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TRANSLATING TERMS OF THE FUNCTIONAL BASIS INTO BIOLOGICALLY MEANINGFUL KEYWORDS

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ABSTRACT

Biology has long been 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 couldn't always be used to identify the most relevant biological analogies, as the vocabularies between biology and engineering are sufficiently distinct. Therefore, a method of identifying biologically meaningful keywords that correspond to engineering keywords was developed.

Here, we apply and refine this method by generating biologically meaningful keywords for the terms of the Functional Basis, which is widely accepted as a standardized representation of the functionality of engineering products.

We present insights gained on the selection of biologically meaningful keywords for the function sets based on semantic relations. We then observe the use of our keywords by providing 4th year undergraduate design students with the biologically meaningful keywords that are related to the desired functions of their design projects.

1. INTRODUCTION

Biomimetic design involves the use of biological phenomena as inspiration for solving engineering problems. Humans have borrowed many ideas from biology to innovate and solve problems: from studying birds to invent flying mechanisms to mimicking human body parts for various mechanical applications. Many of these ideas were based on chance observation or preexisting knowledge of biological phenomena. That is, while solving engineering problems, engineers perceived or recollected certain biological phenomena and connected two domains to generate solutions.

Despite the many successful examples of biologically inspired design that resulted as described above, we believe that engineers can take more full advantage of the vast amount of biological knowledge sources already in existence. Such sources are quickly expanding, especially at the molecular and cellular levels of biological organization (Rebholz-Schuhmann et al., 2005). Having access to such knowledge rather than being limited to one's own existing knowledge of biology is likely to result in more novel and useful concepts.

To take advantage of the large amount of biological information already in natural language format, e.g., texts, papers, etc., our approach is to directly search such information for occurrences of keywords that describe the intended function of engineering designs. However, past work revealed obstacles based on differences in lexicons between the domains of engineering and biology, i.e., words widely used in engineering might be used uncommonly or in different senses in biology (Chiu & Shu, 2005). Many match results thus may not be relevant and helpful for engineers. Therefore, a retrieval process was developed that finds biologically meaningful keywords corresponding to engineering keywords based on natural language analysis.

This method is adapted and refined here to generate biologically meaningful keywords that correspond to terms of the Functional Basis developed by Stone & Wood (2000). The Functional Basis has been widely accepted as a standardized set of engineering terms used for functional modeling.

The biologically meaningful keywords we generate serve as a thesaurus for the function set. Once engineers model a problem using terms of the Functional Basis, the corresponding biologically meaningful keywords can be used to identify relevant biological phenomena specific to the problem.

Note that both the function set and our biologically meaningful keywords are in verb form. Verbs are commonly used in functional decomposition to formulate keywords that describe functionality (Stone & Wood, 2000). Using a verb to represent biologically meaningful keywords is also significant. Doing so allows engineers to explore various biological phenomena related to the verb function rather than remaining fixated with a particular biological phenomenon associated with a noun (Chiu & Shu, 2007). For example, for the function "protect," searching with keyword "cover" will result in the identification of a variety of phenomena related to covering and protecting. However, searching for the biological noun "cuticle" will only result in details related to cuticles, the thin outermost non-cellular layer covering parts of plants and invertebrates, which represents only one means in biology to enable protection and covering.

This paper presents how a set of biologically connotative and significant words was systematically retrieved by searching a biological corpus with the function set words. We present an objective approach for selecting which of these biologically meaningful keywords are more useful, by discussing how they are usually found and associated with the original keyword through semantic relations. We present the biologically meaningful keywords for the function set, "protect," followed by how they were used by 4th year undergraduate mechanical engineering students to generate concepts for their design course projects.

2. NOMENCLATURE

Biologically significant: used to denote a word identified as part of biology term defined in either Oxford Dictionary of Biology (Hine & Martin, 2004) or Biology-online.org (Biology-Online, 2007).

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

Biological meaningful: used to denote either biologically connotative or biologically significant as defined above.

Bridge word: a verb other than the original search verb that is modified by nouns frequently associated with the original verb. Refer to Section 4.3 for an example.

Corpus: a collection of written texts on a particular subject (Waite, 2007).

Functional Basis: a set of function (verbs) and flow (nouns) terms describing the operations that transform input flows to output flows in a product or system.

Hypernym: a word with a broad meaning that more specific words fall under (Waite, 2007). For example, "to prevent" is a hypernym of "to inhibit."

Keywords: character strings used to search for text documents or passages that contain instances of these strings.

Mutual entailment: Entailment represents a relation between X and Y where if X is true, then Y must be true. In a mutual entailment, if X entails Y, then Y entails X (Saeed, 2004).

Object: a noun or noun phrase acted on by an active transitive verb or a preposition (Waite, 2007), e.g., in "a virus enters the cell," "cell" is the object of the verb "enters."

Prepositional phrase: a phrase that starts with a preposition, for example, "into the water."

Sense: the meaning of a word.

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 hierarchy that groups words into sets of synonyms called "synsets," e.g., "to stop" and "to halt" would be 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 (WordNet 3.0).

3. BACKGROUND AND PREVIOUS WORK

In this section, we explain why analogical reasoning between biology and engineering is particularly promising and the approaches taken to support biologically inspired design. We summarize our approach to enable biomimetic design, emphasizing our method to identify biologically meaningful keywords that can be used to search biological sources.

