Supporting Biomimetic Design by Categorizing Search Results and Sense Disambiguation, with Case Studies on Fuel Cell Water Management Designs

by

Ji Ke

A thesis submitted in conformity with the requirements for the degree of Masters of Applied Science
Graduate Department of Mechanical and Industrial Engineering
University of Toronto

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Mechanical and Industrial Engineering
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Abstract

Biology is a good source of analogies for engineering design. One approach of retrieving biological analogies is to perform keyword searches on natural-language sources such as books, journals, etc. A challenge in retrieving information from natural-language sources is the potential requirement to process a large number of search results. This thesis describes two methods on improving the relevancy of the search results. The first method is inserting metadata such as part-of-speech, word sense and lexicographical data for each word in a natural-language. The second method is categorizing the search results, using WordNet relationships and Wikipedia structures as ontologies. Although this research is still exploratory, initial qualitative observations demonstrate successful identification and separation of biological phenomena relevant to either desired functions or desired qualities. The benefits of embedding metadata are demonstrated through a case study on the redesign of a fuel cell bipolar plate. A prototype was constructed with ability to passively prevent prolonged catastrophic flooding.
Acknowledgments

I would like to express my thanks to my supervisors, Professor L.H Shu and Professor J.S. Wallace, for their engagement, guidance and insight. I would also like to thank my committee members, Professor W.L. Cleghorn and Professor M. Grüninger for their generosity and time.

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And above all, I thank my family: my Mom, for her endless care, and my Dad, for his timeless knowledge.
## Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table of Contents</td>
<td>iv</td>
</tr>
<tr>
<td>List of Tables</td>
<td>viii</td>
</tr>
<tr>
<td>List of Figures</td>
<td>ix</td>
</tr>
<tr>
<td>List of Appendices</td>
<td>xii</td>
</tr>
<tr>
<td>Nomenclature</td>
<td>xiii</td>
</tr>
<tr>
<td>List of Acronyms</td>
<td>xvi</td>
</tr>
<tr>
<td>1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Thesis objectives</td>
<td>2</td>
</tr>
<tr>
<td>1.2 Literature reviews</td>
<td>2</td>
</tr>
<tr>
<td>1.2.1 Related work in design theory and methodology</td>
<td>2</td>
</tr>
<tr>
<td>1.2.2 Related work in biomimetic design</td>
<td>5</td>
</tr>
<tr>
<td>1.2.3 Related work in natural language processing</td>
<td>5</td>
</tr>
<tr>
<td>1.3 Case study of biomimetic design: fuel cell water removal conceptual design</td>
<td>6</td>
</tr>
<tr>
<td>1.4 Thesis Outline</td>
<td>7</td>
</tr>
<tr>
<td>2 Improvements for biomimetic search engine</td>
<td>9</td>
</tr>
<tr>
<td>2.1 Biomimetic search engine introduction</td>
<td>9</td>
</tr>
<tr>
<td>2.2 Server hardware</td>
<td>9</td>
</tr>
<tr>
<td>2.3 Sources for biological information</td>
<td>10</td>
</tr>
<tr>
<td>2.3.1 Life, the Science of Biology</td>
<td>10</td>
</tr>
<tr>
<td>2.3.2 PubMed Bookshelf</td>
<td>11</td>
</tr>
<tr>
<td>2.3.3 Google Scholar</td>
<td>11</td>
</tr>
<tr>
<td>2.4 Challenges with biomimetic design</td>
<td>11</td>
</tr>
<tr>
<td>2.4.1 Word sense and part-of-speech</td>
<td>12</td>
</tr>
<tr>
<td>2.4.2 Abstract objects</td>
<td>12</td>
</tr>
</tbody>
</table>
4.1.5 Future work

4.2 Fuel cell design

5 Case study: Fuel cell design generation

5.1 Problem Definition

5.2 Related work in PEMFC water management

5.3 Search Keywords

5.3.1 Function based search keywords

5.3.2 Quality based search keywords

5.4 Search results filtering

5.4.1 Filtering by categorizing the results

5.4.2 Filtering by results by POS

5.4.3 Filtering by eliminating abstract results

5.5 Identified biological phenomena

5.5.1 Water strider’s leg

5.5.2 Lotus effect

5.5.3 Extremophiles

5.5.4 Rod cells

5.5.5 Membrane Osmosis

5.5.6 Water/nutrient transport in plants

5.5.7 Water transport based on capillary action

5.6 Design objective

5.7 Concepts Generated

5.7.1 Superhydrophobic surface

5.7.2 Mechanically actuated ball valves

5.7.3 Ferro fluid

5.7.4 Venturi Ejector
5.7.5 Passive water removal using a semi-permeable membrane and osmosis .......... 67
5.7.6 Passive water removal using PES hollow tubes and capillary action ............ 69

6 Conclusion ................................................................................................................. 81

6.1 Categorization ..................................................................................................... 82
6.2 POS identification, sense disambiguation and abstract object identification .......... 82
   6.2.1 Separate results by search keyword POS and sense .................................... 83
   6.2.2 Remove results where keywords act on abstract nouns............................... 83
6.3 Case study: PEMFC water management system design .................................... 83
6.4 Future work and recommendation .................................................................... 84

Bibliography .............................................................................................................. 86

Appendices ................................................................................................................. 92

Copyright Acknowledgements ..................................................................................... 104
List of Tables

Table 1: BioSearch server specifications .......................................................................................... 9
Table 2: Differences between each BioSearch version ...................................................................... 18
Table 3: Example Categories at Different Levels ............................................................................ 31
Table 4: Summary of the benefits of individual improvements of BioSearch ................................. 35
Table 5: A typical user action in BioSearch v0.3 ............................................................................ 37
Table 6: Design concepts and biological phenomena stimuli used ..................................................... 52
Table 7: Results for different opening sizes ..................................................................................... 57
Table 8: Recommended ferromagnetic particles from Ferrotec Corporation ..................................... 63
Table 9: Mapping from biological phenomena to redesign of fuel cell bipolar plate ...................... 67
Table 10: Mapping from biological phenomena to redesign of PEMFC bipolar plate ...................... 71
List of Figures

Figure 1: A functional basis representation of a power screwdriver (Stone & Wood, 2000) .......... 3
Figure 2: Map of the levels of division and type of metadata for each level in a corpus ............ 16
Figure 3: Sense prompt after user entered “defend” as search keyword .................................... 19
Figure 4: Functional basis to biological keyword GUI ............................................................... 21
Figure 5: Partial display of a result section ................................................................................. 22
Figure 6: A partial MySQL table showing the POS and sense data for each word ................. 23
Figure 7: Screenshot of the user/group management GUI ......................................................... 24
Figure 8: Category trace for the noun Phagocyte ..................................................................... 27
Figure 9: Representation of Wikipedia-Based Taxonomy Structure ....................................... 30
Figure 10: Screenshot of the Biomimetic Search Tool User Interface .................................... 33
Figure 11: Category trace for “Phagocyte, scavenger cell” ....................................................... 34
Figure 12: Sample category list for a search in BioSearch v0.41 ............................................. 34
Figure 13: Recommended biomimetic design procedure for BioSearch v0.3 ......................... 36
Figure 14: Group 5 – Gravity assisted bike storage rack ......................................................... 39
Figure 15: Group 6 – Method to quickly replace a scratched/worn table top for office furniture 39
Figure 16: Group 9 – Improving rider comfort by redesigning bicycle seats ............................ 40
Figure 17: Group 12 – improve rider visibility by using anti-camouflage ............................... 41
Figure 18: Group 13 – Echolocation based proximity system for bicycles ............................ 42
Figure 19: Typical PEMFC bipolar plate configuration ............................................................. 44
Figure 20: Related words of "wet" based on WordNet v3.0 relationships ........................................... 47
Figure 21: Membrane osmosis ........................................................................................................... 50
Figure 22: Water transplant in plants .................................................................................................. 51
Figure 23: Rhizoids on liverworts ....................................................................................................... 52
Figure 24: Geometry that induces lotus effect ...................................................................................... 54
Figure 25: Geometry that induces lotus effect ...................................................................................... 54
Figure 26: Dot / line patterns that were printed on an overhead transparency to create the lotus effect surface ..................................................................................................................... 56
Figure 27: Differences between the three liquid - solid / solid - air interfaces ................................. 56
Figure 28: A ball blocking fluid passage .............................................................................................. 58
Figure 29: Schematics for the mechanically ball valve design .............................................................. 59
Figure 30: Machined prototype ........................................................................................................... 60
Figure 31: Ferrofluid, with a magnet under the glass (Photo by Gregory F. Maxwell, GNU Free Documentation License) .............................................................................................................................. 61
Figure 32: Schematic of the ferro fluid concept ..................................................................................... 62
Figure 33: Conceptual representation of the Venturi ejector concept .................................................. 64
Figure 34: CAD modeling of the Venturi ejector concept (Section view) .............................................. 65
Figure 35: Prototype of the Venturi concept, with one of the fittings removed, exposing the internal 0.25mm ID hypodermic tube ................................................................................................. 66
Figure 36: Passive water removal using semi-permeable membrane and osmosis ............................... 67
Figure 37: Proposed PEMFC bipolar plate configuration ........................................................................ 69
Figure 38: Back-lit photograph of the micro-channel features that induces capillary action ...... 70
Figure 39: Water removal with a switchable humidifier ................................................................. 71

Figure 40: Prototype detail .................................................................................................................. 72

Figure 41: Physical prototype .............................................................................................................. 73

Figure 42: PES hollow tubes from Diapes PES-150, Photo by Ian Pang .......................................... 73

Figure 43: Experimental Setup ........................................................................................................... 74

Figure 44: Water removal time (fan high) .......................................................................................... 76

Figure 45: Water removal time (fan low) .......................................................................................... 76

Figure 46: Water removal time (fan off) .......................................................................................... 77

Figure 47: Water removal rate (summary) ......................................................................................... 78

Figure 48: Water removal time when the PES hollow tubes are nearing maximum carrying capacity ...................................................................................................................... 78

Figure 49: Frame capture of a video of the experiment ................................................................. 80
List of Appendices

A. Full categorized results ........................................................................................................ 92
   1. Results for Splice: ........................................................................................................... 92
   2. Results for Collect:......................................................................................................... 93
   3. Results for Extract:........................................................................................................ 94
   4. Results for Trap:........................................................................................................... 94
   5. Results for Delete:......................................................................................................... 95
   6. Results for Degrade:.................................................................................................... 96
   7. Results for Beat:........................................................................................................... 97
   8. Results for Separate:.................................................................................................... 98
   9. Combined results (removing redundant categories): ................................................... 100

B. Partial list of biological phenomena .................................................................................... 101

C. Workflow for automatic corpora import ............................................................................... 104
## Nomenclature

<table>
<thead>
<tr>
<th>Search related</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Abstract noun</strong></td>
</tr>
<tr>
<td><strong>Antonym</strong></td>
</tr>
<tr>
<td><strong>Biomimetic search engine</strong></td>
</tr>
<tr>
<td><strong>Biomimetic search tool (BioSearch)</strong></td>
</tr>
<tr>
<td><strong>Categorization</strong></td>
</tr>
<tr>
<td><strong>Corpus (plural: Corpora)</strong></td>
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<tr>
<td><strong>Data mining</strong></td>
</tr>
<tr>
<td><strong>Engine (Search)</strong></td>
</tr>
<tr>
<td><strong>Hypernym</strong></td>
</tr>
<tr>
<td><strong>Hyponym</strong></td>
</tr>
<tr>
<td><strong>Match excerpt</strong></td>
</tr>
<tr>
<td><strong>MySQL</strong></td>
</tr>
<tr>
<td><strong>Natural-language</strong></td>
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<tr>
<td><strong>Ontology</strong></td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td><strong>Part-of-speech</strong></td>
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<tr>
<td><strong>PHP</strong></td>
</tr>
<tr>
<td><strong>Phrase Group</strong></td>
</tr>
<tr>
<td><strong>Polysemous</strong></td>
</tr>
<tr>
<td><strong>Precision</strong></td>
</tr>
<tr>
<td><strong>Recall</strong></td>
</tr>
<tr>
<td><strong>Section</strong></td>
</tr>
<tr>
<td><strong>Stimulus</strong></td>
</tr>
<tr>
<td><strong>Synsets</strong></td>
</tr>
<tr>
<td><strong>Word sense disambiguation</strong></td>
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<tr>
<td><strong>WordNet</strong></td>
</tr>
</tbody>
</table>

