biological analogies, which may not be otherwise found if the engineering keywords describing the problem were used for the search instead.

This retrieval algorithm is adapted and refined here to generate biologically meaningful keywords that correspond to functional terms of the functional basis developed by Stone and Wood [4]. The functional basis has been widely accepted as a standardized set of engineering terms used for functional modeling. We believe that this translation is a significant step toward allowing engineers better access to biological analogies for design. Once engineers functionally model a desired product, they can look up the corresponding biologically meaningful keywords and use them to search for relevant biological analogies.

The functional basis consists of generic taxonomies of engineering functions, defined as function sets, and associated flows to describe product functionality [5]. Function sets are represented by verbs, and flows are represented by nouns. In this work, we translated the function sets to obtain biologically meaningful keywords that are verbs as well. Using verbs to serve as biologically meaningful keywords enables engineers to explore various biological phenomena related to the verb function, rather than focusing on a particular biological phenomenon associated with a noun [6,7]. For example, for the engineering function "protect," searching with the keyword verb "cover" will locate various phenomena related to covering and protecting. However, searching for the biological noun "cuticle" will only result in information related to cuticles. A cuticle is the thin outermost noncellular layer covering parts of plants and invertebrates and is only one means in biology to enable covering and protection.

This paper presents how biologically meaningful keywords for the function sets of the functional basis were systematically identified. First, we present nomenclature used in this paper before discussing relevant work and describing the retrieval algorithm. Next, we present identification criteria for selecting the most useful biologically meaningful keywords and discuss how these new keywords usually form specific semantic relations with the original functional keywords. We then present a set of biologically meaningful keywords that correspond to function sets of the functional basis, discuss preliminary assessments of the identification criteria, and provide examples of how fourth-year undergraduate mechanical engineering students successfully used some of the

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keywords to generate concepts for design projects. We conclude by discussing the significance of our work and future research possibilities.

2 Nomenclature

Biologically meaningful: used to denote a keyword that may be more effective in searching biological text than the corresponding engineering keyword. A biologically meaningful keyword could be either biologically significant or connotative as defined below [3].

Biologically significant: used to denote a word identified as part of a biology term defined in Biology-online.org [3,8].

Biologically connotative: used to denote a word that is not part of a biology term defined in the biology reference above but appears in definitions of biology terms [3].

Bridge verb: a verb other than the original search verb that is modified by nouns frequently associated with the original verb. A bridge verb is a potential biologically meaningful keyword [3]. Refer to Sec. 4.3 for a detailed example.

Causal relation: a relation where one action is caused by another action, e.g., in a phrase "A chases B, and B flees," the verbs "chase" and "flee" are said to be in a causal relation.

Corpus: a collection of written text on a particular subject.

Correspondent: Not used in functional modeling with the functional basis but enables mapping from terms that are not in the functional basis to terms that are [4]. In our work, we used correspondents to expand the search queries for related keyword groups.

Function set: terms of the functional basis used to represent engineering product functions and are classified into three levels or classes: primary, secondary, and tertiary [4].

Hood: in WordNet, contains a group of words that are troponyms of a generic hypernym that defines the hood [9].

Hypernym: a word with a broad meaning that more specific words fall under. For example, plant is a hypernym of tree as a tree is a specific type of plant.

Keyword group: a domain-general group of function sets organized based on WordNet hoods. Our biologically meaningful keywords are categorized using keyword groups.

Sense: the meaning of a word. Words can have multiple senses, which are enumerated in WordNet [10]. For example, the first sense of "tree" refers to a woody plant and the second sense of "tree" refers to a diagram with branches, e.g., "family tree."

Troponym: a word that denotes a specific manner of doing something, e.g., "to shield" is a troponym of "to protect."

WordNet: an online lexical database that groups words into hierarchical sets of synonyms called *synsets*. For instance, "to stop" and "to halt" belong to one synset. It then organizes these synsets based on their semantic relations to each other, e.g., one synset term being a troponym of another [10].

3 Background

In this section, we describe how analogical reasoning between the domains of biology and engineering is particularly promising for design and outline the approaches taken to support biologically inspired design. We also discuss the significance and usefulness of the functional basis.

3.1 Interdomain Analogical Reasoning. Many researchers agree that analogical reasoning plays a key role in creative design [11–13]. In particular, analogical transfer across different domains (cross-domain) seems to provoke more creative ideas than analogical transfer within the same domain (within-domain). Bonnardel [14] examined characteristics of analogical sources that lead to more creative designs and found that cross-domain sources inspired designers more than within-domain sources. Hon and Zeiner [2] found that existing ideas from one domain could appear new and creative when they change form in another domain. Benami and Jin [15] found that analogies from different domains provided more creative and novel ideas, and the most ambiguous form of stimuli lead to the most ideas. Such ambiguity is more likely to be present when relating a source that is in a different domain from the design domain. Tseng et al. [16] also found that presenting distantly related ideas stimulated innovative or creative solutions when designers had open goals.

Cross-domain analogical transfer involves transfer of deeper relations than within-domain analogical transfer [17]. In within-domain transfer, perceptual similarities such as shape and forms are often mapped from a source to a target. Cross-domain transfer, on the other hand, requires designers to map relational patterns such as functional similarities from a source to a target. This can be challenging because an analogical source and a possible design solution may not exhibit perceptual similarities.

Biomimetic design requires cross-domain analogical transfer and thus involves the challenge of retrieving and recognizing relevant analogies. Gordon [18] observed that biology provides the richest source of direct analogies for creative solutions. However, many successful biomimetic solutions or designs were inspired from perceptual or intuitive recognition of similar forms or functions in biology. There are many possible biological analogies that remain unrecognized, and an engineer's limited knowledge of biology hinders the identification and application of relevant biological analogies. Section 4 presents approaches that aim to facilitate cross-domain analogical transfer from biology to engineering.