3.1 Design by Analogy and Biology

Analogical reasoning has been identified as a key approach in achieving creativity in design (Goel, 1997). Bonnardel (2000) discusses the nature of potential sources of inspiration and why they are important. Kryssannov et al., (2001) define inspiration as knowing what to adapt and borrow from previous experience, and creativity as how to use that which is borrowed. Therefore, inspiration precedes creativity, and sources of ideas precede inspiration.

Biology has been recognized as a promising source of analogies. Gordon (1961) observed that for creative thinking, biology provided the richest source of direct analogies. Also, the difference in domains between biology and engineering provides another advantage. Bonnardel (2000) pointed out that "interdomain" analogical sources inspired designers more. Benami and Jin (2002), while studying the stimulation and facilitation of cognitive processes, found that analogies from different domains provided more creative and novel ideas.

3.2 Past Work in Biomimetic Design

There have been several efforts in identifying viable biological phenomena for engineering design and providing examples of successful analogies (Vincent, 2003; Lindemann & Gramann, 2004; Bar-Cohen, 2006). Bar-Cohen proposes compiling a database that describes biological principles in terms of engineering needs. Vincent and Mann (2002) suggest extending the TRIZ database to include biological phenomena.

A potential drawback of such databases is that constructing and updating them represent a significant undertaking. Bar-Cohen (2006) predicted that creating such a database would also require personnel with expertise in both engineering and biology. Another concern is that the process of creating and organizing the database may be subject to personal biases.

Therefore, our approach is to provide engineers with search keywords that will enable them to explore the enormous amount of biological knowledge already available in natural-language format, e.g., texts, papers, etc. Bioinformatics scientists have taken a similar approach, e.g., there are different text mining and extraction techniques for MEDLINE, a database containing over 14 million articles (Moon & Singh, 2005, Ohta, 2007, Berardi et al., 2005).

Our approach to supporting biomimetic design has been used to successfully solve problems including those in design for remanufacture (Vakili & Shu, 2001; Hacco & Shu, 2002) and handling and assembly of microparts (Shu et al., 2006).

3.3 Summary of retrieval method

In this section, we summarize a process previously developed to identify biologically meaningful keywords based on word collocation and frequency analysis (Chiu & Shu, 2007). The work described in this paper builds on and refines the previous method.

3.3.1 Selecting original keywords

The initial keyword is a verb that describes the desired functionality of a particular design solution. The synonyms, hypernyms, and troponyms of the initial keyword are then generated using WordNet. WordNet is an online lexical database that organizes words into sets, called "synsets," based on their semantic relationships to each other (WordNet 3.0).

A corpus is then searched using the initial and related words, which together comprise the original keywords. The initial biological corpus selected was *Life: the Science of Biology* (Purves et al., 2001), an introductory university-level textbook. Other selections for corpus can be easily added or substituted for the initial search, or used to find more detailed information once relevant phenomena are identified using the initial corpus searched.

3.3.2 Screening search matches

After the corpus is searched using the original keywords, the results are 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". Matches containing "conduct" in the sense of "manage or control," as in conducting a survey, are not relevant and removed. Matches containing the searched keyword in a related sense, but acting on abstract objects are also less useful. For example, when searching for "support," the match "to support the hypothesis" is not helpful since it does not describe a physical phenomenon, which is typically more useful in solving mechanical design problems.

3.3.3 Identifying "bridge verbs"

Nouns that occurred most frequently in the text excerpts corresponding to match results were identified. These nouns typically modified either the original search keyword or another verb, which was then designated as a "bridge verb" (Chiu and Shu, 2007). Because high-frequency nouns tend to appear in the description of the more dominant biological phenomena associated with our original search keyword, "bridge verbs" modified by these nouns likely represent the biologically meaningful keywords desired.

3.3.4 Categorizing the list of bridge verbs

The biological meaningfulness of the list of bridge verbs was then determined using two dictionaries of biological terms, Oxford Dictionary of Biology (Hine & Martin, 2004), and Biology-online.org (Biology-Online 2007). Two criteria were then developed. When a word (or its other grammatical forms) is a term or part of a term that is defined in the dictionaries, 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".

The list of bridge verbs is then sorted by the frequency it occurs in the dictionaries. Such lists tend to consist of a central "dense" region where the majority of biologically significant words are found. Words that are either too common or too specific were found less likely to be promising in previous work. Also observed was that the biologically connotative words found in the "dense" region were likely to serve as useful keywords (Chiu & Shu, 2007).

4. METHOD

We adapted the method previously developed to generate biologically meaningful keywords corresponding to terms of the Functional Basis. In this section, we provide examples and additional insights gained during our retrieval process.

4.1 Selecting original keywords

Instead of expanding the original search word with its synonyms, troponyms and hypernyms as previously performed, we grouped the function words under the same class (the most generic group of function sets) based on similarities found in WordNet. These groups included not just the secondary and tertiary function words, but also their correspondents. For example, "protect" was grouped with function words "prevent", "inhibit," and "shield" as shown in Figure 1.

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

(Functional Basis)

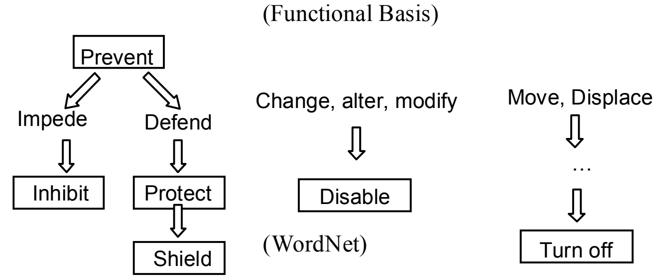

Figure 1. Keyword groupings in Functional Basis vs. WordNet. Top: Functional basis grouping. Bottom: WordNet grouping where "disable" and "turn off" are in different groups from "prevent".