**Fuel cell related**

<p>| <strong>Bipolar plate</strong> | An electrically conductive plate that enables gas flow, electron conduction and water removal in a PEMFC |</p>
<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catastrophic flooding</td>
<td>Excessive liquid water buildup that severely reduces fuel cell performance</td>
</tr>
<tr>
<td>Membrane electrode assembly (MEA)</td>
<td>An assembly consisting of a proton exchange membrane, electrodes and catalyst in a PEMFC</td>
</tr>
<tr>
<td>Proton exchange membrane fuel cell (PEMFC)</td>
<td>A type of fuel cell that operates at a relatively low temperature</td>
</tr>
</tbody>
</table>
# List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIDLab</td>
<td>Biomimetics for Innovation and Design Laboratory</td>
</tr>
<tr>
<td>BSE</td>
<td>Biomimetic Search Engine</td>
</tr>
<tr>
<td>DPI</td>
<td>Dots Per Inch</td>
</tr>
<tr>
<td>DTM</td>
<td>Design Theory and Methodology</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphic User Interface</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>MEA</td>
<td>Membrane Electrode Assembly</td>
</tr>
<tr>
<td>MySQL</td>
<td>My Structured Query Language</td>
</tr>
<tr>
<td>NLP</td>
<td>Natural Language Processing</td>
</tr>
<tr>
<td>PEMFC</td>
<td>Proton Exchange Membrane Fuel Cell or Polymer Electrolyte Membrane Fuel Cell</td>
</tr>
<tr>
<td>PES</td>
<td>PolyEtherSulfone</td>
</tr>
<tr>
<td>PHP</td>
<td>Pre Hypertext Processor</td>
</tr>
<tr>
<td>POS</td>
<td>Part of Speech</td>
</tr>
<tr>
<td>ROM</td>
<td>Recursive Object Modeling</td>
</tr>
<tr>
<td>SVO</td>
<td>Subject – Verb - Object</td>
</tr>
</tbody>
</table>
1 Introduction

Biomimetic design methodology examines nature and emulates our surroundings to solve design problems. The transfer of knowledge between the biology domain to the engineering domain is desirable due to the observation that analogies from conceptually different domains have resulted in more creative design solutions (Benami and Jin 2002). Gordon (1961) also noted that the specific domain of biology provides the richest source of direct analogies.

Biomimetic design has generated innovations in diverse fields such as mechanical design, computer algorithms and manufacturing processes. Obvious biomimetic designs such as the use of fish to inspire underwater robots and birds to inspire planes are common. Higher-level biomimetic designs, such as the use of leaf abscission to inspire the remanufacturing process (Hacco and Shu 2002) and biomimetic design for the lunar environment (Davidson, et al. 2009) require a systematic search of biological systems.

Despite the demonstrated usefulness of biological analogies in design, designers are likely limited by their personal knowledge of biology. Researchers such as Linsey et al. (2007) support the idea that designers require tools and systematic methods to access cross-domain knowledge.

The Biomimetics for Innovation and Design Laboratory’s (BIDLab) approach to support biomimetic design involves searching for instances of functional keywords in biology knowledge sources in natural-language format, e.g., books, papers, etc. Matched text excerpts containing keywords are examined for relevant biological phenomena that can be applied to the engineering problem of interest. This method takes advantage of the extensive biological information already existing in natural-language format. The computational implementation of this method is in the form of a search engine. This search engine’s (hereby referred as BioSearch) capabilities and its shortcomings will be discussed in the later chapters.

There are two main shortcomings with the natural-language processing (NLP) approach to support biomimetic design:

1. Many engineers do not have expertise in biology; therefore, engineers might have difficulties initiating knowledge searches in the biology domain due to lexical differences. To solve this problem, a method was developed to use word collocation and frequency
analyses to identify biologically meaningful keywords that bridge the different lexicons of the fields of biology and engineering (Chiu and Shu 2007). Furthermore, Cheong et al. (2008) translated terms of the Functional Basis into biologically meaningful keywords, not obviously related to the functional keywords, to use as search keywords.

2. The second shortcoming is due to the vast amount of biology information that exists in natural language format. A typical search will potentially result a large number of matches, some of which are irrelevant. The present thesis will focus on my effort in solving this shortcoming.

1.1 Thesis objectives

This thesis has two main objectives. The first objective is to detail improvements made to BioSearch so it is more accessible to users while improving the usefulness of the results. The second objective is to detail case studies that use BioSearch as a creative tool to solve engineering design problems, including a case study I have done on generating biologically inspired designs for the fuel cell water management system.

1.2 Literature reviews

Due to the wide scope of this thesis, this initial literature review section will be limited to the references that are fundamental to this thesis. There will be other literature reviews in other chapters that are relevant to local contents.

1.2.1 Related work in design theory and methodology

Biomimetic design is part of design theory and methodology. More specifically, it falls into the branch of creativity-based design using stimulation methods (Tomiyama 2006). Tomiyama argues that by exposing designers to a collection of knowledge that they never experienced, it is expected that their imagination can be stimulated to conceive more creative designs. The collection of knowledge can be in the form of books, archives, other related designs or unrelated knowledge domains such as biology.
1.2.1.1 Functional Basis

Domain specific language poses a challenge in biomimetic design. Similar functions in biology domain and engineering domain might be described by different words. To solve this problem, Chiu & Shu (2007) and Cheong et al. (2008) translated terms of the Functional Basis into biologically meaningful keywords. The Functional Basis is a design language compiled by Hirtz et al. (2002) that helps with the basic understanding of functions in engineering design. The functional basis can clearly and concisely describe the functions of a design in information modeling, design archiving, and standardizing design terminology. Figure 1 shows a sample functional basis representation.

**Figure 1**: A functional basis representation of a power screwdriver (Stone & Wood, 2000)
1.2.1.2 Ontology and functional representation

One of the shortcomings of the BIDLab’s approach to biomimetic design is the potentially large amount of search results, with a large amount of irrelevant results. Categorization can help with comprehension of a large amount of data. Ontology, or classification of existing things, is an active area of study; the relationship between engineering design and function has always been an area of interest for engineering. In the paper presented by Kitamura and Mizoguchi (2009), the research looks into functions’ ontological characteristics and their relationship to ontological engineering. By identifying and defining specific categories of function in this area, it is possible to draw connections between the functional category and existing definitions of the function identified from literature. Using this information, a hypothetical product life cycle is proposed, with the role of the function outlined within this cycle. From this model, the roles of different functions can be identified, as well as allow the definition of answers such as the defining factors of a function as well as the role it plays in the production process.

Function and its role in fields such as engineering design, artificial intelligence, value engineering and philosophy have been investigated in the past. However, the biggest obstacle in understanding function is its multiple roles and definitions outlined by the setting. Functional knowledge, such as functional decomposition, has been difficult to define due to its various components, such as the system breakdown and the relationships between each individual factor. However, due to its lack of definition, engineers tend to apply their own explanations to functional knowledge, leading to difficulty in the passing on of knowledge significant to any field. Even when taken directly from a given literary definition, it is difficult to understand function due to its indistinct relationship to all elements within a system.

Kitamura and Mizoguchi’s paper seeks to answer some questions and define some factors of ontology in the area of function such as where does a function exist (the relationship between a product and its function), what does the function depend on (relationship between a designer/user and the function), when does a function take up a role (changes in function during the product life cycle). From the hypothetical model derived from these hypotheses, it was determined that ontological features and functions play a role in consistent function modeling. The relationships of these different functions dictate whether or not a given system will operate successfully with the individual factors working together. By not trying to define one common concept of function
but rather trying to target which conditions would allow the successful relationship between various functions within a given system, Kitamura and Mizoguchi were able to outline upper-level functions in their ontology.

1.2.2 Related work in biomimetic design

BIDLab’s approach to biomimetic design is one of two main approaches for biological knowledge retrieval. The other approach to support biomimetic design is to create a database of biological phenomena organized by engineering function (Vincent and Mann 2002, Lindermann and Gramann 2004). Modern implementations of this method include asknature.com (Benyus, et al. n.d.), a community-supported source of biological knowledge. However, the creation of such resources may be both time consuming and resource intensive. This database creation process may also be subject to the compilers’ own knowledge and bias. Additionally, the rapid growth of biological knowledge provides further challenges for the updating of such a system (Spasic, Nenadic and Ananiadou 2003, Rebholz-Schuhmann, Kirsch and Couto 2005).

1.2.3 Related work in natural language processing

Natural-language processing, or NLP, is a field that combines computer science and linguistics that studies the interactions between computer and human language. NLP overlaps with computational linguistics and artificial intelligence. I am interested in NLP because I am using computer programs to extract information from natural (human) language.

1.2.3.1 Thesaurus for natural-language-based conceptual design

Natural language is a central factor in conceptual design due to its role in the operation and expression of a function within a design process. It also plays a large role in the genitive processes of the design and can be used to convey various theories, idea development, as well as solution generation for any given design problem. However, when compared to mathematical algorithms and equations, natural language lacks the ability to effectively express a function. In the studies conducted by Yamamoto et al. (2009), a thesaurus was developed in order to perform semi-automatic extraction of word structure hierarchy that is applied to the function dividing process of a vital function within a design process. Several studies have looked into the role of functions in supporting conceptual designs, with a function being a subject, verb, object, and additional information that convey an expression of behavior. In this particular study by
Yamamoto et al., the process of function dividing was investigated. A function is decomposed into sub-functions that comply with the original function, and these sub-functions are then used to develop a working thesaurus that aids in function searches as well as expression and operation of the function in question. The thesaurus was created through use of semi-automatic extraction of word hierarchy, and used as a search method and function operation.

1.3 Case study of biomimetic design: fuel cell water removal conceptual design

I have done several case studies to assess the effectiveness of the BioSearch improvements. During these case studies, I focused on designing and improving the fuel cell water removal mechanism using the biomimetic design approach.

Proton exchange membrane fuel cells (PEMFCs) are used in low-temperature power generation applications. The polymer membrane inside the PEMFC must be properly hydrated and kept at a controlled temperature of ~70 °C to efficiently conduct protons. The proton conductivity of the polymer electrolyte membrane is directly proportional to its water content. Fuel cell operating conditions and membrane characteristics determine the membrane water content (U.S. Department of Energy 2005).

Water, a product of the fuel-cell reaction, must also be removed from the cathode side to prevent congestion, or flooding, in the oxidizer flow channels. At high current densities, the rate of water production can exceed the cathode flow field water removal rate. Liquid water can build up and stagnate in the flow channels. This reduces the flow of oxidizer to the cathode and reduces the overall efficiency of the fuel cell. A mechanism that removes accumulating liquid water continuously from the flow channels is required. Desirably, the mechanism will use minimum or no energy and will not have a drying effect on the membrane. A common strategy to minimize flooding in a serpentine flow field is to supply a high oxidant flow rate to force liquid water out of the system. However, the small flow channel cross-section (1mm x 1mm) and the long flow channel length (a few meters) require a relatively high inlet oxidant pressure. Use of parallel flow channels can reduce the pressure differential across the flow field by orders of magnitude compared to serpentine channels (Litster, et al. 2007). However, parallel channels are susceptible to uneven airflow through the channels with potential complete blockage by flooding, which degrades performance.
Typically, the PEMFC’s bipolar plate contains the water removal mechanism. Part of my research is to generate concepts for liquid water removal that can be incorporated into a bipolar plate. The biomimetic design approach for concept generation is demonstrated and used to identify possible liquid water removal solutions.

Some of the characteristics of biological systems that might be relevant to fuel cell design include:

- Efficient use of materials and energy: biological organisms usually use the minimum amount of energy and materials needed to survive, excessive material and energy use decrease chance of survival (Paturi and Clarke 1978).
- High tolerance: Living systems can operate in a wide range of conditions. They are able to adapt to variations in their environment. (Affholter and Arnold 1999).
- Environmentally sustainable: Biological systems survive by recycling materials and energy (J. Benyus 1997).
- Independent, self-regulating: Organisms and cells have brains and are self-controlled. Organisms maintain internal functions through homeostasis the maintenance of steady levels of metabolism, chemicals and temperature (Galbraith, et al. 1989).
- Precise: Biological synthesis is very precise (Paturi and Clarke 1978) even though they require minimal energy, machinery and control relative to most man-made synthesizing methods (Bond, Richman and McNaughton 1995).
- Diverse: The biological world offers a huge scope of solutions and adaptations, from microorganisms to ecological systems.
- Suitable: Biological systems are always well suited to the given environment (Paturi and Clarke 1978). Self-assembling: through mechanisms like synthesis, reproduction, and succession, biological systems automatically create and re-create tissues (Bond, Richman and McNaughton 1995), organisms and ecosystems, respectively.