3.2 Other Work in Biomimetic Design. There have been several efforts relevant to identifying and applying biological phenomena to engineering design. Singh et al. [19] identified analogies in nature for their transformation principles, which help designers create innovative products that can transform between different configurations. Wilson and Rosen [20] applied reverse engineering to biological systems to extract the biological strategy after the appropriate analogy is already identified. Bar-Cohen [21] identified many solutions that can be developed using biological analogies and suggested constructing a database of biological principles in terms of engineering needs. Vincent [22] extended the theory of inventive problem-solving (TRIZ) database to include biological phenomena and created a BioTRIZ matrix. TRIZ is a methodology that provides an algorithmic problem-solving approach based on a knowledge base of past patents [23].

3.3 Approach Taken at the University of Toronto. Creating and updating databases of biological phenomena, however, represent a tremendous undertaking. This challenge becomes more significant as researchers must keep up with rapidly increasing biomedical knowledge [24]. Creating and organizing such databases would require personnel with expertise in both engineering and biology [21] and could be subject to personal bias. Instead of constructing a database of biological phenomena, our approach is to provide engineers with search keywords that enable them to explore the enormous amount of biological knowledge already available in natural-language format, e.g., texts, papers, etc. Our initial efforts focused on the functions, instead of entities, in biology to find analogies because functions are more logically transferred between domains [25]. Vincent [26] supports that an important step in biomimetic design is the transfer of biological functions to engineering contexts.

Vakili and Shu [25] initiated the use of synonyms of engineering functional keywords to increase the number of relevant biological phenomena found while searching a biological corpus. Chiu and Shu [1] incorporated the use of WordNet [10] to determine synonyms, hypernyms, or troponyms for engineering keywords. Singh et al. [19] also used synonyms of engineering keywords to search for biological analogies for their transformation principles in biological literature.

Chiu and Shu [3] developed a systematic algorithm that uses natural-language analysis, specifically word collocation and frequency analysis, to facilitate cross-domain information retrieval by identifying potential biologically meaningful keywords.

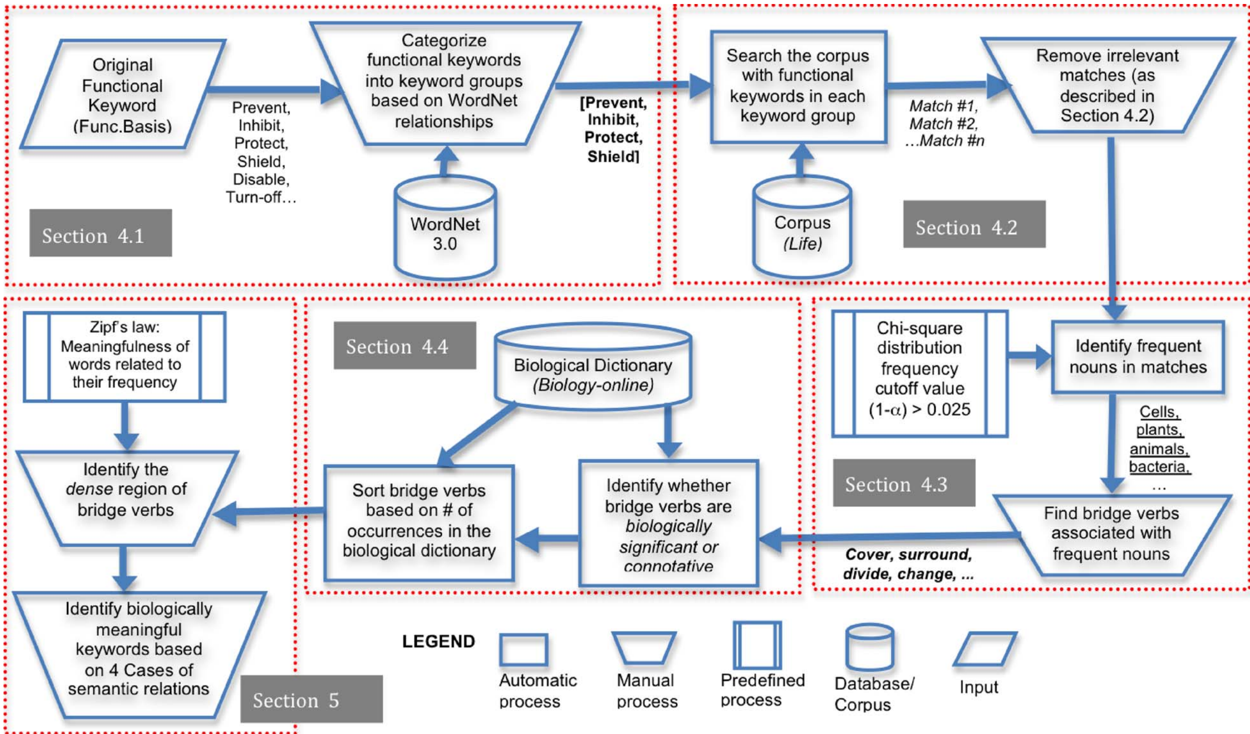

Fig. 1 A flowchart showing the sequence and different steps of the biologically meaningful keyword translation algorithm, with references to the corresponding sections

The natural-language search approach to supporting biomimetic design has been used successfully in past case studies, including the redesign of snap fits to facilitate remanufacture [27], the handling and assembly of microparts [28], and protection of space equipment from lunar dust [29].

3.4 Functional Basis. In this work, biologically meaningful keywords corresponding to the function sets of the functional basis are identified. The functional basis developed by Stone and Wood [4] has been widely accepted as a standardized set of engineering terms used for functional modeling. It provides formalized representations in function-based design by using a set of generic vocabulary. This reduces ambiguity at the modeling level, makes processing information easier at the concept level, and increases the uniformity of information within functional models. We believe that translating the functional basis into biologically meaningful keywords is a significant contribution to the field of design theory and methodology.

The functional basis describes product functions with a verb-object format in a domain-general language. Domain-general descriptions are essential in transferring and relating functions of one system to another. Wilson and Rosen [20] support that functional abstraction is required in reverse engineering of biological systems. Although domain-general descriptions provide benefits, retrieving useful information from the specific domain of biology requires domain-specific keywords. Our translation of the functional basis to biologically meaningful keywords provide the bridge between domain-general and domain-specific keywords.