These words are associated with each other as hypernyms/troponyms in WordNet. Several reasons for this reorganization method are detailed below.

Using WordNet, we are able to categorize functional keywords based on natural language contexts, rather than engineering specific contexts. The ability to group words this way improves our results. By searching with several related functional words including the correspondents, we obtain more matches, and can create a larger frequency list to better assess the location of the previously mentioned "dense" regions of biologically significant keywords.

In addition, there were some functional keywords for which corresponding biologically meaningful keywords could not be obtained. Reasons include functional keywords either being mostly used in different grammatical forms, e.g., "steady", or not producing any matches at all in a biology corpus, e.g., "digitize". Our grouping technique allows engineers to search using biologically meaningful keywords for other functional keywords within the same sub-group, when their original keyword has none. For example, for "steady," one could search using biologically meaningful keywords for "stabilize." Similarly, for "digitize," one could search using the biologically meaningful keywords for "encode," which is in the same group and has a related meaning. This grouping of functional keywords is also helpful when one wishes to simply consider additional biologically meaningful keywords by examining similar function words within the same sub-group.

Under this grouping technique, it is possible that the same biological keyword could appear under more than one group. This occurs mainly because some words represent meanings that overlap with more than one sense. For example, the keyword "conduct" (also a correspondent for "transmit") was retrieved as a biologically meaningful keyword for both of the two groups containing Functional Basis keywords "transmit" and "transport" (see Figure 4). Therefore, by searching using the biologically meaningful term "conduct" to look for relevant phenomena associated with "transmit," one may obtain results of which some are associated with "transport."

4.2 Screening search matches

Some functional keywords are widely used in biology but with a different sense from that in engineering. 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 (Hirtz et al., 2002). We did not consider matches with keywords used in different senses, since they did not tend to be useful.

4.3 Identifying bridge verbs

For the keyword "protect," some of most frequent nouns in the match results were "plants", "cells", "embryos", and "body". We then identified the bridge verbs that modified these nouns. This process is illustrated with the excerpt below where the original keyword "protect" led to the frequent noun "embryo", which is modified by the bridge verb "surround".

> "Within the shell and ***surround***ing the <u>embryo</u> are membranes that **protect** the embryo from desiccation..."

4.4 Categorizing the list of bridge verbs

Based on the Oxford Dictionary of Biology and the Biology-Online Dictionary, we determined whether each bridge verb is biologically significant or connotative. For our "protect" example, one of the bridge verbs, "inhibit" was a physiology term that was defined, and therefore "inhibit" was denoted biologically significant. On the other hand, "surround" was not defined in the biological dictionaries but was nonetheless used in the definition of other biological terms, and was therefore denoted biologically connotative. Figure 2 shows the part of the list of biologically meaningful keywords for "protect", where there is a higher density or concentration of shaded terms that correspond to biologically significant terms.

Once the list of biologically significant and connotative keywords is sorted by frequency of occurrence, the next step is to investigate which words are most promising. We begin by examining words in the "dense" region of biologically significant words. Words that occur less frequently tend to be more biologically specific, and are considered more carefully than more frequent ones, that tend to be too general. The discussion section presents the process in more detail.

	Biology dictionary count	Biologically significant?	Density
say	360	no	9
sense	330	yes	10
inhibit	324	yes	11
bind	323	yes	12
change	314	no	12
insert	313	yes	13
press	312	no	13
lead	302	no	13
supply	297	yes	14
take	288	no	14
cover	287	yes	15
live	286	yes	16
secrete	278	yes	17
open	254	no	17
attach	252	no	17
lose	238	no	17
flow	237	no	17
indicate	235	no	17
become	232	no	17
present	231	no	17
operate	225	yes	18
determine	224	no	18
affect	221	yes	19
depend	220	yes	20
work	218	no	20
activate	213	yes	21
fuse	208	no	21
add	203	no	21
divide	202	yes	22
link	199	yes	23
stimulate	196	yes	24
release	188	yes	25
contract	178	yes	26
extract	172	yes	27
distribute	168	no	27
control	167	yes	28
prevent	163	no	28
prevent	163	no	28
expose	160	no	28
poison	160	yes	29
support	159	no	29
generate	157	yes	30
radiate	156	yes	31
surround	151	no	31
break	142	no	31
cleave	140	yes	32
elevate	140	no	32
block	139	no	32
arise	138	no	32

Figure 2. The "dense" region of biologically significant (shaded) bridge verbs for "protect".

5. RESULTS

This section addresses the identification of the biologically meaningful keywords. Although we developed and used a systematic retrieval process, deciding which of the resulting keywords are likely to be more promising can be subjective. Here we provide four cases of how the more useful biologically meaningful keywords usually appear in search results. These cases can serve as guidelines for finding biologically meaningful keywords for other sets of engineering keywords or from another corpus in the future.

5.1 Case 1 – Synonymous pair

Many groups or pairs of words are used synonymously in the biological domain. In a few cases, these words 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 and specific verb. An example of this is shown below:

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

Here, "convert" is the Functional Basis word used to locate the above match, and "transduce" is the biologically meaningful keyword found. Both "convert" and "transduce" bear the same meaning of changing the form of energy. Interestingly, a "transducer" is a very common device in engineering that transforms one type of energy into another. Although engineers are likely to be familiar with this term, they may not know that it is also a widely used term in biology.