1.4 Thesis Outline

This thesis consists of five main chapters. Chapter 2 describes the current difficulties associated with the BIDLab’s approach to support biomimetic design. Chapter 3 describes my effort to improve the BioSearch tool by attempting to solve the difficulties mentioned in chapter 2.
Chapter 4 describes an initial study on the improved BioSearch tool. Chapter 5 describes in detail a case study of using the BioSearch tool to improve a fuel cell water management system. Finally, chapter 6 summarizes my thesis and also presents my conclusions and recommendations for future work.
2 Improvements for biomimetic search engine

2.1 Biomimetic search engine introduction

My thesis involves the improvement of the biomimetic search tool (BioSearch); the computational engine that processes the user input and displays the relevant search results is called the biomimetic search engine (BSE). BioSearch was previously developed to locate biological knowledge in natural-language format by finding occurrences of keywords describing the engineering problem. While difficulties common to natural-language processing occurred, this approach does not require the tremendous and somewhat subjective task of categorizing all biological phenomena by engineering function. Thus, this approach can readily take advantage of the enormous amount of biological knowledge already in natural-language format.

There are several limitations with the original BioSearch, which are explained in detail in section 2.4. These limitations all revolve around the fact that the original BioSearch is a simple string search engine that cannot solve the main shortcomings of BIDLab’s natural-language search approach to the biomimetic design method as described in Chapter 1. The shortcomings can be summarized as: 1) engineers have difficulties initiating knowledge searches in the biology domain and 2) the difficulties of having too many search results, hindering comprehension of the results.

2.2 Server hardware

BioSearch runs on a single quad-core server, a Dell Inspiron 530 with the following specifications:

<table>
<thead>
<tr>
<th>Table 1: BioSearch server specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU</td>
</tr>
<tr>
<td>Number of physical processing cores</td>
</tr>
<tr>
<td>Number of virtual processing cores</td>
</tr>
<tr>
<td>CPU Frequency</td>
</tr>
<tr>
<td>L2 cache size</td>
</tr>
</tbody>
</table>
Due to the nature of the problem, the BioSearch server is unable to process large and complex searches that include sense disambiguation and categorization in real time. It is one of my objectives for improvements to the BioSearch to be efficient.

### 2.3 Sources for biological information

#### 2.3.1 Life, the Science of Biology

The initial source of biological information, Life, the Science of Biology, by Purves et al. (2001), is the reference text for an introductory biology course at the University of Toronto. This text is suitable for the purposes of the BIDLab’s biomimetic design approach for two reasons. First, the book is at a level that is easily understood by those who have little or no background in biology. Second, the book is general and covers several levels of biological organization, from the molecular (e.g., DNA) to the ecosystem level. BioSearch was developed to look for occurrences of functional words describing the engineering problem within the electronic copy of this text. As previously reported, while this initial source may not give enough details to inspire a novel solution, it is useful for identifying relevant phenomena that can then be further researched in more advanced sources. Subsequent sources could involve more specific texts to find details on relevant phenomena such as those on molecular and cell biology, plant physiology and animal physiology.
2.3.2 PubMed Bookshelf

PubMed bookshelf is a collection of biomedical books that can be searched and viewed online freely. Since PubMed is public accessible and its contents exist in a machine-readable format, it is relatively easy to implement a data mining script to download and convert the PubMed books into a biomimetic search engine compatible format.

Some of the books with potential as great sources for the biomimetic search engine include:

- Molecular Cell Biology by Lodish et al., New York: W. H. Freeman & Co.; c1999
- Immunology and Evolution of Infectious Disease by Frank, Princeton (NJ): Princeton University Press; c2002

The books listed above should provide detailed information in their respective fields.

2.3.3 Google Scholar

Google Scholar is an extension of the Google search engine that indexes the full text of scholarly literature and US patents. It can be a useful source for the biomimetic search engine as Google Scholar updates (or data-mines through the internet) frequently.

2.4 Challenges with biomimetic design

Along with advantages, there are challenges involved with the two main biomimetic approaches. For the biomimetic design involving creating a database, the creation of such a resource may be both time consuming and resource intensive. The process may also be subject to the compiler’s own knowledge and bias. Additionally, the rapid growth of biological knowledge provides further challenges for the updating of such a system (Spasic, Nenadic and Ananiadou 2003) (Rebholz-Schuhmann, Kirsch and Couto 2005).

Different challenges are presented for the BIDLab’s natural-language search approach. The main challenges are imprecise search keywords and the potentially high number of matches. Both challenges lead to irrelevant results. Hacco and Shu (2002), Chiu and Shu (2004), and Shu (2006) described some situations that may lead to irrelevant matches.
2.4.1 Word sense and part-of-speech

Words may be polysemous, or have multiple senses or meanings. For example, the word “seal” has many senses, ranging from to close off or isolate, to the aquatic mammal. Matches for “seal” in the aquatic mammal sense are not relevant to searches for “seal” in the closing off or isolating sense. Part-of-speech (POS) may help distinguish between some but not all senses. For example, the aquatic mammal sense only occurs in the noun form of “seal”, but the closing off or isolating sense may occur in multiple POS, i.e., noun or verb, forms of “seal”. Word sense disambiguation (WSD) aims to distinguish between possible alternative interpretations of words. We can clarify the intended search by specifying the sense for polysemous keywords such as “seal”.

2.4.2 Abstract objects

An abstract object is an entity that does not exist physically. Examples of abstract objects include ideas, feeling and concepts. Many engineering design problems involve physical objects. A match where the grammatical object of a search keyword is an abstract entity tends not to be as useful. For example, when searching for “stimulate”, matches regarding stimulating muscles may be more useful than those regarding stimulating interest. Abstract objects might be useful for disciplines such as information technology and scheduling, however, such are not part of this thesis scope.

2.4.3 Cross-domain lexical differences

Another challenge arises because engineers and biologists use different lexicons or terminology to describe related phenomena. For example, searching for the keyword “clean” for a problem involving cleaning did not locate many useful matches. When a biological domain expert was asked for alternative keywords, the keyword “defend” was suggested since some organisms clean as a defensive mechanism. However, “defend” is related to “clean” neither intuitively, for most engineers, nor lexically, e.g., as a synonym. Chiu and Shu (2007) developed a bridging mechanism based on certain semantic relations that identify such non-obvious, but highly relevant, biologically connotative keywords.
2.5 Proposed solutions to the natural language biomimetic design method

There are two main attempts to improve the natural language biomimetic design tool; both are designed to improve the precision and recall of the search results. I believe that improving the precision and recall of the search results facilitates processing and comprehension of biomimetic search results, thus supporting the use of biological analogies in design.

Precision and recall are two important statistical measurements that define the effectiveness of search engine information retrieval.

- Precision is a measure of the fraction of retrieved documents that are relevant to a query, and can be defined as: \( \text{Precision} = \frac{tp}{tp+fp} \) (Number of correct results divided by the number of all returned results)

- Recall is a measure of the fraction of the documents that are relevant to be retrieved in a query, and can be defined as: \( \text{Recall} = \frac{tp}{tp+fn} \) (Number of correct results divided by the number of results that should have been returned)

Where \( tp \) is true positives, \( fp \) is false positives and \( fn \) is false negatives, with respect to type I and type II errors in statistical hypothesis tests.

A low precision search engine, such as the original biomimetic search engine, returns many irrelevant results. A low recall search engine does not return all of the relevant results. The new biomimetic search engine should improve both precision and recall. Two proposed solutions are categorization of the search results and incorporating metadata to the corpora.

2.5.1 Categorization of the search results

Librarians have long used classification systems to enable categorization. More recently, some computer search engines have directory systems to help cope with the exponential growth in the number of web pages. In the design domain, a number of ontologies (Stone and Wood 2000, Kitamura, Washio, et al. 2006, Gero and Kannengiesser 2007) have been developed to structure and describe design concepts and their relationships. However, these categorization systems still require people to manually identify categories and perform the categorization. To manually
categorize all of biological information for the purpose of biomimetic design is a daunting task. This thesis describes two methods to automatically categorize search results.

Two basic principles exist for categorization (Levitin 2002). The first states that categorization should provide maximum information with the least cognitive effort. The second principle states that categorization information must be in the form of structured entities. Both principles are applied in the creation of the present computerized categorization method.

Automated categorization methods provide several benefits: Sorting a large number of search results into categories facilitates information navigation. The categories provide an overview in the form of one-to-two word summaries of the matched text excerpts. This overview quickly presents the diversity of the biological phenomena associated with the search keyword, several of which may reveal unexpected solutions. Upon surveying the category contents, the designer can more quickly focus on those matches that are most promising, as well as filter out less promising results.

2.5.2 Metadata for individual word in the corpora

Metadata is data that describes data. Metadata, along with the data they describe, can be stored, managed and queried in a database. Metadata are designed to enhance the primary data they describe; for example, the metadata for a digital photograph may include the time of creation, the location where the photo was taken, and the camera settings. These metadata can help with archiving, searching and identification of the metadata tagged photo. Likewise, it is possible to improve the precision and recall of the biomimetic search engine if the corpora are tagged with relevant and useful metadata.

I proposed that inserting metadata such as part-of-speech, word sense and lexicographical data for each word in a natural-language source can help users identify relevant biological stimuli for biomimetic design. By inserting metadata into the corpora, the search results can be better organized for more efficient review, which facilitates comprehension of the search results.

I proposed that metadata tags should be inserted into the following five levels of detail in a natural-language corpus.
• Chapter level: In this level, metadata describes how each chapter interacts with other chapters. Due to the broad scope of contents in a chapter, metadata in this level should not be used to understand the content of the chapter, but for navigation and archiving use.

• Paragraph level: Generally, a single paragraph describes a single idea. Under this assumption, metadata in this level should contain the paragraph’s main idea.

• Sentence level: Sentences consist of a single clause (subject and predicate) that can express a statement. Metadata in this level should contain the key relationships between the subject, the object and the predicate.

• Phrase-group level: Phrase groups include recognition of multi-words (e.g., noun phrases, verb phrases) and proper names. We also need to identify the relationships between words in a phrase group (e.g., subject of a verb, adjective of a noun).

• Word level: We need to identify the sense and the part-of-speech for each word in order to process paragraph, sentence and phrase-group level metadata. The sense and part-of-speech data are therefore metadata for each word.

Figure 2 shows a map of the resolution division levels and types of metadata associated with each level. The three different types of metadata used are:

• Relational metadata: How each element within the division levels is related to each other. For example, metadata may include subject-verb-object (SVO) identities within a sentence.

• Navigation metadata: Mainly for GUI use, to match user input to the correct position in a corpora. For example, chapter numbers, section numbers.

• Identity metadata: Identify the content of the element within the division. For example, sense and part-of-speech for a word.

The “+” symbol in Figure 2 quantifies the correlation between the division levels and the metadata type. For example, “Phrase group” metadata contains mainly relational metadata, as indicated by 5 “+”s, while it contains only few navigation metadata, as indicated by 1 “+”.
Figure 2: Map of the levels of division and type of metadata for each level in a corpus
3 Natural language processing for the biomimetic search engine

BioSearch is a computer based search engine that locates biological knowledge in natural-language format by finding occurrences of keywords describing the engineering problem. While difficulties common to natural language processing occurred, this approach does not require the tremendous and somewhat subjective task of categorizing all biological phenomena by engineering function. Thus, this natural-language processing approach can readily take advantage of the enormous amount of biological knowledge already in natural-language format.