4 Methods

We adapted and refined the algorithm previously developed [3] to generate biologically meaningful keywords that correspond to the function sets of the functional basis. In this section, we summarize this process and provide examples and insights gained from implementing the algorithm. Figure 1 presents a flowchart of the overall algorithm and identifies sections of the paper that describe the corresponding steps of the algorithm.

4.1 Identifying Original Functional Keywords. We first identified the original functional keywords that describe the engineering problem to search a biological corpus. The corpus selected for our study was *Life: the Science of Biology* [30], an introductory university-level biology textbook. The corpus is written in natural-language format and explains biological phenomena in a detailed yet understandable manner. Other texts could easily replace the current corpus or be added for the initial search.

The original functional keywords are composed of the function sets in the functional basis and their *correspondents*, which are not used in functional modeling but "enables mapping between terms that are not used in the modeling to terms that are" [4]. These keywords would return matches with biological phenomena that are possible analogies and frequently, the biologically meaningful keywords of interest are contained in these matches.

The function sets were grouped based on lexical similarities found in WordNet [10]. WordNet is an online lexical database that organizes words into a hierarchy of *synsets*, i.e., sets of synonyms. In a typical WordNet hierarchy, more generic words, i.e., hypernyms, are found on the top, while more specific words, i.e., troponyms, are found at the bottom. For example, Fig. 2 shows that, "prevent" is an inherited hypernym of "inhibit," "protect," and "shield." Conversely, "shield" is a troponym of "protect."

We manually regrouped the function sets and the correspondents into *keyword groups* based on whether they belong to the same WordNet *hood* [9]. Headed by a more generic word, a hood contains troponyms of this generic word. In Fig. 2, "prevent" defines its own specific hood, and functional basis terms that are troponyms, "inhibit," "protect," and "shield" belong in this hood. The higher-level function set term, "stop," does not belong in this hood and would form another keyword group. In this paper, we designate keyword groups with associated function set terms in capitalized letters, e.g., PREVENT+INHIBIT. The search matches of the original functional keywords in PREVENT+INHIBIT, e.g., "prevent," "inhibit," "protect," and "shield," are analyzed together to generate a set of biologically meaningful keywords for the keyword group.

(Functional Basis)

Class (Secondary)	*Tertiary*	*Correspondents*
Stop		**End, halt, pause, interrupt, restrain**
	Prevent	Disable, turn-off
	Inhibit	Shield, insulate, protect, resist

(WordNet)

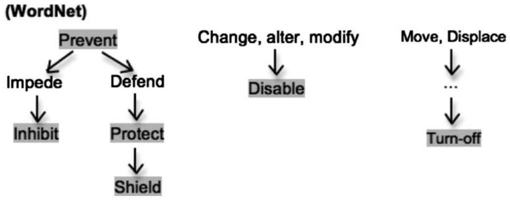

Fig. 2 Top: keywords in the functional basis [5]. Bottom: keywords regrouped based on WordNet where "disable" and "turn-off" are in different groups from "prevent."

Grouping several related original functional keywords together improves the results of the retrieval algorithm. By searching with a number of related function sets and correspondents, we can obtain more matches and create a larger list of potential biologically meaningful keywords. This is especially important if a certain function set on its own is not frequently used in biology. A large number of matches helps us to systematically assess potential biologically meaningful keywords using a frequency analysis, which will be explained later.

One limitation of this keyword grouping is that the same biologically meaningful keyword could appear under more than one group. This occurs mainly because many words have more than one sense. For example, "transduce" was retrieved as a biologically meaningful keyword for both keyword groups TRANSMIT and TRANSPORT. Therefore, when using the biologically meaningful term "transduce" to find relevant phenomena associated with TRANSMIT, one may also obtain results that are associated with TRANSPORT.

4.2 Screening Search Matches. Search results obtained using the original functional keywords were manually examined to remove any matches that use the keywords in senses unrelated to the intended search. For example, "conduct" could be intended in the sense of "transmitting by conduction" or in the sense of "manage or control" as in conducting a survey. Uses of "conduct" in the second sense are not relevant and were removed from the match results. Some words are used in different senses because they have domain-specific meanings in biology. For example, "reduce" and "fix" are used to describe chemical processing of molecules or substances in biology. In fact, most match results for both words refer to these chemical phenomena rather than phenomena that "reduces" a flow or "fixes" a flow path, as implied by function definitions [4].

Matches containing the original functional keyword in a related sense but acting on abstract objects are also less useful. For example, when searching with "support," the match "to support the hypothesis" is not helpful since it does not describe a physical phenomenon, e.g., "to support the load," which is typically more useful in solving mechanical design problems.

4.3 Identifying Bridge Verbs. Excerpts of the relevant match results were stored and a word-count computer script was used to find the frequency of each word appearing in the excerpts. A frequency analysis was then performed to identify the most frequently appearing nouns. Based on the similarity to the chi-squared distribution with one degree of freedom, cutoff values of $(1\text{-}\alpha) > 0.025$ were used to identify the most frequent nouns [3].

These frequent nouns are typically associated with either the original functional keyword or another verb. The verb other than the original functional keyword is then designated a *bridge verb* [3]. These bridge verbs are potential biologically meaningful keywords because the frequent nouns associated with these verbs tend to appear in the description of the more dominant biological phenomena retrieved with the original functional keyword.

For example, for the functional keyword "protect," the most frequent nouns in the match results include "plant," "cell," "embryo," and "body." We then identified the bridge verbs that are associated with these frequent nouns by examining the corresponding excerpts. An excerpt from Purves et al. [30] retrieved by the keyword "protect" will be used to illustrate:

"Within the shell and ***surround***ing the embryo are membranes that **protect** the embryo from desiccation…"

Here, "protect" was the original functional keyword and "embryo" is one of the most frequent nouns. We then observed that "surround" is also associated with "embryo," therefore designating it a potential biologically meaningful keyword.