Figure 3 depicts the different relationships between "convert" and "transduce" in the biological domain and WordNet. Although "convert" and "transduce" are used synonymously in biology, in the WordNet hierarchy, "transduce" is an inherited troponym of "convert."

Class (Primary)	*Secondary*	*Tertiary*	*Correspondents*
Convert	Convert		Condense, create, decode, …

(Functional Basis)

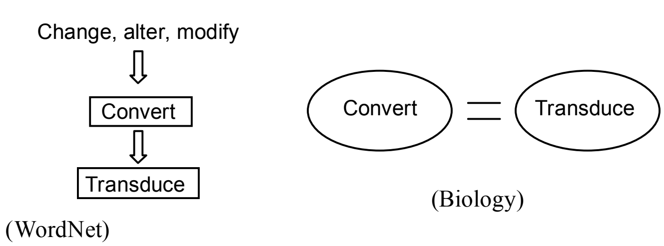

Figure 3. Synonymous pair relationship. Top: Functional basis grouping. Bottom left: WordNet grouping. Bottom right: Synonymous pair relationship between "convert" and "transduce" in biology indicated by the symbol "=".

5.2 Case 2 – Implicitly synonymous pair

In the example given for the first case, it is easy to recognize the synonymous biologically meaningful word. However, there are cases when synonymous words are present, but in a separate phrase or sentence. They require a closer investigation of search results than the first case, and most such synonyms appear in this manner, which is illustrated below:

> "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 passage, "conduct" and "transport" are used as synonyms. We determined this by looking for two verbs that describe the same action performed on the same object. Although these two verbs are used synonymously here, neither the Oxford Thesaurus (2006) nor Merriam-Webster Thesaurus (2007) identifies these words to be synonyms of each other. These two words, although similar but bearing different meanings in conventional English, are used interchangeably in biology. Figure 4 shows the different relationships between the two words in the Functional Basis, WordNet, and biology.

In the Functional Basis, "conduct" and "transport" both appear under the same secondary class term "transfer", and the corresponding biologically meaningful keywords for one can also serve for the other. "Transmit" and "transport" lie separately on the same tertiary level, under "transfer," but "conduct" is one of correspondents of "transmit," not "transport." In WordNet, "conduct" and "transmit" both fall under the more general term "transport", illustrating another difference in grouping between the Functional Basis and WordNet. However, the significant relationship between "conduct" and "transport" we found in biology motivates us to group them together in our keyword set.

Secondary	*Tertiary*	*Correspondents*
Transfer		Carry, deliver
	Transport	Advance, lift, move
	Transmit	Conduct, convey

(Functional Basis)

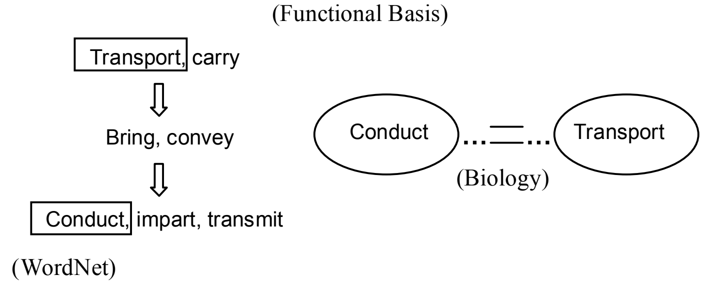

Figure 4. Implicitly synonymous pair relationship. Top: Functional basis grouping. Bottom left: WordNet grouping. Bottom right: Implicitly synonymous pair relationship between "conduct" and "transport" in biology indicated by the symbol **"…=…".**

5.3 Case 3 – Biologically specific form

Biologically meaningful words can sometimes be a troponym of an engineering word. Naturally, such words tend to be specific to biological phenomena. Some examples include "photosynthesize" from "convert", and "mutate" from "transform" as presented below:

> "**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, "mutate" is a specific method in biology that "transform(s)" a gene segment into another. An engineer with some biological knowledge may be able to recognize the relationship once "mutate" is presented as a biologically meaningful word for "transform".

Figure 5 compares the word relationships between the Functional Basis, WordNet and biology for "mutate" and "transform". Mutate, not surprisingly, is not listed in the Functional Basis. Both "mutate" and "transform" are direct troponyms of "change" in WordNet. However, "mutate" is a specific form of, or a troponym of, "transform" in biology.

Secondary	*Tertiary*	*Correspondents*
Convert		Condense, create, decode, …, process, solidify, transform

(Functional Basis)

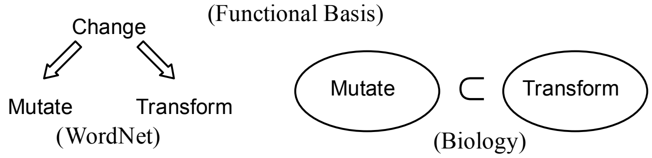

Figure 5. Biologically specific form relationship. Top: Functional basis. Bottom left: WordNet grouping. Bottom right: Biologically specific form relationship between "mutate" and "transform" represented by the symbol ⊂, indicating that "mutate" is a specific form of "transform" in biology.