The original biomimetic search tool (referred as BioSearch version 0.1 hereafter) has aided in several design exercises, including design for remanufacturing (Hacco and Shu 2002), the micro-assembly gripper (Shu, et al. 2006), and more recently, dust protection in the lunar environment for the Canadian space agency (Davidson, et al. 2009). In the following sections, I will describe my efforts in adding and improving functions in the biomimetic search engine. Please note that four major versions and various minor versions of the Biomimetic search engine exist. Only major milestones are discussed in this thesis (listed in Table 2); screenshots in this section are taken from different versions. Please see Table 2 for the differences between each BioSearch version. A former BIDLab student wrote BioSearch v0.1; subsequent versions (v0.2 – v0.41) were developed in the course of writing this thesis.
### Table 2: Differences between each BioSearch version

<table>
<thead>
<tr>
<th>Version</th>
<th>Search Keyword Options</th>
<th>Functional Keywords Translation</th>
<th>Result Display</th>
<th>Corpora Storage</th>
<th>Corpora Import</th>
<th>Categorization Method</th>
<th>Abstract Filter</th>
<th>Part-of-speech Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>Partial boolean</td>
<td>n/a</td>
<td>Text</td>
<td>String text</td>
<td>Manual</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>0.2</td>
<td>Stemmer, boolean</td>
<td>n/a</td>
<td>Text, figures</td>
<td>WordPress MySQL</td>
<td>CVS import</td>
<td>Wikipedia ontology</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>0.3</td>
<td>Stemmer, boolean</td>
<td>Available</td>
<td>Text, figures</td>
<td>Custom MySQL</td>
<td>Custom PHP import</td>
<td>Wikipedia, SVO</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>0.4</td>
<td>Stemmer, boolean</td>
<td>n/a</td>
<td>Text</td>
<td>Custom MySQL</td>
<td>Custom PHP import</td>
<td>n/a</td>
<td>n/a</td>
<td>Stanford Tagger</td>
</tr>
<tr>
<td>0.41</td>
<td>Sense search</td>
<td>n/a</td>
<td>Text</td>
<td>Custom MySQL</td>
<td>Custom PHP import</td>
<td>Sense Categorization</td>
<td>Available</td>
<td>Stanford Tagger, Sense Tagger</td>
</tr>
</tbody>
</table>

#### 3.1 Search keyword input improvements

BioSearch v0.1 can only process simple string searches. BioSearch v0.1 often generates irrelevant results due to imprecise initial search keyword selection. For example, search for mend will generate results such as Mendel, tremendous, or amend.

The new BioSearch engines uses two different methods to improve search keyword inputs. BioSearch versions 0.2 - 0.4 use the Porter stemming algorithm to reduce inflected words to their root form (for example, the root form of *mended is mend*). The Porter stemming algorithm is a stemmer written by Martin Porter in 1980; it is the de-facto standard algorithm used for English stemming (Wikimedia Foundation 2010). The implementation used in BioSearch is the freeware version of the algorithm written by Martin Porter (2006).
BioSearch v0.41 uses WordNet senses as search queries. String search queries are reduced to their senses. When we search by WordNet senses, users are required to select the sense or senses to initiate a search as seen on Figure 3. Please see section 3.10.3 for more information on WordNet senses integration into BioSearch v0.41.

BioSearch versions 0.2 - 0.4 also support standard search engine Boolean operations as listed below.

- **OR** Search for either one, such as “price high OR low” searches for “price” with “high” or “low”.
- **“-”** Search while excluding a word, such as “apple -tree” searches where word “tree” is not used.
- **“+”** Force inclusion of a word, such as “Name +of +the Game” to require the words “of” & “the” to appear on a matching page.
- **“*”** Wildcard operator to match any words between other specific words.

BioSearch v0.41 only supports the comma as a search keyword separator, as sense search makes the rest of the Boolean operators obsolete.

Figure 3: Sense prompt after user entered “defend” as search keyword
The following example illustrates the usefulness of search by sense:

When a user wants to search for “seal”, typical search engines will return results that contain all verb and noun form of “seal”. The verb form of word “seal” can refer to sealing an opening, while the noun form of word “seal” can refer to the mammal seal or a joint. The first problem is to determine that the POS of the word, since “seal” in verb form differs from “seal” in noun form. However, after determining the POS of a word, it might still be ambiguous, as the noun form of “seal” can have multiple meanings. In this case, word sense disambiguation can be used to maximize the differences between possible alternative interpretations of the words. By differentiating the word senses of the query, we can narrow our search results for polysemous keywords such as “seal”.

3.2 Biology - Engineering domain keyword translation integration

Cheong et al. translated terms of the Functional Basis into biologically meaningful keywords. Research has shown that it is more effective to use biologically meaningful keywords when searching for biology phenomena using the biomimetic search engine. The current biomimetic search engine contains a GUI for users to systematically find biologically meaningful keywords from a list of predefined functional basis.

As shown in Figure 4, the functional basis and its correspondent keywords are listed on the left side of the page, and the matching biological keywords are listed on the right side of the page. Users can easily access the translated biological search keywords from within the biomimetic search engine. The likely occurrences are the number of matches from the biological keywords within the primary corpus: Life, the Science of Biology (Purves, et al. 2001).
Figure 4: Functional basis to biological keyword GUI

3.3 Output refinement

Like modern search engines, BioSearch returns search results in a list of excerpts as shown in Figure 5. The search keywords in the result excerpts are highlighted in bold.

Clicking on an excerpt will lead the user to the full results with text and figures.
Corpora are divided into individual words and stored in a MySQL information storage system. Each word occupies a row in this system; 20 columns of metadata describe each word (As seen in Figure 6). Information such as the POS, words’ location in the corpus, words’ relation to other words in the phrase group, and lexicographer information, are several important metadata that are stored in the MySQL information storage system.

There are several reasons why MySQL is the relational information storage system of choice:

- Open source enables BioSearch to be deployed economically and the storage engine to be modified.
- Scalability, since a MySQL database can be easily scaled to fit more corpora into the BioSearch database.
- Low resource footprint makes MySQL a good choice for a low-end content server such as the Dell Inspiron 530.
- Good community support, various tutorials and online help forums are available for free.
3.5 Automatic corpora import

Corpora need to be imported to the biomimetic search tool before a search can be initiated. Chapters and sections need to be identified and tagged for indexing purposes. For BioSearch v0.1, chapters and sections are manually divided and stored as string files, a time and resource intensive task. BioSearch v0.2 and above uses a MySQL information storage system for quick information retrieval. As a result, BioSearch v0.2 and above require corpora to be divided to a higher resolution to include individual sentences, phrase groups and words. Dividing corpora to high resolution is a task too rigorous for manual processing.

Therefore, several automatic corpora importers are implemented for BioSearch v0.2 and above. All importers follow the flowchart shown on Appendix C. Time required to automatically import a corpus depends on whether the importer needs to process the sense and part-of-speech identification. For BioSearch v0.2 - v0.3, the corpora import process is a few minutes for an average sized text book, for BioSearch v0.4 and above, it takes about a day to process the same amount of data due to the added calculations required to identify sense and part-of-speech for every word in the corpus.
3.6 User / Group management

User management is crucial for group work and save/load search results. Group activities and projects are common in concept generation; therefore, a user/group data management is built into BioSearch v3.0 and above. The main purpose is for design groups to share and comment on the search results and collectively generate concepts based on the saved searches.

Figure 7 shows the user/group management GUI. Users can save and share search results with the members of the design group, and members of the design group can comment on the search result and offer design concepts with the group.

![Screenshot of the user/group management GUI]

3.7 Word sense disambiguation

One known difficulty with identifying contents in corpora is the polysemous nature of the English language. A possible solution is to use WordNet to disambiguate words into senses.
WordNet represents each word with synsets, which is a set of words that are considered to be synonyms for a particular concept. The new BioSearch’s objective is then to use an algorithm to identify the correct sense of a word in a given context. In computational linguistics, WSD aims to identify the sense, or meaning, of a word in a given sentence. By correctly identifying the sense of words in corpora, we can more accurately find relevant biological analogies for biomimetic design. The disambiguation algorithm used is called Word Sense Disambiguation by Michelizzi et al. (2008). A WSD tagged corpora may offer the following advantages over a corpora that is not WSD tagged:

1. Improved relevance of search results by removing matches with keywords in unintended senses.

2. Identified alternative synonymous terms for use as search keywords. For example, phagocyte and scavenger cell are synonymous. Knowing this synonymous relationship enables return of matches for both phagocyte and scavenger cell when searching for one or the other.

3. Categorized search results by tracing the hierarchy of hyponyms/hypernyms, or words with more narrow/general meanings.

4. Separation/removal of abstract results by identifying whether a noun is an abstract or physical entity.

Modern WSD engines are only approximately 60% accurate in precision and recall (Agirre, Márquez and Wicentowski 2007). Therefore, to reduce the effects of incorrect sense tagging, the biomimetic search engine identifies several likely senses of each word based on word occurrences of a tagged corpus with similar context. The WSD algorithm incorporated into the biomimetic search tool was developed by Pedersen et al. (2005) based on second order co-occurrence vectors of pieces of text (Schütze 1998).

3.7.1 Related work in word sense disambiguation

3.7.1.1 Recursive object model

Zeng (2008) converts natural English text into recursive object model (ROM) diagrams. ROM is helpful with respect to the understanding of product requirements, design scenarios, or
formulating quality standards. ROM uses part-of-speech, word sense and phrase groups to mathematically determine the relationships between words in corpora. The result is a structured overview of a section of corpora; from this view, users (or machine) can easily understand the content of the corpora.

Although ROM is designed for project requirement understanding, the ROM’s method of using part-of-speech and word sense disambiguation inspired me to use similar methods to understand the content of corpora.

3.7.1.2 Cascaded finite-state transducers

Hobbs (Hobbs 2002) describes how he used cascaded finite-state transducers to automatically understand the content of a natural language corpus. The cascaded finite-state transducer first determines the part-of-speech of the elements in a sentence, and then attempts to conform the sequence of elements to pre-established patterns (i.e. subject-verb-object). An implementation of this approach is SRI International’s FASTUS system. The FASTUS system was developed to automatically extract information for the intelligence community.

3.8 Part-of-speech determination

I used Stanford Tagger v1.6 to determine the POS and phrase group of each word in the corpora; this POS algorithm is based on a word’s definition and relationship to other words in a sentence (Toutanova, et al. 2003). I chose this tagger because it is over 97% accurate and provides the following features:

1. Can be trained to learn unknown words, i.e., learning algorithms, which is useful for domain-specific corpora.

2. Able to determine POS of unknown words based on surrounding words, which is very useful for domain-specific corpora.

3. Able to recognize phrase groups, or substructures of a sentence (e.g., noun groups, verb groups), also known as chunking.

The accuracy of this tagger can be further improved with additional input into the learning algorithm.
### 3.9 Abstract search result determination

After the phrase group is identified, WordNet is used to determine if the noun in the phrase group is a physical or abstract entity. Nouns that describe intangible entities, such as theory or skill are abstract nouns. A WordNet word sense hierarchy can be constructed by tracing the hypernyms, more general words, or categories, of each noun. For example, Figure 8 shows the hypernym trace of phagocyte identifying it as a physical, not abstract, entity.

Figure 3.8 shows phagocyte classified as an animate thing, then more generally as a physical entity, with entity as the root hypernym. Most nouns are either physical or abstract.

![Category trace for the noun Phagocyte](image-url)

**Figure 8: Category trace for the noun Phagocyte**
3.10 Categorizing search results

Categorizing search results aims to overcome the obstacle of processing a potentially large numbers of matches when searching for biological analogies to support design. Specifically, I attempted to develop a method to effectively categorize and display search results. I believe this work will facilitate processing and comprehension of biomimetic search results, thus supporting the use of biological analogies in design.

Categorization is the process in which ideas and objects are recognized, differentiated and understood (Wikimedia Foundation 2010); it is fundamental in illustrating relationships between the subject and objects of knowledge. Librarians have long used classification systems to enable categorization. More recently, some computer search engines have directory systems to help cope with the exponential growth in the number of web pages. In the design domain, a number of ontologies (Stone and Wood 2000, Kitamura, Washio, et al. 2006, Gero and Kannengiesser 2007) have been developed to structure and describe design concepts and their relationships. However, these categorization systems still require people to manually identify categories and perform the categorization. To manually categorize all biological information for the purpose of biomimetic design is a daunting task. The following subsections of this chapter describe two methods to automate search results categorization.

Two basic principles exist for categorization (Levitin 2002). The first states that categorization should provide maximum information with the least cognitive effort. The second principle states that categorization information must be in the form of structured entities. Both principles are applied in the creation of the automated categorization methods.

3.10.1 Related work in search results categorization

Search result categorization is actively researched for many diverse applications, e.g., search engines, library cataloguing, management, linguistics, data mining, etc. Most categorization techniques require the user to manually assign a category to a database entry before a category search can be performed. For example, the ontology-based annotation framework, a metadata scheme that uses functionality based semantics to relate the information content of engineering design documents, requires the authors to insert the metadata into the design documents (Kitamura, Washio, et al. 2006).
Currently, challenges exist in using computational language processing techniques to automatically categorize without human intervention. Perhaps this is the reason why some major search engines still do not have an automatic categorization system in place. Nevertheless, the following are some approaches toward real-time categorization.