4.4 Categorizing the List of Bridge Verbs. The list of bridge verbs was classified into two groups using an online biological dictionary [8]. When a word (or one of its grammatical forms) is a term or part of a term that is defined in the dictionary, the word is labeled as *biologically significant*. When a word is not part of a defined term but is used in the definition of other terms, the word is labeled as *biologically connotative*. A computer script was used to automatically search the biological dictionary database with each bridge verb.

For the keyword group PREVENT+INHIBIT, one of the bridge verbs, "bind" was a defined term and was therefore denoted biologically significant. On the other hand, "surround" was not a defined term in the biological dictionary but was nonetheless used in the definition of other biological terms and therefore was denoted biologically connotative.

We then used a computer script to automatically determine the frequency of each bridge verb in the biological dictionary [8]. The list of bridge verbs was then sorted in descending order by frequency of occurrence. The sorted lists tend to consist of a central dense region where the majority of biologically significant words are found. Words that occur less frequently tend to be more biologically specific and are considered more carefully than more frequent words that tend to be too general. The biologically connotative words found in this dense region were likely to serve as useful keywords [3].

5 Identification of Biologically Meaningful Keywords

The algorithm initially developed by Chiu and Shu [3] can generate a list of potential biologically meaningful keywords. However, each keyword group may contain between 100 and 200 bridge verbs. Therefore, criteria are needed to identify the most useful biologically meaningful keywords. While examining the bridge verbs, we recognized four semantic relations formed between the most useful biologically meaningful keywords and the original functional keywords. Based on these four cases described below, we were able to systematically identify the most useful biologically meaningful keywords.

5.1 Case 1: Synonymous Pair. Many words are used synonymously in the biological domain and appear in the same sentence almost adjacent to each other. Usually, this occurs when a certain biological phenomenon is explained first by a more commonly used verb, followed by a more biologically meaningful verb. An example from Purves et al. [30] follows:

"This information is received and **converted**, or ***transduced***, by sensory cells into electric signals…"

Here, "convert" is the original functional keyword used to locate the above match, and "transduce" is the biologically meaningful keyword identified. Both "convert" and "transduce" bear the same meaning of changing the form of energy in biology.

(Functional Basis)

Class (Primary)	Secondary	Tertiary	Correspondents
Channel	Transfer		Carry, deliver
		Transport	Advance, lift, move
		Transmit	Conduct, convey

Fig. 3 Function set terms under secondary class, "transfer," where "conduct" is under tertiary class "transmit," not "transport"

Although "convert" and "transduce" are used synonymously in biology, in the WordNet hierarchy, "transduce" is an inherited troponym of "convert."

5.2 Case 2: Implicitly Synonymous Pair. For the above case, locating the synonymous biologically meaningful word is straightforward. However, these synonymous words sometimes appear in a separate clause or sentence. These require a closer investigation of search results than the first case, and most such synonyms appear in this manner.

"The xylem of tracheophytes ***conducts*** water from roots to aboveground plant parts. It contains conducting cells called tracheary elements, which undergo programmed cell death before they assume their function of **transporting** water and dissolved minerals."

In this excerpt by Purves et al. [30], "conduct" and "transport" essentially describe the same action performed on the same object and are used interchangeably in biology. Although these two verbs are used synonymously here, neither the *Oxford Thesaurus* [31] nor the *Merriam-Webster Thesaurus* [32] identifies these words as synonyms of each other.

As shown in Fig. 3, "conduct" and "transport" both appear in the functional basis under the same secondary class set "transfer," so the corresponding biologically meaningful keywords for one could also serve for the other. In the hierarchical organization of the functional basis, "transmit" and "transport" lie separately on the same tertiary level, under "transfer," but "conduct" is one of the correspondents of "transmit," not "transport." In WordNet, "conduct" and "transmit" both fall under the more general term "transport," another example difference in grouping between the functional basis and WordNet.

5.3 Case 3: Biologically Specific Form. Biologically meaningful words can sometimes comprise a particular manner or form of accomplishing an original functional keyword specific to biological phenomena. Some examples include "photosynthesize" as a specific manner to enable "convert" and presented below, "mutate" as a specific manner to enable "transform."

"***Mutations*** of one of the homeotic genes, bithorax, **transform** the third thoracic segment into a second copy of the second thoracic segment."

In the above excerpt from Purves et al. [30], "mutate" is a specific means in biology to "transform" a thoracic segment into another. Both "mutate" and "transform" are direct troponyms of "change" in WordNet. However, "mutate" is a specific manner of, or a troponym of, "transform," based on biological phenomena. "Mutate," not surprisingly, is not part of the functional basis.

5.4 Case 4: Causal Relation. Case 4 follows a higher-order relation than the first three cases and is called a causal relation. That is, one action is performed to enable another action. The following is an example passage from Purves et al. [30]:

"Humans **absorb** amino acids by ***breaking down*** proteins from food."

In this example, the action of "breaking down" proteins leads to the action of "absorbing" amino acids. Most of the biologically meaningful keywords identified for the functional basis fall under this category. Another example of a causal relation from Purves et al. [30] is:

"Concentric layers of muscle tissue enable the stomach to ***contract*** to **mix** food with the digestive juices."

In the above example, the biologically meaningful keyword "contract" allows or enables another action, that of "mix." Word pairs, such as those identified above, are related in biology, but often no relationship between them is identified in WordNet. An engineer with limited biological knowledge would not likely recognize the biologically meaningful keywords associated in causal relations.

Furthermore, we found a causal relation to be more useful when the biologically meaningful word is the verb that allows or enables the action of the original functional keyword. For example, in searching for a biologically meaningful keyword for "mix," the below excerpt from Purves et al. [30] was found:

"Two strains of bacteria allow genetic material to **mix** and recombine to ***produce*** cells containing…"

In this case, "mix" is the verb that enables the "producing" of cells, but we do not learn anything about how the mixing is done. The purpose of the biologically meaningful keyword is to identify strategies that solve the problem associated with the original functional keyword. That is, engineers are likely more interested in how biological phenomena achieve a desired function than the actions that result from the desired function in biology.