5.4 Case 4 – Mutually entailed pair

Investigation of the above three cases is rather straightforward. It follows a simple semantic relationship that the biologically meaningful word is either synonymous or is a more specific sense of the engineering word. However, Case 4 follows a symmetric relationship called mutual entailment. That is, one action is performed to enable another action, while the sequence of two action words can be switched with an appropriate prepositional phrase (Saeed, 2004) as illustrated below:

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

can be reorganized as follows without altering its meaning:

> "Humans ***break down*** proteins from food to **absorb** amino acids."

Figure 6 depicts the mutually entailed pair of "absorb" and "break down" in the biological domain. Chiu and Shu (2007) recognized that biologically connotative words having this symmetric relation with the original keyword are unobvious but very useful bridge words. Most of the biologically meaningful keywords retrieved for the Functional Basis fall under this category. More examples of mutual entailment are:

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

> "The lining of the gut is not digested because it is **protected** by a ***covering*** of mucus."

In the above two examples, the biologically meaningful keywords "contract" and "cover" allows or enables another action, that of "mix" and "protect," respectively. Each sentence could be restructured similar to the absorb/break down example and preserve the original meaning.

Word pairs, such as those above, are related in biology, but often no relationship between them is identified in WordNet. A person with limited biological knowledge would not likely have identified or recognized the biological meaningful keyword.

Secondary	*Tertiary*	*Correspondents*
Store		Accumulate
	Contain	Capture, enclose
	Collect	Absorb, consume, fill, reserve

(Functional Basis)

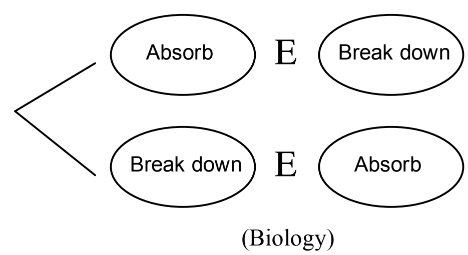

Figure 6. Mutually entailed relationship. Top: Functional basis. Bottom: Mutually entailed relationship using the symbol "E" indicating that "absorb" entails "breakdown," or vice versa.

Furthermore, we found this symmetric relation to be useful only when the biologically meaningful word is the verb that allows or enables the action of the engineering keyword. For example, in searching for a biologically meaningful keyword for "mix," the below excerpt 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 keywords is to identify phenomena that provide analogies to solve the problem associated with the original keyword. That is, engineers are likely more interested in how a function is achieved by analogous biological phenomena than the actions that result from the functional keywords in biology.

5.5 Biologically meaningful keywords for "protect"

To confirm the relevance of the biologically meaningful keywords we generated, we presented the following keywords for "protect" to groups of 4th year undergraduate mechanical engineering students in a design course.

Protect	Cover, Surround, Inhibit, Destroy

These keywords were used to search the biological corpus, *Life* (Purves et al., 2001) and identify relevant phenomena to help generate concepts for the students' projects. All four keywords were located in the "dense" region of biologically significant keywords in the bridge word list. The concepts developed by the students follow.

6. APPLICATION EXAMPLES

Each student project group was asked to develop an innovative product that serves as or provides protection for sports or hobbies. From the four biologically meaningful keywords for "protect," "cover" and "surround" were used in the students' redesigns of bicycle and hockey helmets. We present our own possible solutions that enable protection in shoe cushioning and laptop computers, based on biological phenomena identified through the use of the remaining two keywords "inhibit" and "destroy".

6.1 Keyword "Cover"

One of the student groups aimed to design a bicycle helmet that could be conveniently stored and carried 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 of a biological phenomenon 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 Figure 7. 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 Figure 8. When a user releases the tension of the straps, the segmented plates would separate, allowing the helmet to be flattened for easier storage and carrying.

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.

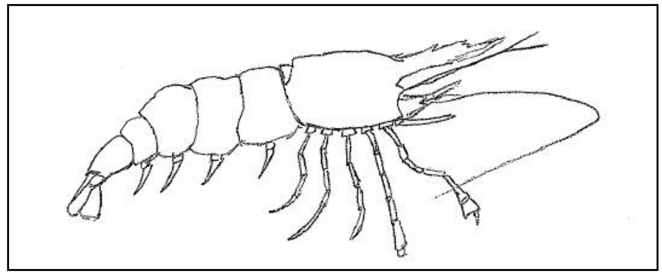

Figure 7. An example of an arthropod's segmented body, drawn by H. Cheong.

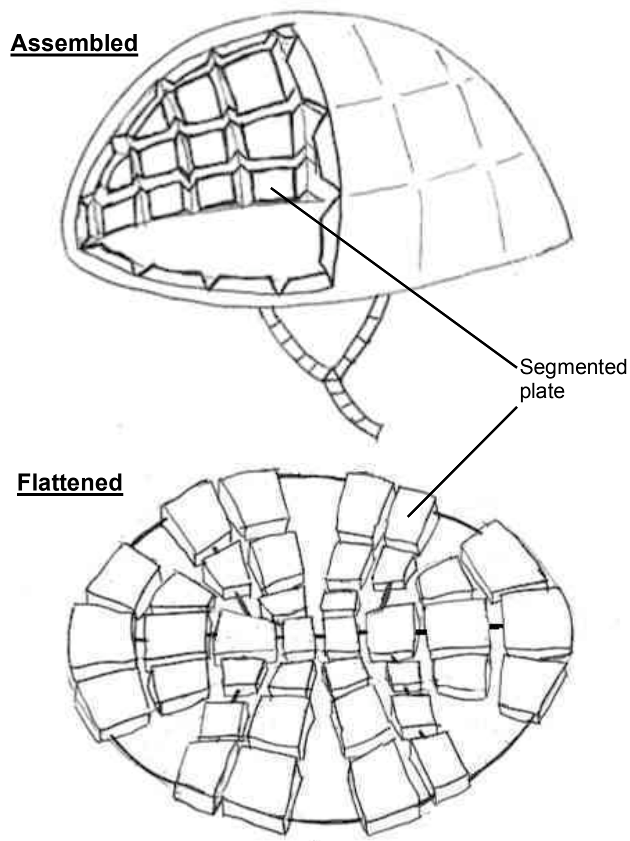

Figure 8. Helmet with segmented internal plates, drawn by H. Cheong based on student concepts.