### 3.10.1.1 WordNet semantic similarity
Hao et al. (2008) use name-entity recognition and part-of-speech analysis to retrieve a verb-noun pair from a search result. They then use a semantic similarity algorithm based on WordNet to calculate the similarity between each text excerpt and each pre-defined category to determine the category for the match. A preliminary experiment using this method demonstrated that 72.7% of the matches are correctly categorized.

### 3.10.1.2 WordNet based Perl implementation of relatedness measures
Pedersen et al. (2007) used six existing domain-independent measurements to compute the similarity between information in a biomedical context. The semantic measurements include three path-based ones using the WordNet hierarchy, two information content-based measurements, and a vector-based measurement. This last measurement creates context vectors that represent the meaning of concepts derived from word frequency analysis of several corpora. However, when compared with the results of manual similarity assessment by nine medical professionals, the results of these six computational methods of similarity measurement were generally poor.

### 3.10.1.3 Support Vector Machine
Chen and Dumais (2000) describe the Support Vector Machine (SVM) that used 13,352 pre-classified web pages to train a model. In practice, fewer than 70% of the webpages were correctly identified by the SVM method. However, test subjects were observed to find information 50% faster once the websites have been categorized.

### 3.10.2 BioSearch Categorization using Wikipedia ontology
Categorization requires a hierarchal ontology and a system to identify and map the search results into the ontology. This section describes a categorization engine based on the Wikipedia ontology; the next section describes a categorization engine based on the WordNet ontology.
Using Wikipedia structures as ontology is my initial effort to categorize search results. Before the actual categorization of search results, a pre-search calculation is used to determine the categories; this process needs only to be performed once. The pre-search calculation extracts category structures from the Biology category entry from Wikipedia.

Wikipedia’s content has been used extensively for academic research (Prescott 2006). Wikipedia categories have recently been used to identify concepts (Syed, Finin and Joshi 2008). Furthermore, the biological ontology structure within Wikipedia is more detailed, better structured, and better referenced than the ontologies of other promising resources such as Bio-Medicine.org (Bio-medicine 2009) and Biology-Online.org (Biology Online n.d.).

Both categories and articles are extracted from Wikipedia. Categories consist of super-categories and sub-categories. Biology is the only super-category for the current biomimetic search tool; other super-categories will be considered for future work. The resulting taxonomy structure is predominantly hierarchical, with some redundant and possibly undesired interconnections, an example of which is shown in Figure 9.

![Representation of Wikipedia-Based Taxonomy Structure](image)

**Figure 9: Representation of Wikipedia-Based Taxonomy Structure**

### 3.10.2.1 Category Structure Compilation

A computer program extracts categories and corresponding articles from Wikipedia. The titles of the articles are used as category triggers. A category trigger is a word or a group of words that the categorization engine will search for in each match excerpt. If the trigger is found, then the matched section will be classified under the category that triggered it.
Sub-categories are hierarchical and exist at different levels. Immediately direct sub-categories of the super-category “Biology” are labeled level 2, and subsequent sub-categories are more specific than the previous level, and are numbered incrementally. We observed that higher numbered categories are more likely to contain detailed and technical articles, increasing their value as design stimuli.

However, more specific categories are also more likely to be noise categories. Noise categories are encountered due to the interconnectedness of the Wikipedia taxonomy structure. An example noise category is “Chemical Weapons”, which is a sub-category of both the super categories "Biology" and "Weapons" as shown in Figure 9. Another undesired effect of using a more specific category level is over-categorizing. Over-categorizing arises when categories are too finely defined, which might result in a large number of categories. A category cut-off level is selected to balance the negative effects of noise categories and over-categorizing and the desired qualities of category specificity and useful content.

Table 3 shows the difference in scope between the different levels of categories. One can choose one or a combination of category levels to view search results. We observed for most problems that category level 4 is a good balance between specificity and usefulness. To enhance search results further, the Porter stemming algorithm is used to remove common morphological and inflexional endings from words (Porter 2006). A MySQL stop-word list is used to filter out common words that do not add semantic value (Oracle Corporation 2008).

**Table 3: Example Categories at Different Levels**

<table>
<thead>
<tr>
<th>Category Level</th>
<th>Specificity</th>
<th>Sample Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very General</td>
<td>Biology</td>
</tr>
<tr>
<td>2</td>
<td>General</td>
<td>Neuroscience, Genetics, Organisms</td>
</tr>
<tr>
<td>3</td>
<td>Specific</td>
<td>Eukaryotes, Bioluminescence, Biomolecules</td>
</tr>
<tr>
<td>4</td>
<td>Very Specific</td>
<td>Lipids, Cellular respiration, Neurotransmitters</td>
</tr>
</tbody>
</table>
3.10.2.2 Categorization Engine

To initiate the process, the user enters search keywords. The biomimetic search tool looks for instances of the keywords, generating excerpts consisting of one or two sentences surrounding the search keyword from the corresponding section. The categorization engine then searches for the category triggers within the excerpt. If the category triggers exist within the excerpt, the section that contains the excerpt is categorized under the category trigger.

3.10.2.3 Categorized Results

After the categorization engine processes the excerpts and sorts them into categories, the results are displayed in three levels, containing increasing detail: 1) the list of categories, 2) the match excerpts, and 3) the sections containing the matches. Figure 10 is a screenshot of example-categorized results.

The biomimetic search tool’s user interface mimics the “Column View” mode found in modern operation systems (e.g., Apple’s Finder). In this interface, columns represent different levels of information, increasing in detail from left to right. Column contents are expanded by clicking on a sub-category (represented by a folder icon, Figure 10, label 1) or a section title (represented by a file icon, Figure 10, label 2). The one or two sentences corresponding to the match excerpt appear when the mouse is moved over a section title (Figure 10, label 3). As intended, the category lists give minimal information but provide an overview of the matches. The match excerpt gives more information by displaying one or two sentences surrounding the keyword, and the entire section (Figure 10, label 4) that contains the match excerpt gives the most information.
3.10.3 BioSearch Categorization using WordNet ontology

All nouns in WordNet are classified under the top level category “entity”, either as an abstract entity or a physical entity (see section 3.11). Further division is possible to increase the specificity of a sense. For example, Figure 11 shows the hypernym/hyponym relationship for a sense of the word “phagocyte”. Multiple hypernym/hyponym relationships within WordNet can be merged to form a single multi-layered conceptual ontology to categorize BioSearch search results.

An example of WordNet categorized results is shown on Figure 12. Some categories that do not contribute to the comprehension of the search results can be hidden (i.e. animated being, object). However, categories that are relatively specific, such as “craniate” and “gamete”, convey enough information to assist in comprehension of the search results that are classified under these categories.
Figure 11: Category trace for “Phagocyte, scavenger cell”

Figure 12: Sample category list for a search in BioSearch v0.41
## 3.11 Chapter summary

Table 4 summarizes the improvements and benefits of the BioSearch additions. The additions are collectively aimed to address two of the challenges associated with natural-language search for biological phenomena: A large number of matches and possible irrelevant matches.

### Table 4: Summary of the benefits of individual improvements of BioSearch

<table>
<thead>
<tr>
<th>Section</th>
<th>Improvement name</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Search keyword input improvements</td>
<td>Search by sense, Boolean search, Reduce search words to its root form</td>
</tr>
<tr>
<td>3.2</td>
<td>Biology - Engineering domain keyword translation integration</td>
<td>Access to biologically meaningful search keywords</td>
</tr>
<tr>
<td>3.3</td>
<td>Output refinement</td>
<td>Include figures and text formats</td>
</tr>
<tr>
<td>3.4</td>
<td>Corpora storage</td>
<td>Flexible and faster corpora storage</td>
</tr>
<tr>
<td>3.5</td>
<td>Automatic corpora import</td>
<td>Better than labor and time consuming manual corpora import</td>
</tr>
<tr>
<td>3.6</td>
<td>User / Group management</td>
<td>Able to save, resume, comment and share search results</td>
</tr>
<tr>
<td>3.7</td>
<td>Word sense disambiguation</td>
<td>Improve relevance of results by removing results with unintended senses, Identify alternative synonymous search terms, categorize search results by senses hierarchy, remove abstract results</td>
</tr>
<tr>
<td>3.8</td>
<td>Part-of-speech determination</td>
<td>Determine POS and phrase group of each word, needed for the POS process</td>
</tr>
<tr>
<td>3.9</td>
<td>Abstract search result determination</td>
<td>Filter out abstract results, display physical results</td>
</tr>
<tr>
<td>3.10</td>
<td>Categorizing search results</td>
<td>Helps processing and comprehension of biomimetic search results</td>
</tr>
</tbody>
</table>
4 Applications of biomimetic search engine

In this chapter, I will go over an experiment I have done with student designers using BioSearch. Chapter 5 will detail my own attempts in using BioSearch to develop a fuel cell water management subsystem.

4.1 Experiments with MIE440 engineering design course

MIE440 is an engineering design process course with emphasis on theory and methodology related to conceptual design. The course teaches design by analogy, particularly biological analogies. BioSearch v0.1 was used for the previous MIE440 students to find biological phenomena. For the 2009 fall term, MIE440 students were presented with the option to use BioSearch v0.3 for their concept generation.

4.1.1 Recommended BioSearch procedure

![Figure 13: Recommended biomimetic design procedure for BioSearch v0.3](image)

4.1.2 User action logging

BioSearch v0.3 was used for the experiment, as it was the latest version available at the time of the experiment. Features that were tested include user/group management, Wikipedia integration and categorization of the search results. A user action logger was implemented to track user’s actions. If users agree to BioSearch’s end user license agreement, their user name is also logged, if not, only their IP address is logged. Time is also logged with the associated user action; therefore a time-based map can be drawn out to connect the thought process of each user based on the recorded data.
Users in this case are the students of 2009-fall class of MIE440. I briefed the users with a 20min introduction of BioSearch v0.3 that includes a sample case study.

Table 5: A typical user action in BioSearch v0.3

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>IP</th>
<th>Action</th>
<th>Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/8/06</td>
<td>16-23-52</td>
<td>128.100.48.236</td>
<td>login</td>
<td>(username hidden)</td>
</tr>
<tr>
<td>9/8/06</td>
<td>16-24-53</td>
<td>128.100.48.236</td>
<td>wizard</td>
<td>ON</td>
</tr>
<tr>
<td>9/8/06</td>
<td>16-25-31</td>
<td>128.100.48.236</td>
<td>wizard</td>
<td>pollinate disperse</td>
</tr>
<tr>
<td>9/8/06</td>
<td>16-25-31</td>
<td>128.100.48.236</td>
<td>search</td>
<td>pollinate disperse</td>
</tr>
<tr>
<td>9/8/06</td>
<td>17-02-22</td>
<td>128.100.48.236</td>
<td>search</td>
<td>disperse</td>
</tr>
<tr>
<td>9/8/06</td>
<td>17-02-46</td>
<td>128.100.48.236</td>
<td>f-view</td>
<td>94</td>
</tr>
<tr>
<td>9/8/06</td>
<td>17-05-38</td>
<td>128.100.48.236</td>
<td>q-cata</td>
<td>Zoology</td>
</tr>
<tr>
<td>9/8/06</td>
<td>17-05-48</td>
<td>128.100.48.236</td>
<td>f-view</td>
<td>74</td>
</tr>
<tr>
<td>9/8/06</td>
<td>17-05-59</td>
<td>128.100.48.236</td>
<td>f-view</td>
<td>128</td>
</tr>
<tr>
<td>9/8/06</td>
<td>17-06-09</td>
<td>128.100.48.236</td>
<td>f-view</td>
<td>135</td>
</tr>
<tr>
<td>9/8/06</td>
<td>17-06-10</td>
<td>128.100.48.236</td>
<td>f-wiki</td>
<td>exoskeleton</td>
</tr>
</tbody>
</table>

4.1.3 Results

Table 5 shows a partial list of recorded user actions. Although in this example, I am only including 11 data points out of more than a thousand recorded actions, these 11 data points show a typical user interaction with BioSearch. The following is a translation of the data in Table 5 to user behavior:

1. User logged in

2. User turned on the search wizard (Finding biologically significant function words using the functional basis translator)

3. User selected engineering functions "pollinate" and "disperse", the biologically significant search keywords for the functional basis "transport"

4. User initiated a search using "pollinate" and "disperse"

5. BioSearch v0.3 should return 86 results; the user browsed through some of them

6. User decided to narrow down the search term to just "disperse"

7. BioSearch v0.3 should return 63 results
8. User initiated the f-view command, which enables the full view of a section from the corpus that contains the search excerpt. Section 94 was chosen for full view.

9. User decided to use categorization (q-cata command) to narrow down the number of results, the category user decided to use is “Zoology”.