6 Presentation of Biologically Meaningful Keywords

Table 1 contains the biologically meaningful keywords for function sets of the functional basis. Below we provide suggestions on how to use the keywords.

For each keyword group, biologically meaningful keywords are listed by decreasing percentage of collocation with the original functional keywords. For example, under the keyword group TRANSFER, 60% of the matches retrieved by the biologically meaningful keyword "conjugate" collocated with the original functional keywords, "transfer," "shift," or "move." Another biologically meaningful keyword "break" only had 8% collocation with those three original functional keywords. Searching with the keyword "break" may retrieve more biological phenomena but at the risk of more irrelevant matches, while searching with the keyword "conjugate" could lead to a small number of specific but possibly more relevant, biological phenomena related to the function of TRANSFER.

Keyword groups may include specific correspondents presented in parenthesis. The biologically meaningful keywords listed beside the parenthesized correspondent were associated only with that correspondent. In other words, the matches retrieved with these biologically meaningful keywords would contain only one specific correspondent that was used as an original functional keyword. The organization of keywords by correspondents conveys that these keywords are particularly useful when that specific correspondent best describes the desired functions.

We recommend that biologically meaningful keywords that result in a high number of total matches and low collocation rates (shown in right most columns of Table 1) be used in conjunction with the original functional keywords in an and-search when searching the biological corpus. Examples of such keywords include "bind," "stimulate," and "activate." These keywords are widely used in biology and would provide a possibly unmanageable number of matches. Retrieving passages that contain both the two types of keywords, biologically meaningful as well as functional, would limit the number of matches yet likely provide a sufficient number of initial matches.

In addition, we found that these widely used biologically meaningful keywords do not by themselves form useful analogies. Usually, there is another action performed between the action de-

Table 1 Biologically meaningful keywords for functional terms of the functional basis

Functional basis keyword groups	Biologically meaningful keywords	% of colloc.[a]	# of matches[b]
BRANCH + SEPARATE + DIVIDE			
Correspondents:	Speciate	68	66
Sort, diverge, split,	Diverge	44	39
detach, isolate, cut	Segregate	35	34
	Furrow	33	9
	Evolve	18	424
	Denature	17	36
	Grow	16	786
	Reproduce	14	537
	Cleave	14	80
	Surround	11	209
	Stimulate	9	289
	Contract	3	226
	Activate	2	256
(Detach)	Retract	14	7
	Bend	12	33
	Fold	8	74
DISTRIBUTE			
Correspondents:	Hydrolyze	41	75
Disperse, dissipate,	Burst	32	31
diffuse, release	Discharge	29	14
	Stimulate	26	289
	Circulate	26	164
	Fuse	23	120
	Secrete	21	232
	Concentrate	21	58
	Pass through	20	139
	Break down	20	125
	Diffuse	15	238
	Stretch	15	89
	Bind	14	483
	Segregate	12	34
	Change shape	9	71
(Release)	Lyse	26	23
	Decompose	13	31
	Condensate	6	16
	Fold	5	74
	Catalyze	5	125
(Dissipate)	Evaporate	6	47
REMOVE + EXTRACT			
Correspondents:	Collect	11	72
Purify, filter, strain	Extract	10	61
	Trap	8	49
	Delete	7	43
	Degrade	6	36
	Beat	5	39
	Separate	3	308
TRANSFER			
Correspondents:	Conjugate	60	32
Shift, move	Beat	41	39
	Transport	27	283
	Couple	22	58
TRANSFER (cont'd)			
	Break	8	196
	Pollinate	7	74
	Bind	6	483
	Attract	3	96
(Move)	Change shape	52	71
	Organize	10	134
	Shift	7	67
TRANSPORT			
Correspondents:	Transport	19	283
Convey, conduct,	Transduce	10	99
carry	Communicate	6	109
	Bind	6	483
	Extend	3	95
	Collect	3	72
	Stimulate	2	289
	Contract	1	226
(Carry)	Pollinate	9	74
	Disperse	4	123
IMPORT			
Correspondents:	Osmose	16	31
(Enter)	Pass through	15	139
	Squeeze	14	21
	Diffuse	7	238
	Insert	5	132
	Release	4	508
	Secrete	3	232
	Transport	3	283
	Fold	1	74
EXPORT			
Correspondents:	Contract	1	266
Dispose, destroy,			
empty, eject			
(Destroy)	Inactivate	6	52
	Denature	6	36
	Attach	3	200
	Break down	2	125
	Bind	1	483
	Cleave	1	80
(Empty)	Excrete	1	111
	Fuse	1	120
TRANSMIT			
Correspondents:	Contract	12	226
Convey, deliver	Transduce	8	99
	Communicate	6	109
	Conduct	1	106
TRANSLATE			
	Transcribe	27	347
	Synthesize	12	310

Table 1 (*Continued.*)