6.2 Keyword "Surround"

Using "surround," the following biological phenomenon was found useful 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 9 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 securely remain on the user's head.

In this example, the keyword "surround" identified 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.

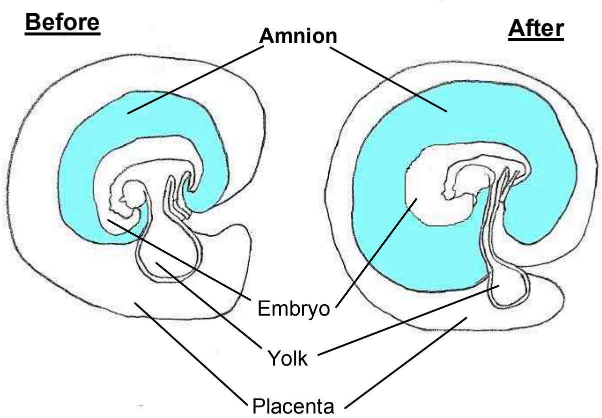

Figure 9. Amnion (shaded) and the embryo it protects. As the embryo develops, its surrounding amnion also grows. Figure drawn by H. Cheong.

6.3 Keyword "Inhibit"

The above examples illustrate the mapping process used to incorporate a phenomenon, located by biologically meaningful keywords, into a design concept. Previous studies (Mak and Shu, 2004a, 2004b) detail the process whereby engineers recognize and perform the analogical mapping between the biological source and the target engineering domains.

An interesting additional facet we found is that, for some phenomena, there are preliminary or intermediate actions that link the engineering keyword to the biologically meaningful keyword, an example of which follows:

"Golgi tendon organs ***inhibit*** a contraction that becomes too forceful, triggering relaxation and **protecting** the muscle from tearing."

In essence, Golgi tendon organs "protect" the muscle by "inhibiting" (biologically meaningful keyword) a contraction. But inhibition does not directly provide protection; rather the intermediary process of "relaxation" must be present.

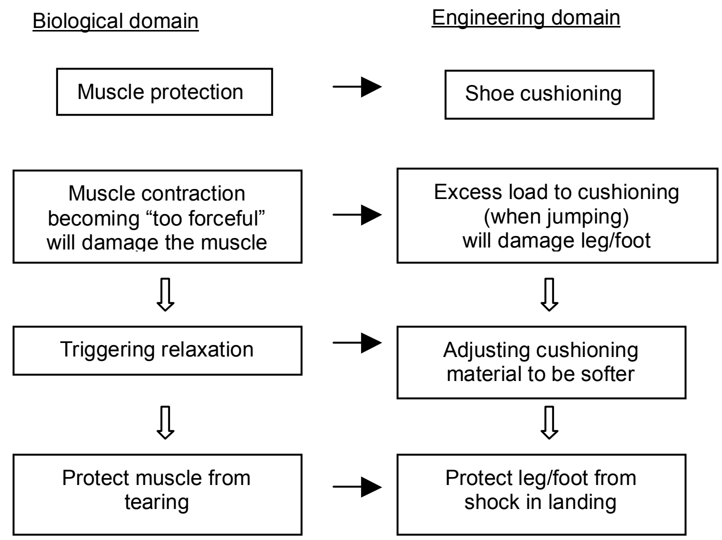

Figure 10. Mapping between biological and engineering domain for the shoe cushioning example.

We can relate the above phenomenon to sports shoe cushioning. For sports such as basketball and volleyball, where jumping is required, shoe designers have developed cushioning systems on the sole to relieve impact and prevent injuries to athletes' legs and feet. While making the cushioning material more compressible can absorb more shock, it will hinder athletic performance in sprinting or making quick lateral movements, where stiffer material gives better stability.

One possible solution that draws an analogy from the Golgi tendon organs is to interactively adjust the compression rate of shoe cushioning based on the athlete's activity. By default, shoe cushioning can be set to firm to optimize performance. When starting a jump, the shoe receives an excess load and the cushioning will be compressed to a greater extent (analogous to muscle contraction becoming too forceful). An interactive shoe can respond by making the cushioning softer (relaxation), and therefore absorbing more shock when the user lands. Figure 10 shows the mapping performed in this analogy. After we developed this concept, we found that Adidas had released an intelligent shoe called "adidas_1," that is based on a technology that adapts in real time to find the right cushioning level based on the athlete's activity (Adidas Press, 2005).

6.4 Keyword "Destroy"

Although seemingly counterintuitive, "destroy" was identified as a biological keyword for "protect". Chiu and Shu (2007) discussed the possibility of a useful pseudo-antonym relationship resulting from their retrieval process. Our results in fact showed several phenomena related to defense systems and regulation enzyme activities that protects by "destroying". An example follows:

"…an antibody protein can be made that binds to a virus if the virus ever enters the bloodstream, and this binding results in the virus being **destroyed**."