10. User used f-view on section 74, 128 and 135.

11. User wanted to learn more about “exoskeleton”, therefore the user initiated the f-wiki command, which opens a Wikipedia page on exoskeleton within BioSearch v0.3.

It is apparent that the user correctly used BioSearch’s features to help select a useful search keyword, then systematically narrowed down the search results, finally finding and investigating a phenomena that might help with the concept generation. Although it is unknown if the user actually generated a concept from the above search, it was interesting to see that a user who had minimal training with BioSearch was able to correctly apply the natural language biomimetic design approach (Figure 13) with attempts to systematically filter out results.

### 4.1.4 Designs from MIE440 Fall 2009 class

The 2009 MIE440 class had a choice between either improving the commuter cyclist experience or doing furniture design as their term project. Several groups documented the BioSearch v0.3 design process in their project reports. The following are some excerpts from the reports.
**Biomimetic Search Tool**

<table>
<thead>
<tr>
<th>Functional Basis</th>
<th>Biological Keywords</th>
<th>Keywords with Relevant Matches</th>
<th>Relevant Matches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Move</td>
<td>Shift, change shape, organize</td>
<td>Shift</td>
<td>1. The quaternary structure of a protein consists of subunits</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Blood flows back to the heart through veins</td>
</tr>
<tr>
<td>Store</td>
<td>Concentrate, convert, photosynthesize, deposit, dissolve</td>
<td>None</td>
<td>None of those have relevant matches.</td>
</tr>
</tbody>
</table>

The second relevant match is selected for further review as following:

“Gravity causes blood accumulation in veins and edema. The back pressure that builds up in the capillaries when blood accumulates in the veins shifts the balance between blood pressure and osmotic potential so that there is a net movement of fluid into the intercellular spaces.” [4]

A storage rack with wires, wheels, and weights is generated from the second relevant match. When the user exerts a light pull on the handle underneath the rack, the storage base will lower down to the user by gravity. The storage unit can return to its original position by exerting a light pull on the weights hanging on both sides of the rack. The wheels switch around and shift the forces when either weight or the handle is pulled.

**Figure 14: Group 5 – Gravity assisted bike storage rack**

**5. Problem:** Want to create a method to replace a scratched/worn table top at minimal effort and cost without interfering with the normal function of the table top.

- Biomimetic Option - Search for ‘repair’ - Associated with plants which seal themselves and sacrifice the outside layer (example from lecture) - Concept - Create multiple layers of the top surface finish. As the surfaces degrade, they can be removed to reveal a new layer underneath.

**Figure 15: Group 6 – Method to quickly replace a scratched/worn table top for office furniture**
Concept 2: BIOMIMETIC SEARCH TOOL

Keyword used: distribute
Associated biological keywords used: stretch, change shape
Note: Change shape retrieved no results, thus only articles with the word “stretch” were utilized

1st Match: “Organisms have changed over Billions of Years 1”
Biological Phenomena
- Aquatic birds have toes that include a webbing that “stretches” when the toes are spread.
Concept Generated
- Collapsible seat - A seat that would incorporate 2 rods with a thick cloth material spanning across the rods, creating a structure similar to that of a hammock. When the rider wishes to remove and store the seat, the rods could collapse with the cloth material folding in the middle making it very easy to store in a small bag.

Concept Generation MIE440 Group 9

2nd Match: “Membranes are Dynamic 92”
Biological Phenomena
- A hypotonic cell absorbs an excessive amount of water and maintains a pressure that “stretches” the cell wall.
Concept Generated
- Dynamic seat - A mechanism connected to the wheels will pump a fluid to apply pressure to the supporting shaft of the seat to raise it. As such, the seat would raise when the rider is in motion and lower when the bike is stopped. This allows for easy mounting and dismounting as well as provides a more comfortable position for the rider when they are forced to stop say by a traffic light.

3rd Match: “The list of other hormones is long 727”
Biological Phenomena
- As blood pressure increases, this causes the walls of the heart to “stretch” activating mechanical receptors which in turn release hormones.
Concept Generated
- Pressure sensitive seat - When the rider sits on the seat, the pressure created will force a fluid in the supporting shaft of the seat to raise it for riding. This is to allow for ease of mounting and dismounting.

Figure 16: Group 9 – Improving rider comfort by redesigning bicycle seats
CONCEPT 2: BIOMIMETIC CONCEPT GENERATION

The biomimetic search tool available at http://biodesign.mie.utoronto.ca provided instances of signal detection and response generation analogous to those that may improve bicycle safety for commuter cyclists. By way of an introduction, the portal offers a list of verbs describing processes that occur within a biological context and catalogues a series of fields in which these processes take place. As a group, we used the following keywords in our search for biological processes that mimic the engineering function of safety our bicycle will be expected to satisfy. They are sorted in order of Functional Basis and Biological Keyword. The relevant matches produced by each search and final concept generated are highlighted below.

Keywords: Detect > Be Stimulated
Relevant Match: Rhodopsin is responsible for photosensitivity 805. The article describes how the presence of rhodopsins in the human eye enables photosensitivity. It elaborates on the structure of rhodopsins and details the changes in shape caused by the presence or absence of light that lead to responses.

Keywords: Display > Signal
Relevant Match: Chromatophores enable animals to change colour 846. Chromatophores are pigment-containing cells in the skin that can change the colour and pattern of an animal. The article provides insight into the types of chromatophores and the functions of the nervous and hormonal systems in changing the colour of an animal based on the situation it finds itself in.

Concept Generated

The biomimetic concept utilizes principles underlying the two aforementioned notions of photosensitivity and camouflage. Photosensitivity is the ability to detect light and camouflage refers to a prey animal changing its appearance to blend in with its surroundings to avoid predators.

The idea is to apply a coating to the bicycle frame of a substance that can detect light incident on it. Consequently, it will act as a sort of ‘anti-camouflage’ and change its appearance to distinguish it from its surroundings. So, for instance, the bicycle will be brightly illuminated in the dark and less so under conditions of high visibility.

Figure 17: Group 12 – improve rider visibility by using anti-camouflage
1) Concept generated using the online biomimetic search tool:

The keywords used to obtain this concept were emit, and detect. The biological analogy used was echolocation, which is used by animals such as bats in order to help them navigate in places where sight is limited. Echolocation is a process in which the animal regularly emits a signal of a specific frequency. Based on the frequency of the returned signal, the animal can determine its distance from surrounding objects. This allows the animal to navigate around obstacles while avoiding collisions.

The concept we came up with is as speed sensor as well as a proximity would be attached to the bicycle. The would measure the speed (V) of the the proximity sensor would be used to distance (d) from any object directly in bicycle. These two parameters would each other using the equation for speed. This equation can be rearranged to time (t) available before the cyclist with the object in front of him/her (t = ).

Furthermore, average human reaction time, and time required to stop (including speed, coefficient of friction of rubber on pavement) can be summed to give a critical time (t_critical). This critical time would correspond to the minimum time needed for the cyclist to stop under the given conditions. The system would then have an algorithm to always calculate t and t_critical. If at any point t is less than or equal to t_critical the system would determine that the cyclist does not have sufficient time to react, brake, and stop, without colliding with the object in front of him/her. In this situation actuators attached to the brakes of the bicycle would engage, allowing the bicycle to safely stop, avoiding an otherwise inevitable collision.

Figure 18: Group 13 – Echolocation based proximity system for bicycles

Previous concept generation studies used independent raters to evaluate the novelty and usefulness of each generated concept (Chiu and Shu 2008, Cheong and Shu 2009). Although no formal rating was done for the concepts illustrated in Figure 14 to Figure 18, it is clear that the novelty and usefulness varies between concepts. For example, group 13’s echo position system might be useful, but it is not novel because similar systems have already been deployed for automobiles and marine vehicles. In contrast, group 12’s anti-camouflage system is both novel and useful in my opinion.

I would like to conclude based on the results from the 2009 MIE440 term project that the BioSearch v0.3 has made biomimetic design more accessible to the students based on the following two observations:
1. Despite the usefulness and novelty rating variation between concepts, each group appeared to have successfully identified relevant biological phenomena to assist in their engineering design concept generation.

2. Most groups have also used advanced features such as the functional basis translator and categorization engine to help their search process.

4.1.5 Future work

Unfortunately, after the conclusion of the experiment, I realized that my data collection method is missing several key data points necessary to make the results conclusive. Namely, the users’ design intent should be recorded before the biomimetic design search, and the users’ generated concepts should be recorded after the biomimetic design search.

4.2 Fuel cell design

From 2008 -2010, I used BioSearch extensively for fuel cell concept generation with emphasis on improving the PEM fuel cell water removal system. The following chapter details my effort.
5 Case study: Fuel cell design generation

In section 1.3 we saw that biology is a good source for design stimuli in fuel cell concept generation. I would like to now apply the biomimetic design method to a wide range of fuel cell types and design for all fuel cell components, especially the membrane, electrolyte, gas/liquid delivery system, cooling system and reactant disposal. Unfortunately, due to time and resource constraints, I focused my efforts on the water management component of the PEMFC, especially the problem of cathode flooding as defined below.

5.1 Problem Definition

As mentioned in section 1.3, proton exchange membrane fuel cells (PEMFCs) are used in low-temperature power generation applications. The polymer membrane inside the PEMFC must be properly hydrated and kept at a controlled temperature of 70 °C to efficiently conduct protons. The proton conductivity of the polymer electrolyte membrane is directly proportional to its water content. Fuel cell operating conditions and membrane characteristics determine the membrane water content (U.S. Department of Energy 2005). Figure 19 shows a typical PEMFC bipolar plate configuration.

![Figure 19: Typical PEMFC bipolar plate configuration](image)

Water, a product of the fuel-cell reaction, must also be removed from the cathode side to prevent congestion, or flooding, in the oxidizer flow channels. At high current densities, the rate of water production can tax the ability of the cathode flow field to remove it. Liquid water can build up and stagnate in the flow channels. This reduces the flow of oxidizer to the cathode and reduces
the overall efficiency of the fuel cell. A mechanism that removes accumulating liquid water continuously from the flow channels is required. Desirably, the mechanism will use minimum or no energy and will not have a drying effect on the membrane. A common strategy to minimize flooding in a serpentine flow field is to supply a high oxidant flow rate to force liquid water out of the system. However, the small flow channel cross-section (1mm x 1mm) and the long flow channel length (meters) require a relatively high inlet oxidant pressure. Use of parallel flow channels can reduce the pressure differential across the flow field by orders of magnitude compared to serpentine channels (Litster, et al. 2007). However, parallel channels are susceptible to uneven airflow through the channels with potential complete blockage of one by flooding, which degrades performance.

Typically, the PEMFC’s bipolar plate contains the water removal mechanism. My focus is to generate concepts for liquid water removal that can be incorporated into a bipolar plate. The biomimetic design approach for concept generation is demonstrated and used to identify possible liquid water removal solutions.

5.2 Related work in PEMFC water management

A number of researchers have achieved recent advances in both passive and active PEMFC water removal:

1. Active water removal using EO pump

Litster et al. (2007) incorporated an electro-osmotic pump for water removal. This active water management system prevents flooding and provides rapid recovery from severe flooding. A power density improvement of up to 60% at low air stoichiometry was observed.

2. Passive water removal using capillary force

Metz et al. (2008) described a capillary droplet actuation system for passive water removal. Excess liquid water is transported away from the oxidant flow channel by geometry induced capillary force.

3. Passive water removal using wicks
Strickland et al. (2009) demonstrated a passive water management system using in-situ polymerization to mold and deposit wicks on the channel walls. The integrated wicks increase performance for very low air stoichiometry.

5.3 Search Keywords

Most searches for biological phenomena are performed on Life, the Science of Biology (Purves, et al. 2001) due to the reasons explained in section 2.3.1. There are two types of search keywords that were used to initiate a search: For BioSearch v0.2 to 0.3, function based search keywords are used to initiate a search, for BioSearch v0.4 to 0.41, quality based search keywords are used. The reason for using the different types of search keywords and search keyword examples are listed in the following subsections.

5.3.1 Function based search keywords

The first step of this process is to select the search keywords. The results of Cheong et al’s (2008) work that identified biologically meaningful keywords for function terms of the functional basis describe functions with verb-object pairs in a domain generic format (Stone and Wood 2000).

The function basis “Remove + Extract” most accurately describes the problem, as water and heat must be removed from the fuel cell. The corresponding biological meaningful keywords generated by Cheong et al. (2008) include Splice, Collect, Extract, Trap, Delete, Degraded, Beat and Separate.