Functional basis keyword groups	Biologically meaningful keywords	% of colloc.	# of matches
GUIDE			
Correspondents:	Communicate	6	109
Conduct, direct,	Extend	3	95
steer, straighten,	Transport	3	283
	Arrange	3	112
(Direct)	Hold	2	124
ROTATE			
Correspondents:	Wind	4	26
Spin, turn			
CONNECT + COUPLE + JOIN + LINK			
Correspondents:	Extend	15	95
Attach, assemble	Project	14	50
	Hold	14	124
	Stretch	13	89
	Overlap	10	29
	Activate	7	256
	Bind	4	483
MIX			
Correspondents:	Fragment	26	127
Add, combine	Exchange	10	220
	Cleave	9	80
	Bind	6	483
	Break down	4	125
	Contract	1	226
(Combine)	Cross over	65	34
(Add)	Degrade	8	36
ACTUATE			
Correspondents:	Change shape	11	71
Initiate, turn on,	Bind	9	483
enable	Stick	6	53
	Activate	5	256
	Change structure	4	53
	Regulate	3	401
	Absorb	2	172
(Enable)	Adapt	7	286
	Evolve	4	424
(Initiate)	Excite	1	69
REGULATE			
Correspondents:	Kill	10	102
Control, limit	Protect	9	161
CHANGE			
Correspondents:	Evolve	7	424
Adjust, adapt	Specialize	6	164
(Adjust)	Adapt	1	286
INCREASE + INCREMENT			
Correspondents:	Relax	29	42
Amplify, enhance	Stimulate	18	289
	Activate	14	256
	Contract	10	226
	Project	10	50
	Grow	7	786
	Molt	7	44
	Develop	3	843
	Fold	3	74
DECREASE + DECREMENT			
Correspondents:	Hyperpolarize	21	29
Delay, dampen	Oppose	20	15
	Constrict	8	39
	Stimulate	3	289
	Inhibit	3	190
	Narrow	2	47
	Bind	1	483
(Dampen)	Bulge	6	17
SHAPE			
Correspondents: (Form[c])	Aggregate, bend, bind, branch, break down, combine, condense, differentiate, divide, fold, fuse, germinate, grow, link, pair, polymerize, project, protrude, rearrange, shed, split, stick together, surround, twist, unite		
(Compact)	Coil	10	30
(Compress)	Enlarge	3	33
	Contract	2	226
CONDITION			
Correspondents:	*No keyword*		
Prepare			
STOP			
Correspondents:	Lyse	9	23
End, interrupt	Cut	5	134
	Inhibit	2	190
	Activate	2	256
	Bind	1	483
PREVENT + INHIBIT			
Correspondents:	Cover	17	121
Protect, shield	Bind	14	483
	Destroy	10	68
	Stimulate	9	289
	Surround	9	209
	Inhibit	7	190
	Release	7	508
STORE			
Correspondents:	Concentrate	16	58
Accumulate	Convert	12	146

Table 1 (*Continued.*)

Functional basis keyword groups	Biologically meaningful keywords	% of colloc.	# of matches	Functional basis keyword groups	Biologically meaningful keywords	% of colloc.	# of matches
STORE (cont'd)				SENSE + DETECT			
	Photosynthesize	12	205	Correspondents:	<Receptor>	34	503
	Deposit	10	49	Perceive, feel,	Receive	20	172
	Dissolve	7	69	recognize, discern	Be stimulated	14	217
					Bind	14	483
COLLECT							
Correspondents:	Digest	30	267	(Recognize)	Curl	50	2
Capture, absorb,	Break down	18	125		Protrude	12	17
consume	Convert	10	146		Encounter	4	55
	Reduce	9	312				
	Feed	9	183	MEASURE			
				Correspondents:	Emit	48	33
(Absorb)	Cleave	10	80	Determine, identify,	Recognize	18	203
				locate	Isolate	9	137
CONTAIN							
Correspondents:	Enclose	46	78	DISPLAY			
Enclose, fill,	Swell	17	35	Correspondents:	Convey	20	10
replenish	Surround	15	209	Show, expose, emit	Behave	12	374
	Extend	5	95		Change shape	8	71
	Grow	5	786		Signal	8	399
	Develop	4	843		Bind	5	483
SUPPLY				(Expose)	Stick out	43	7
Correspondents:	Nurture	17	6		Unwind	17	12
Provide	Break down	5	125		Denature	14	36
	Convert	4	146		Change structure	6	53
	Degrade	3	36		Break down	1	125
CONVERT				(Emit)	Convert	2	146
Correspondents:	Specialize	48	164				
Encode, create,	Cut	26	134	SIGNAL + INDICATE + TRACK			
generate, evaporate,	Recombine	26	135	Correspondents:	Signal	3	399
condense,	Transduce	23	99				
transform, integrate,	Degrade	14	36	(Mark)	Communicate	4	109
differentiate,	Synthesize	14	310				
	Photosynthesize	13	205	SUPPORT + STABILIZE + SECURE			
	Stimulate	13	289	Correspondents:	Anchor	21	24
	Transcribe	12	347	Hold	Connect	20	167
	Fuse	12	120		Wrap	13	15
	Contract	11	226		Divide	3	277
	Divide	10	277		Bind	2	483
	Decompose	10	31		Develop	2	843
	Break down	9	125				
	Activate	8	256	POSITION			
	Mutate	7	299	Correspondents:	*No keyword*		
	Reproduce	6	537	Orient, locate			
(Evaporate)	Transpire	37	27				
(Condense)	Coil	10	30				

[a]% of collocation: % of matches that contain both the particular biologically meaningful keyword and the associated FB keywords.
[b]Number of matches: Number of instances the particular biologically meaningful keyword was found in the corpus.
[c]Form: We listed different mechanisms of "forming" in biology.

scribed by a biologically meaningful keyword and the action described by the original functional keyword, as illustrated in the following example from Purves et al. [30].

"***Binding*** of an inducer **changes the shape** of the repressor and prevents the repressor from binding to the operator."

While the biologically meaningful keyword "bind" and the original functional keyword "prevent" form a causal relation in the above excerpt, an intermediary action "change shape" is present between them. Such intermediary action provides more detailed information of how the function "prevent" is achieved.

Table 2 Agreeability index between the translating author and each examiner for nontraining function groups

	Set 1 (PREVENT+)[a]	Set 2 (CONNECT+)[b]	Set 3 (COLLECT)
Examiner 1	Training	0.714	0.833
Examiner 2	0.714	Training	0.833
Examiner 3	0.714	0.857	Training
Average	**0.714**	**0.786**	**0.833**

[b]PREVENT+INHIBIT.
[b]CONNECT+COUPLE+JOIN+LINK.

This suggests that finding an intermediary action can lead to recognizing more search keywords that could be meaningful.

7 Preliminary Validation of the Process for Identifying Biologically Meaningful Keywords

The lead author translated the function sets into the biologically meaningful keywords using the four cases presented in Sec. 5 as criteria for identifying the keywords. We wanted to validate the reliability of the criteria by comparing the results of having independent examiners apply the criteria to identify biologically meaningful keywords for three keyword groups.