A possible solution for protecting computers against liquid spills was developed using this phenomenon. In this concept, a virus is analogous to the liquid spilled into the computer. When a spill is detected, additional heat or other chemical or physical action can be generated within the computer to accelerate the evaporative or other process of neutralizing the liquid before the spill reaches more sensitive components. An analogy is made with the preemptive process acting like the antibody protein to destroy, or eliminate, the liquid spill that has entered the computer.

7. SUMMARY AND CONCLUDING REMARKS

This paper introduced the process of translating the terms of the Functional Basis into biologically meaningful keywords. Some of these biologically meaningful keywords are illustrated in Appendix A. Engineers can use these keywords to search biological sources to find relevant biological phenomena that may not be identified using only the original function word. Using a previously developed natural language based process (Chiu & Shu, 2007), we objectively and systematically generated a list of biologically significant and connotative keywords. We then identified the more promising keywords based on their semantic relationships with the original engineering keywords. Often, these words exhibit a relationship called mutual entailment, where the biologically meaningful keyword allows or enables the action of the engineering keyword. In other cases, biologically meaningful words are synonymous to or represent a more specific form of the engineering keyword, which can be found either in the same or different phrases.

Future work involves systematically assessing the usefulness of the biologically meaningful keywords in the concept generation process. We began this process by illustrating how biologically meaningful keywords for "protect" were used by undergraduate design students to generate concepts for their design projects. Controlled experiments could be conducted to validate the degree of innovation present in designs generated with our biological keywords.

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REFERENCES

Adidas Press, 2005, "adidas Introduces the World's First Intelligent Basketball Shoe," Herzogenaurch, Germany. Accessed at http://www.press.adidas.com/

Bar-Cohen, Y., 2006, "Biomimetics – Using Nature to Inspire Human Innovation," Bioinsp. Biomim., 1, pp. 1-12.

Benami, O., and Jin, Y., 2002, "Creative Stimulation in Conceptual Design," Proceedings of ASME DETC/CIE, Montreal, QC, Canada, DETC2002/DTM-34023.

Berardi, M., Lapi, M., Leo, P., and Loglisci, C., 2005, "Mining Generalized Association Rules on Biomedical Literature," Proceedings of IEA/AIE, Bari, Italy, 3533, pp. 500-509.

Biology-Online. (2007). Accessed at http://www.biology-online.org

Bonnardel, N., 2000, "Towards Understanding and Supporting Creativity in Design: Analogies in a Constrained Cognitive Environment," Knowledge-Based Systems, 13/505-513.

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 & Manufacturing, 21/45-59.

Chiu, I., and Shu, L.H., 2005, "Bridging Cross-domain Terminology for Biomimetic Design," Proceedings of ASME IDETC/CIE, Long Beach, CA, DETC2005-93101.

Goel, A.K., 1997, "Design, Analogy and Creativity," IEEE Expert Intelligent Systems & Their Applications, 12/62-70.

Gordon, W.J.J., 1961, "Synectics," Harper & Row, NY.

Hacco, E., and Shu, L.H., 2002, "Biomimetic Concept Generation Applied to Design for Remanufacture," Proceedings of ASME DETC/CIE, Montreal, QC, Canada, DETC2002/DFM-34177.

Hine, R.S., and Martin, E., eds., 2004, *A Dictionary of Biology*, Oxford University Press, New York.

Hirtz, J., Stone, R.B., McAdams, D.A., Szykman, S., and Wood, K.L., 2002, "A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts," NIST Technical Note, 1447.

Kryssannov, V.V., Tamaki, H., and Kitamura, S., 2001. "Understanding Design Fundamentals: How Synthesis and Analysis Drive Creativity, Resulting in Emergence," Artificial Intelligence in Engineering, 15, pp. 329-342.

Lindemann, U., and Gramann, J., 2004, "Engineering Design Using Biological Principles," Proc. Int. Design Conf., Dubrovnik, Croatia, 2, pp. 18–21.

Mak, T.W., and Shu, L.H., 2004a, "Abstraction of Biological Analogies for Design," Annals of the CIRP, 53/1:117-120.

Mak, T.W., and Shu, L.H., 2004b, "Use of Biological Phenomena in Design By Analogy," Proceedings of ASME DETC/CIE, Salt Lake City, UT, DETC2004/DETC-57303.

Merriam-Webster Online (2007). http://www.m-w.com/

Miller, G.A., Beckwith, R., Fellbaum, C., Gross, D., and Miller, K., 1993, "Introduction to WordNet: an on-line lexical database," Five Papers on WordNet, pp. 1-25. Accessed at ftp://ftp.cogsci.princeton.edu/pub/wordnet/

Moon, N., & Singh, R., 2005, "Experiments in Text-based Mining and Analysis of Biological Information from MEDLINE on Functionally-related Genes," Proc. 18th Int. Conf. on Systems Engineering, Las Vegas, NV, 326-331.

Ohta, T., 2007, "Semantic Retrieval for the Accurate Identification of Relational Concepts Based on Deep Syntactic Parsing," Journal of Information Processing and Management, 49, pp. 555-563.

Purves W.K., Sadava, D., Orians, G.H., and Heller, H.C., 2001, *Life, The Science of Biology,* 6/e, Sinauer Associates, Sunderland, MA.