5.3.2 Quality based search keywords

The design objective is to transport water efficiently. The corresponding quality or adjective that accurately describes this design objective was initially unclear to the authors. Therefore, WordNet was used to explore and identify potential search keywords. The initial starting keyword, ,”wet” was chosen for two reasons. First, “wet” is a common adjective with several related adjectives within the WordNet hierarchy, increasing our chances of finding more relevant search keywords. Second, “wet” loosely describes the design objective, increasing the resulting excerpts’ chance of containing biological phenomena that can lead to design concepts.
Our past work found WordNet relationships to be excellent sources for alternative keywords (Hacco and Shu 2002, Chiu and Shu 2004). Since antonyms and synonyms are key relationships for adjectives, they were used to obtain additional search keywords. Figure 20 shows the partial exploratory path taken to find search keywords within WordNet.

![Diagram showing related words of "wet" based on WordNet v3.0 relationships]

**Figure 20: Related words of "wet" based on WordNet v3.0 relationships**

The following adjectives were some of the chosen keywords: damp, evaporative, excretory, flooded, fluid, humid, soggy, hydraulic, hydrophilic, moist, osmotic, wet, and dry.

### 5.4 Search results filtering

I used the following three filtering methods to decrease the number of irrelevant results.

#### 5.4.1 Filtering by categorizing the results

As discussed in section 3.7 and 3.10.3, BioSearch first presents the search results under level 2 categories (Table 3) where the single level 1 category in our case is “biology”. Level 2 categories such as "physiology" and "organisms" are fairly generic. Higher numbered categories are more detailed, where the category titles themselves may reveal unexpected insights. In most cases, category titles and hierarchy reveal a large amount of information on the search results inside the categories. For example, while I might be interested in a category called “Biological processes”, I probably want to ignore search results that are classified in a category called “Cell imaging”. In Appendix A, the boxed entries indicate the categories, the unboxed entries indicate search excerpt titles, and the lines indicate the category hierarchy relationships. Appendix B contains a partial list of search excerpts from Appendix A with corresponding biological phenomena identified from these results.
5.4.2 Filtering by results by POS

When using adjectives as search keywords, BioSearch returned 180 unique result excerpts, of which 28 were automatically removed as the match excerpt used the keyword in a different POS than specified. Some adjectives can also be used as nouns and verbs. For example, while more useful to this case study as an adjective, the word “fluid” occurs very commonly in the corpus as a noun in less relevant contexts. Nouns are generally not preferred as search keywords, as nouns tend to bias designers towards preconceived biological phenomena (Chiu and Shu 2004) and do not provide analogies with respect to functions or qualities. By identifying the POS of the keyword, the biomimetic search tool can selectively omit search results obtained with search keywords having a particular POS.

5.4.3 Filtering by eliminating abstract results

Within the remaining 152 result excerpts from the initial quality based search, 87 have search keywords acting on abstract nouns; therefore, they can be automatically excluded from the results. For example, abstract adjective-noun pairs that were removed include wet-conditions and wet-seasons. Of the 180 original result excerpts, 65 passed the filtering process, a 64% reduction in the number of excerpts that would require manual processing. Figure 7 shows the POS and sense selection screen for matches of keyword “wet”.

5.5 Identified biological phenomena

The following are a list of biological phenomena that are either directly influenced the concept generation, or provided valuable insight for future work. Another list of identified biological phenomena matching the categories and results can be found in Appendix B.

5.5.1 Water strider’s leg

Water striders’ legs are hydrophobic, which enable the water striders to stand on water. Recently, Gao and Jiang (Gao and Jiang 2004) explained the water resistance of the leg is due to the hierarchical structure of the legs, which are covered by large numbers of oriented tiny hairs with fine nano grooves. Gao and Jiang demonstrated the water resistance is due more to the physical structure than the chemical properties or coating of the legs.
5.5.2 Lotus effect

The lotus effect describes the phenomenon where dirt particles are picked up by water droplets due to nano surface texture on lotus leaves. The lotus effect applies to other plants and insects in nature as well. The physics behind the lotus effect is surface tension, whereas water droplets tend to minimize contact surface to achieve a spherical shape.

5.5.3 Extremophiles

An interesting phenomenon identified was extremophiles. Engineers who are unfamiliar with extremophiles are unlikely to appreciate the relevance of the corresponding matches. The category title may help facilitate comprehension through lexical analysis, glossary definition or a quick search, and reveal that an extremophile is a type of organism that can survive in extreme geochemical conditions. Archaea and euryarchaeota, discussed in the two matches under this category, are types of extremophiles. The matched excerpts highlight the unique cell membrane structures that enable extremophiles to survive in extreme conditions. One section explains that extreme halophiles (a type of euryarchaeota) are able to conserve water and not dry out due to the high salt content of its surroundings. This phenomenon therefore appears relevant for the design of the bipolar plate.

5.5.4 Rod cells

This match pertains to photosensitivity and the rod cell, rhodopsin. Specifically, the corresponding section explains that the rod cell contains an outer segment of plasma membrane that captures photons of light passing through the cell (Purves, et al. 2001). This phenomenon may therefore be relevant to the case study that involves capturing water molecules.

5.5.5 Membrane Osmosis

Membranes are used in cells to enclose a space that differs chemically and biologically from the outside of the membrane. An important feature is the selectively permeable structure that is formed by a lipid bilayer. Substances are allowed to selectively pass through the membrane due to the differences in concentration and properties of the substances (Purves, et al. 2001). Figure 21 shows membrane osmosis.
5.5.6 Water/nutrient transport in plants

We chose to investigate this particular phenomenon due to similar water transport difficulties faced by leaves and fuel cell bipolar plates. Specifically, both leaves and fuel cell bipolar plates require a mechanism to move water through small channels with relatively high flux. In cohesion-tension theory, which was first proposed by H.H. Dixon (1914), water is drawn up in plants by transpiration. Due to the cohesive and adhesive properties of water, as water molecules evaporate from the stoma, additional water molecules are pulled from the lower part of the plant through xylem, a type of transport tissue.
5.5.7 Water transport based on capillary action

We chose to investigate this particular phenomenon due to the similarities between the fuel cell operating environment and the water transport objective of nontracheophytes. Specifically, both nontracheophytes and fuel cell bipolar plates operate in damp environments and require a mechanism to transport moisture through a barrier.

The text section corresponding to the above match explains that nontracheophytes (liverworts, hornworts, and some mosses) usually inhabit moist environments but lack vascular tissue to circulate liquid (Purves, et al. 2001). Nontracheophytes contain several physical features that assist external water conduction. For example, overlapping leaves, rhizoids (shown in Figure 23), ridged leaves, and tiny warts help water conduction by maximizing the effectiveness of capillary action.
5.6 Design objective

My concepts are designed with the following objectives:

Economical – Fuel cells are currently costly, my designs should not be costly

Manufacturability – My designs should be easy to produce

Functional – My designs should be functional

5.7 Concepts Generated

This section lists the concepts generated based on the identified biological phenomena listed in section 5.6. Table 6 links the biological phenomena with the engineering concepts that the phenomena inspired.

Table 6: Design concepts and biological phenomena stimuli used

<table>
<thead>
<tr>
<th>Design concepts</th>
<th>Biological phenomena stimuli</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superhydrophobic Surface</td>
<td>Water strider’s leg, Lotus effect</td>
</tr>
<tr>
<td>Mechanically actuated ball valves</td>
<td>Membrane osmosis, Rod cells</td>
</tr>
<tr>
<td>Ferro fluid</td>
<td>Membrane osmosis, Extremophiles</td>
</tr>
<tr>
<td>Venturi Ejector</td>
<td>Membrane osmosis, Extremophiles</td>
</tr>
<tr>
<td>Passive water removal using semi-permeable membrane</td>
<td>Water/nutrient transport in plants, Membrane osmosis</td>
</tr>
</tbody>
</table>
Each of these design concepts will be discussed in a sub-section below, starting with the superhydrophobic surface.

5.7.1 Superhydrophobic surface

Superhydrophobic surfaces have contact angles of a water droplet exceeding 150 degrees and a roll-off angle less than 10 degrees (Wang and Jiang 2007). This effect is also known as the lotus effect. There are various research papers on superhydrophobic surface synthesis, including the use of nanopin film (Hosono, et al. 2005) and inter-laminar air pocket-induced hydrophobic surface (Lim, et al. 2007). Both of the aforementioned superhydrophobicity research papers require surface modifications to create micro features similar to the surface of the lotus leaves.

There have been many attempts to create a hydrophobic (90-150 degree water contact angle) flow field in PEMFCs, including applying surface treatments and creating artificial wicks. Although these attempts, especially several hydrophobic surface treatments, showed promise and are used in some commercial products, the water removal problem still remains. I hypothesize that a superhydrophobic flow field will improve water removal performance more than hydrophobic surfaces.

5.7.1.1 Calculations

For my initial investigation on the superhydrophobic flow field surface, I created a model to find out what kind of geometry enables superhydrophobicity. I used the Cassie- Baxter’s equation to calculate the effective contact angle $\theta_c$ for an uneven but structured geometry, such as the one exhibited by the lotus leaves. The equation is as (Wenzel, 1936):

$$\cos \theta_c = \gamma_1 \cos \theta_1 + \gamma_2 \cos \theta_2$$

Where $\theta_1$ is the contact angle for component 1 with area fraction $\gamma_1$, and $\theta_2$ is the contact angle for component 2 with area fraction $\gamma_2$. Figure 24 shows the geometry of interest, so $\theta_1$ and $\gamma_1$ are dictated by the material property and geometry while $\theta_2$ is the contact angle between air and water and $\gamma_2 = 1 - \gamma_1$. 

---

Passive water removal using PES hollow tube and capillary action

Water/nutrient transport in plants, Water transport based on capillary action
For this model, I assumed that the surface is coated with polytetrafluoroethylene (PTFE). From the literature, the contact angle between PTFE and water is 109.2 degrees, and the contact angle between air and water is assumed to be 0 degrees. Therefore, $\theta_c$ is a function of only the area fraction between the land and air.

Figure 24: Geometry that induces lotus effect

![Image of contact angle and area fraction]

Figure 25 illustrates the effective contact angle $\theta_c$ for a PTFE coated surface with a lotus leaf like surface structure. The area fraction is defined by $\frac{\gamma_1}{\gamma_2}$. It appears in order to achieve a superhydrophobic surface with PTFE coating; I need a lotus-like nano structure with 0.2 land-air ratio.
5.7.1.2 Prototyping and results

I designed a way to economically deposit microstructures onto a surface to mimic the nano textures of a lotus leaf. I used BIDLab’s laser printer, a Hewlett Packer Laserjet 2300, to deposit carbon particles on overhead transparency film. Adobe Illustrator was used to draw black and white patterns, where black is the position where the laser printer will deposit carbon particles and white is the position the printer will skip. I used overhead transparency film to prevent the laser toner from being absorbed into paper. Figure 26 shows the prototype pattern that is printed.

I made two types of imprints, dots and lines, with various feature resolutions. For lines, I varied the thickness of black and white lines, and for dots, I tried to space the dots differently by altering the DPI (dots per inch) while maintaining a 0.2 area fraction between black and white areas. There is also a surface with infinite dpi, effectively covering the entire area with carbon deposit for controlled experimentation.

I tested the prototype by depositing water droplets directly on top of the different surface using a syringe. Initial results are promising; visual inspection shows that the contact angle on a 150 dpi surface increased by about 20 degrees compared to water droplets on a plain overhead transparency. Line patterns and other dot patterns also show improvements. To make sure it is the geometry and not the toner ink that is affecting contact angle, I also deposited water droplets on the surface with infinite dpi. The contact angle on the surface with infinite dpi is similar to the contact angle on the overhead transparency, proving it is the surface geometry, not the surface coating that is enhancing the hydrophobicity of the surface. Although I do not have access to equipment to confirm the interaction between water and the prototype, I suspect the water droplets did not achieve the Cassie-Baxter state, but remained at the Wenzel state. Cassie-Baxter state droplets have very high mobility; the reasoning is beyond the scope of this thesis, but it is obvious from Figure 27. In order to achieve Cassie-Baxter state, the droplet’s contact line must overcome the body forces of the unsupported droplet weight and the microstructures must be tall enough to prevent the liquid that bridges the microstructures from touching the base of the microstructures (Extrand 2004). It is possible to balance out the body forces by changing the dpi of the printout, but difficulty remains in modifying the height of the microstructures without using a specialized material deposition machine.
Figure 26: Dot / line patterns that were printed on an overhead transparency to create the lotus effect surface

Figure 27: Differences between the three liquid - solid / solid - air interfaces
5.7.1.3 Application to fuel cell water removal

There have been several PEMFC passive water management designs that focus on coating the flow channels, either with a hydrophobic coating (to prevent sticking), or a hydrophilic coating (to improve water flow). I believe that a superhydrophobic surface can prevent water sticking to the side wall while improving water flow in parallel flow channels. Perhaps with sufficient resources, future work can include creating a Cassie-Baxter state surface using carbon deposition.