7.1 Validation Method. To examine the reliability of the identification criteria, we used an experimental design similar to a k-fold cross-validation involving three independent examiners.

7.1.1 Examiners. Three independent examiners were recruited for validation. The examiners were graduate students in mechanical engineering who have not taken a university-level biology course. All the examiners were fluent in English.

7.1.2 Experimental Design. Three keyword groups with a similar number of biologically meaningful keywords identified were chosen for the experiment: (1) PREVENT+INHIBIT, (2) CONNECT+COUPLE+JOIN+LINK, and (3) COLLECT. The first two keyword groups had seven biologically meaningful keywords each and the last group had six biologically meaningful keywords.

Examiners were first trained to apply the identification criteria to identify biologically meaningful keywords for one keyword group. Each examiner was trained with a different keyword group. Examiners then independently performed the identification task using the criteria on the other two keyword groups. Table 2 presents the experimental design of the validation method, showing which keyword groups were used as the training or testing sets for each examiner.

For each testing set, examiners were presented with 12 or 14 potential biologically meaningful keywords. Half of these keywords were the biologically meaningful keywords identified by the translating author, and the rest were bridge verbs that were not identified as biologically meaningful. Examiners were informed that only half of the potential keywords were biologically meaningful keywords. The sequence of potential biologically meaningful keywords was randomized for each examiner. Examiners were also given all the excerpts from *Life* [30] containing the potential biologically meaningful keywords along with corresponding original functional keywords. Examiners were instructed to read all the excerpts, and for each excerpt, determine whether a potential biologically meaningful keyword and an original function keyword formed one of the four specific semantic relations to be used as criteria. Depending on whether examiners found that the two keywords formed one of the four relations, they identified the particular potential biologically meaningful keyword as an actual biologically meaningful keyword or not. This process is very similar to that performed by the translating author. The only difference was that examiners were provided with a list of 12 or 14 potential keywords to identify half of them as useful, instead of identifying six or seven useful keywords in a list of hundreds of potential keywords. This experimental design eliminates variance associated with different numbers of biologically meaningful keywords that the examiners could identify as well as reduce the examination time.

Table 3 Agreeability index between pairs of independent examiners for each function group

	Set 1 (PREVENT+)[a]	Set 2 (CONNECT+)[b]	Set 3 (COLLECT)
Examined by	Examiners 2–3	Examiners 1–3	Examiners 1–2
Agreeability index	0.714	0.857	0.667

[b]PREVENT+INHIBIT.
[b]CONNECT+COUPLE+JOIN+LINK.

7.2 Validation Results. An *agreeability index* [33] was defined as *agreed*/(*agreed*+*disagreed*).

We calculated two agreeability indices: (1) agreeability between the translating author and each examiner and (2) agreeability between the examiners themselves. The first agreeability index measures how closely the examiners agree with the translating author. The higher the index values, the more likely independent translators would produce a similar list of biologically meaningful keywords to ours. Table 2 shows the agreeability index between the translating author and each examiner.

The second agreeability index measures the agreeability between the two independent examiners who examined the same keyword set. The agreeability values suggest that the identification criteria can be applied reliably by other translators who are not experts in biology. Table 3 shows the agreeability index values for the pairs of independent examiners.

An acceptable agreeability index value in the social sciences ranges from 0.7 to 0.9 with training [33]. Our values are generally within this range. One exception is between examiners 1 and 2 for set 3, which is 0.667 but still close to 0.7. The agreeability results between independent examiners suggest that the identification criteria helped independent examiners to identify similar biologically meaningful keywords. In addition, the agreeability results between the independent examiners and translating author suggest that other examiners could use the identification criteria to produce a similar list of biologically meaningful keywords to the one identified by the translating author. Although only three sets of keyword groups were examined, the results demonstrate the objectiveness of the identification criteria.

7.3 Limitation of the Validation. The validation efforts described in this paper are preliminary. Only a small subset of the translated keywords was used to examine the reliability of the criteria. Also, each examiner did not have to scan the entire list of bridge verbs as the translating author did. In the future, another translator could cross-validate a larger portion of the biologically meaningful keywords to identify a more accurate list of keywords and refine the identification criteria.

In addition, the entire algorithm of the translation process, discussed in Sec. 4, would need to be validated. We could compare the algorithm with an existing natural-language processing technique developed for a similar purpose to measure the effectiveness of our algorithm, e.g., precision or recall rates of bridge verbs. At the time of writing, it was difficult to identify a technique that had a similar purpose to our algorithm. In Sec. 9, we discuss the significance of the biologically meaningful keyword identification criteria.

8 Application Examples

To examine the potential use of the biologically meaningful keywords, we provided the keywords to groups of undergraduate engineering students of a fourth-year mechanical design course.

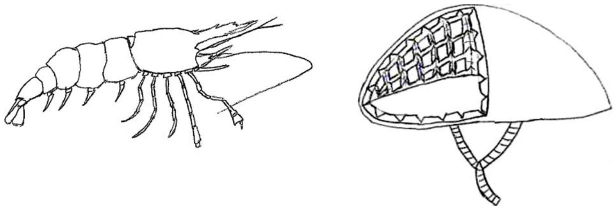

Fig. 4 Left: An example of an arthropod's segmented body. Right: helmet with segmented internal plates.

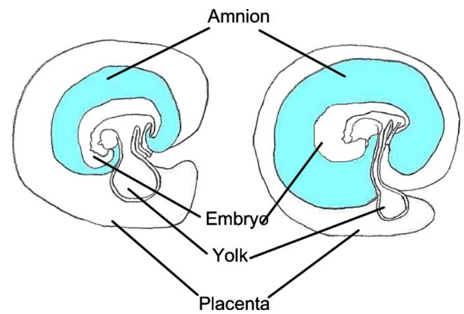

Fig. 5 Amnion and the embryo it protects. As the embryo develops, its surrounding amnion also grows.