Rebholz-Schuhmann, D., Kirsch, H., & Couto, F., 2005, "Facts from Text—is Text Mining Ready to Deliver?," PLoS Biology., 3(2), e65.

Saeed, J.I., 2004, *Semantics 2nd ed.,* Blackwell Publishing Ltd., Malden, MA.

Shu, L.H., Hansen, H.N., Gegeckaite, A., Moon, J., and Chan, C., 2006, "Case Study in Biomimetic Design: Handling and Assembly of Microparts," Proceedings of IDETC/CIE, Philadelphia, PA, DETC2006/DFM-99398.

Stone, R.B., and Wood, K.L, 2000, "Development of a Functional Basis for Design," Journal of Mechanical Design, Transactions of the ASME, 122, pp. 359-369.

Ullman, D., 2003, *The Mechanical Design Process*, Third Edition, McGraw-Hill, New York.

Vakili, V., and Shu, L.H., 2001, "Towards Biomimetic Concept Generation," Proceedings of ASME DETC/CIE, Pittsburg, PA, DETC2001/DTM-21715.

Vincent, J., 2003, "Biomimetic Engineering," European Workshop on Smart Structures in Engineering and Technology, B. Culshaw, eds., Proc. SPIE, 4763, pp. 16-30.

Vincent, J., & Mann, D., 2002, "Systematic Technology Transfer from Biology to Engineering," Philosophical Trans. of The Royal Society: Physical Sciences, 360/159-173.

Waite, M., eds., 2007, *Oxford Dictionary and Thesaurus*, Oxford University Press, New York.

WordNet 3.0 (n.d.). Accessed at http://wordnet.princeton.edu/

ANNEX A

FUNCTIONAL BASIS RECONCILED FUNCTION SET WITH CORRESPONDING BIOLOGICALLY MEANINGFUL KEYWORDS

Class (Primary)	*Secondary*	*Tertiary*	*Correspondents*
Branch	Separate		Isolate, sever, disjoin
		Divide	Detach, *isolate*, release, sort, split, disconnect, subtract
		Extract	Refine, filter, purify, percolate, strain, *clear*
		Remove	Cut, drill, lathe, polish, sand
	Distribute		Diffuse, dispel, disperse, dissipate, diverge, scatter

Channel	Import		Form entrance, *allow*, input, *capture*
	Export		Dispose, eject, *emit*, empty, *remove*, destroy, eliminate
	Transfer		Carry, deliver
		Transport	Advance, lift, move
		Transmit	Conduct, convey
	Guide		Direct, shift, steer, straighten, switch
		Translate	Move, relocate
		Rotate	Spin, turn
		Allow DOF	*Constrain*, unfasten, unlock

Functional Basis search group		**Biological Keywords**
Transfer:	transfer, import, export, shift, exchange, dispose	excrete, contract, breakdown, bind, block, inactivate, conjugate, couple
Transport:	transport, conduct, carry	conduct, diffuse, perfuse, circulate, pump
Transmit:	transfer, convey, deliver	communicate, conduct, transduce, transmit

Connect	Couple		Associate, connect
		Join	Assemble, fasten
		Link	Attach
	Mix		Add, blend, coalesce, combine, pack

Functional Basis words		**Biological Keywords**
Connect:	connect, couple, join, link, attach, assemble	stretch, extend, project, overlap, bind, bond, activate
Mix:	mix, add, combine	break down, fragment, cleave, degrade, contract, cross-over, exchange

Control Magnitude	Actuate		Enable, initiate, start, turn-on
	Regulate		Control, equalize, limit, maintain
		Increase	*Allow*, open
		Decrease	Close, delay, interrupt
	Change		Adjust, modulate, *clear*, demodulate, invert, normalize, rectify, reset, scale, vary, modify
		Increment	Amplify, enhance, magnify, multiply
		Decrement	Attenuate, dampen, reduce
		Shape	Compact, compress, crush, pierce, deform, form
		Condition	Prepare, adapt, treat
	Stop		End, halt, pause, interrupt, restrain
		Prevent	Disable, turn-off
		Inhibit	Shield, insulate, protect, resist

Functional Basis words		**Biological Keywords**
Protect	prevent, inhibit, protect, shield	cover, surround, inhibit, destroy, change shape, bind, release

Convert	Convert		Condense, create, decode, differentiate, digitize, encode, evaporate, generate, integrate, liquefy, *process*, solidify, transform

Functional Basis words		**Biological Keywords**
Convert:	convert, encode	degrade, transduce, photosynthesize, decompose
Transform:	transform, integrate, differentiate	mutate, develop, grow, divide, specialize

Provision	Store		Accumulate
		Contain	*Capture*, enclose
		Collect	Absorb, consume, fill, reserve
	Supply		Provide, replenish, retrieve

Functional Basis words		**Biological Keywords**
Store:	store, collect, accumulate	convert, photosynthesize, concentrate, deposit

Signal	Sense		Feel, determine
		Detect	Discern, perceive, recognize
		Measure	Identify, *locate*
	Indicate		Announce, show, denote, record, register
		Track	Mark, time
		Display	*Emit*, expose, select
	Process		Compare, calculate, check

Support	Stabilize		Steady
	Secure		*Constrain*, hold, place, fix
	Position		Align, *locate*, orient

Functional Basis words		**Biological Keywords**
Support:	support, stabilize, secure, steady, fix, hold	wrap, bind, connect, establish, develop, divide