Each student project group was asked to develop an innovative product that serves as or provides protection for sports or hobbies. Students used the biologically meaningful keywords for PREVENT+INHIBIT to search the biological corpus *Life* [30] and identify relevant phenomena to generate concepts.

8.1 Biologically Meaningful Keyword "Cover". One of the student groups aimed to design a bicycle helmet that could be more conveniently stored while not in use. The helmet still needed to provide enough protection in the case of accident or impact. Using the keyword "cover," the following excerpt from Purves et al. [30] was found:

"The most complex exoskeletons are found among the arthropods. An exoskeleton, or cuticle, **covers** all the outer surfaces of the arthropod's body and all its appendages… The cuticle contains stiffening materials everywhere except at the joints, where flexibility must be retained."

An example of an arthropod body is shown in Fig. 4 (left). Analogous to the arthropod's outer body, the helmet could be segmented internally into multiple protective plates, with flexible joints connecting the segments. During use, straps connecting these plates will position them tightly together in the shape of a conventional bicycle helmet, as shown in Fig. 4 (right). When a user releases the tension of the straps, the segmented plates would separate, allowing the helmet to be flattened for easier storage.

An additional concept generated from this idea was to make these segmented plates replaceable when a user requires a bigger helmet size or one of the plates gets damaged. This was based on the shedding of arthropod exoskeletons when it molts.

8.2 Biologically Meaningful Keyword "Surround". Located by the keyword "surround," the following excerpt from Purves et al. [30] was used by a group that aimed to design hockey helmets that remain more securely on the head upon impact.

"…[The epiblast] splits off an upper layer of cells that will form the amnion. The amnion will grow to **surround** the developing embryo as a sac filled with amniotic fluid."

The amnion is essentially a membranous sac that surrounds and protects the embryo. Figure 5 illustrates how the amnion grows to surround the developing embryo inside the placenta. The students used an analogy that mapped the embryo to the human head, while an inflated air sac embedded inside the helmet acts like the amnion. After a helmet is put on, compressed air will enter the air sac and create a tight fit specific to each user's head shape. Until the user releases the air, the helmet will remain securely on the user's head.

In this example, the keyword "surround" located a phenomenon that gives not just the idea that surrounding provides protection but also the specific method of how surrounding could be performed by filling with fluid.

9 Significance of the Biologically Meaningful Keyword Identification Criteria

The identification criteria for biologically meaningful keywords present a number of significant benefits. The criteria could be used to find biologically meaningful keywords from another corpus or for engineering keywords other than the functional basis terms. More importantly, categorizing particular semantic relations associated with biologically meaningful keywords can contribute toward automating the keyword identification process. To automatically identify whether a certain strategy or an associated keyword in biology is useful, an algorithm must classify the semantic information of excerpts around the keyword. Therefore, an algorithm could be trained with a set of relations, such as the ones presented in this paper, which use specific semantic information in natural-language text to classify useful strategies and the accompanying keywords.

The identification of semantic relations is also important for analogical reasoning. In analogical reasoning, similarities between a source and a target must be identified and mapped. In cross-domain analogical transfer, as required in biomimetic design, designers must recognize structural similarities between biological phenomena and solutions in engineering. Designers could benefit from higher-order relations found in biology and engineering, e.g., causal relations, to recognize structural similarities between the two domains [34,12].

Causal relations in biology define how certain functions achieve other functions. Essentially, they define possible strategies in biology that can achieve an intended engineering solution. In the excerpt from Purves et al. [30]:

"Humans **absorb** amino acids by ***breaking down*** proteins from food."

An engineering solution of "absorption" can be achieved by a biological strategy of "breaking down" entities. Causal relations therefore identify not only biologically meaningful keywords but also relevant and useful strategies as well. Hence, engineers can use the keywords associated with causal relations to extract analogical solutions from biology and achieve desired functions in engineering. In related work, Cheong and Shu [35] observed that recognizing causal relations in descriptions of biological phenomena is essential for novice designers to perform analogical transfer correctly. Other researchers also confirm the relevance of causal relations in biological phenomena for biologically inspired concept generation [36] and database compilation for biomimetic design [37].

10 Conclusions and Future Work

This paper described the process of translating the functional terms of the functional basis into biologically meaningful keywords. The translated list of biologically meaningful keywords is given in Table 1. These keywords can be used to search natural-language biological knowledge sources to find relevant biological phenomena that may not be identified using only the original functional keyword. Using a previously developed natural-language analysis algorithm [3], we objectively and systematically generated a list of potential biologically meaningful keywords for the function sets of the functional basis. We then identified the more useful keywords based on their semantic relationships with the original functional keywords. Often, these words exhibit a causal relation, where a biologically meaningful keyword allows or enables the action of an original functional keyword. In other cases, biologically meaningful words are synonymous to or represent a more specific manner or form of the functional keyword, which can be found either in the same or different phrases.

We believe that the identification of these particular semantic relations is an important step toward automating the translation process. In addition, causal relations that contain biologically meaningful keywords also represent relevant and useful strategies in biology. Recognizing and mapping strategies that are formed by higher-order relations, such as a causal relation, is essential in cross-domain analogical reasoning. The translated biologically meaningful keywords could therefore help engineers retrieve and apply relevant analogies. Facilitating the process of analogical transfer between biology and engineering improves the accessibility of biomimetic design and may increase its use.

Although this paper reported on the preliminary validation results of the keywords identification criteria, more thorough validation of the entire algorithm is necessary in the future. We also intend to systematically assess the usefulness and effectiveness of the biologically meaningful keywords in the concept generation process, especially with more experienced designers. Meanwhile, we presented application examples from fourth-year undergraduate mechanical engineering students who used biologically meaningful keywords for PREVENT+INHIBIT to generate concepts for design projects. In other work, we have demonstrated the usefulness and benefits of the biologically meaningful keywords to conceptualize novel solutions for sensor designs [38] and a lunar dust protection problem in space missions [29]. We believe that these biologically meaningful keywords enable more engineers to apply biomimetic design when appropriate.

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