5.7.2 Mechanically actuated ball valves

Mechanically actuated ball valves are the second design concept listed in Table 6. The function of a mechanically actuated ball valve was implemented at the micro level by embedding micro diameter metal balls in the flow channel as seen in Figure 28. The balls act as valves between the flow channel and a low-pressure channel as seen in Figure 29. Parts from the prototype are shown in Figure 30.

I sourced the balls (0.5 mm diameter chrome coated steel balls) from H.R.T. Precision Steel Ball, a small diameter bearing company. I extracted a rare earth magnet (most likely a neodymium magnet) from an old computer hard disk drive. The metal ball acts as a micro valve between the flow channel and a low-pressure channel where water will be suctioned out from the flow channel when the ball is actuated by the magnet. When the flow channels are flooded, a magnet lifts the balls to unblock the small passage between the flow channels and the low-pressure chamber, much like a steam trap. When water is evacuated from the system, the balls return to their original position due to pressure difference between the flow channel and the low-pressure channel.

I machined several prototypes with different opening sizes from 0.2mm to 0.4mm for the channels connecting the balls and the low-pressure, with results as follows:

Table 7: Results for different opening sizes

<table>
<thead>
<tr>
<th>Opening size</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 mm</td>
<td>Balls tend to get stuck</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>0.3 mm</th>
<th>Balls tend to get stuck</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4 mm</td>
<td>Balls tend to get stuck, gas leakage from the flow fields</td>
</tr>
</tbody>
</table>

The main problem is the actuation of the balls; they tend to get stuck along the actuation shaft. The balls either fail to disengage from the blocking position, or are unable to return to the blocking position. I believe manufacturing difficulties and poor surface finish are the reasons for the balls’ poor actuation performance. I drilled the openings on acrylic, and since the opening is small, acrylic tends to deform due to heat and pressure, making it difficult to have a nice finish on the balls, thereby increasing friction between the balls and the actuation shaft.

![Diagram of a ball blocking fluid passage](image)

**Figure 28: A ball blocking fluid passage**
Figure 29: Schematics for the mechanically ball valve design
I put the mechanically actuated ball valve idea on hold due to the manufacturing difficulties. I believe that, with better material and manufacturing processes, the idea might be viable.

5.7.3 Ferro fluid

Ferro fluid is the third design concept listed in Table 6. Ferrofluids are colloidal suspensions of surfactant-coated magnetic particles in a liquid medium (Berger, et al. 1999). In a magnetic field, ferrofluids magnetize and attract or repel depending on the direction of the magnetic field. Ferrofluids are commonly used in speakers, seals and manufacturing processes. Figure 31 shows ferrofluids under attraction from a magnet.
I have generated a concept of creating a ferrofluid in-situ inside the oxidizer flow channel by injecting magnetic nano particles (~10nm) into the oxidizer inlet. The purpose for the ferrofluid creation is to use the liquid water inside the flow channel as the liquid base for the ferrofluid. When liquid water is converted to a ferrofluid, we can repel the ferrofluid out of the flow channel by using magnets. A simplified diagram is shown in Figure 32.
In order to convert liquid water into a ferrofluid, a proper amount of FeCl₃ and FeCl₂ is required. An example combination that causes the solution to become magnetic is:

\[2FeCl₃ + FeCl₂ + 8NH₃ + 4H₂O \rightarrow Fe₃O₄ + 8NH₄Cl\]

The amount of Fe₃O₄, a type of ferromagnetic mineral, must remain small in order to remain suspended in the liquid medium. Individual particles of Fe₃O₄ must also be small in size to prevent clumping of the ferromagnetic materials, with the optimal size being around 10nm (University of Wisconsin Madison IEG 2008). However, small particles such as Fe₃O₄ attract each other due to van der Walls force; in order to keep Fe₃O₄ separated, surfactant is added to the liquid medium. A surfactant is a type of hydrocarbon that is attracted to the surface of the ferromagnetic particles, creating a coating to prevent attraction between the particles.

Figure 32: Schematic of the ferro fluid concept
After research, I specified three types of ferromagnetic particles from Ferrotec Corporation that can meet this concept's requirement:

### Table 8: Recommended ferromagnetic particles from Ferrotec Corporation

<table>
<thead>
<tr>
<th></th>
<th>EMG111</th>
<th>EMG607</th>
<th>EMG707</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Carrier liquid</strong></td>
<td>Water</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Saturation magnetization</strong></td>
<td>20mT</td>
<td>11mT</td>
<td>11mT</td>
</tr>
<tr>
<td><strong>Viscosity (27°C)</strong></td>
<td>&lt;5 cP</td>
<td>&lt;5 cP</td>
<td>&lt;5 cP</td>
</tr>
<tr>
<td><strong>Nominal diameter</strong></td>
<td>10nm</td>
<td>10nm</td>
<td>10nm</td>
</tr>
<tr>
<td><strong>Initial magnetic susceptibility</strong></td>
<td>1.93 Gauss/Oe</td>
<td>1.7 Gauss/Oe</td>
<td>1.5 Gauss/Oe</td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td>1.18 g/ml</td>
<td>1.10 g/ml</td>
<td>1.10 g/ml</td>
</tr>
<tr>
<td><strong>Magnetic particle concentration (% vol)</strong></td>
<td>&gt;3.6%</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Surfactant</strong></td>
<td>n/a</td>
<td>Cationic</td>
<td>Anionic</td>
</tr>
</tbody>
</table>

The EMG607 and EMG707 particles are more interesting because the ferromagnetic particles are already coated with surfactant. However, due to the small volume of water that needs to be removed in a flow channel and the amount of time needed to separate the ferromagnetic particles, an uncoated ferrofluid solution might also be feasible for this concept. However, due to high cost (~$500 for 8g of ferromagnetic particles), my supervisors and I decided to postpone prototyping for this concept until a more economical alternative is possible.

If I were able to obtain the ferromagnetic particles, there are still several difficulties associated with this concept:

- Contamination of MEA due to the ferromagnetic particles
• Time required to form proper ferrofluid solution is long

• Stirring is required to evenly distribute the ferromagnetic particles

• Ferromagnetic particle are expensive, a method to recycle the ferromagnetic particles is needed

5.7.4 Venturi Ejector

The Venturi ejector is the fourth design concept listed in Table 6. Figure 33 shows a Venturi ejector-based concept, inspired by termite mounds. The Venturi ejector is based on the Venturi effect, where fluid pressure decreases when a fluid flows through a constricted section of a pipe. The Venturi effect is used in applications such as carburetors, fire extinguishers, and aspirators.

The concept shown in Figure 33 shows a PEMFC cathode attached to a Venturi ejector. The Venturi ejector’s outlet has a spring mechanism attached. If the inlet pressure is high enough (by using the compressed air line), the spring plug will disengage and the Venturi ejector will function normally, creating a vacuum in the PEMFC cathode flow channel to evacuate residual water in the flow channel. If the inlet pressure is low (using the oxide supply line), the spring plug will be engaged and the oxide will be supplied to the PEMFC cathode flow channel instead, enabling normal fuel cell operation.

Figure 33: Conceptual representation of the Venturi ejector concept
Figure 34: CAD modeling of the Venturi ejector concept (Section view)

Figure 34 shows a CAD modeling of the Venturi ejector concept. The required operating parameter of this concept can be calculated using the Bernoulli’s principle:

$$\Delta P = \frac{\rho}{2(v_1^2 - v_2^2)}$$

where $\Delta P$ is the pressure difference between any two points along the streamline, and $v_1$ and $v_2$ are the velocities at the two points.
To evaluate the Venturi ejector concept, I constructed a prototype as shown in Figure 35. The Venturi body is machined from a single aluminum rod. The top plate, which represents the fuel cell MEA, is machined from a plate of acrylic with a water injection hole in the middle. I inserted hypodermic tubes into the Venturi body to evaluate the performance for different internal diameters. Compressed air is supplied from a compressed air tank, with pressure regulated by an inline pressure regulator. A spring is not installed in this prototype; switching between the compressed air line and physically closing and opening the outlet simulates the oxidizer line.

The Venturi ejector concept has two critical flaws:
• A Venturi ejector based PEMFC cannot operate continuously. When a PEMFC switches the inlet source from oxidizer to compressed air, the fuel cell will experience a momentary loss of oxidizer, interrupting power generation.

• When a vacuum is generated on the cathode side, the MEA will experience a large pressure difference between the anode and cathode, potentially damaging the MEA.

5.7.5 Passive water removal using a semi-permeable membrane and osmosis.

Passive water removal using a semi-permeable membrane and osmosis is the fifth design concept listed in Table. Figure 36 shows the proposed redesign of the bipolar plate. Water generated at the cathode side is transferred to the low-pressure air channels by osmosis. A selective membrane (e.g., heat-treated porous carbon) prevents oxidizer or fuel from entering the low-pressure air channels. A cross-flow separator prevents fuel/oxide crossing. Table 9 illustrates how the two biological phenomena were mapped to develop the redesign.

![Figure 36: Passive water removal using semi-permeable membrane and osmosis.](image)

Table 9: Mapping from biological phenomena to redesign of fuel cell bipolar plate

<table>
<thead>
<tr>
<th>Biology Domain</th>
<th>Engineering Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-permeable membrane</td>
<td>Selective diffusion to air channel</td>
</tr>
<tr>
<td>Osmosis enables diffusion</td>
<td>→</td>
</tr>
<tr>
<td>--------------------------</td>
<td>---</td>
</tr>
<tr>
<td>Lipid bilayer structure</td>
<td>→</td>
</tr>
<tr>
<td>Transpire through stomata (cools and enables mass flow)</td>
<td>→</td>
</tr>
</tbody>
</table>

Bipolar plate designs related to the proposed concept already exist. An example is an active water management system using an electro-osmotic pump to remove water through a porous carbon bipolar plate. This design has been prototyped with promising results (Litster, et al. 2007). Another example is a water transport plate design that uses the pressure difference between the oxidant flow channel and the fuel flow channel to passively move water across the bipolar plate (Yi, Yang and King 2004).

Having related designs, especially those that have been prototyped, provides partial validation for proposed concepts. The key difference between my design and the existing designs is the use of evaporation as the main mechanism for heat and water management. The advantage of this design may include:

1. Evaporation is generally effective in removing heat.

2. A fuel cell system with the proposed bipolar design can be cheaper due to reduced requirement for heat management as the evaporation process removes some heat.

I did not prototype this concept due to manufacturing difficulties.
5.7.6 Passive water removal using PES hollow tubes and capillary action

![Diagram of PEMFC bipolar plate configuration]

Figure 37: Proposed PEMFC bipolar plate configuration

The sixth and final design concept listed in Table 6 is passive water removal using PES hollow tubes and capillary action. This concept is a true parallel flow channel PEMFC with a modified cathode flow channel as shown in Figure 37. This concept has two distinctive features (Water gap/micro channel and PES hollow tube) that are based on the identified biological phenomena described in section 5.5.6 and 5.5.7.

Table 10 shows how the biological phenomena are translated into the engineering domain.

5.7.6.1 Concept design features

The two main features of this concept are the water gap/micro channel and the PES hollow tube.

Water gap/micro channel

Similar to ridged leaves from section 5.5.6, micro-channels maximize capillary action and direct excess water away from the flow channels. In the physical prototype, arbitrary abrasions on the prototype surface induce capillary action. The arbitrary abrasions are similar to the water transport features on nontracheophytes.
Experiments are also planned with micro-channels in place of random abrasions. Future prototypes will incorporate capillary action inducing features with consistent geometrical patterns. Micro-channels are situated perpendicular to the oxidant flow, with one end connecting the flow channel and the other end connecting to a water removal channel.

Figure 38: Back-lit photograph of the micro-channel features that induces capillary action

Figure 38 shows one of the micro-channel implementations. I tried two types of manufacturing process to economically manufacture the micro-channels: electrical discharge machinery (EDM) on steel and wire cut on aluminum.

**PES hollow tube**

PES hollow tubes function similarly to xylem in plants, efficiently transporting water from the flow channels. Like xylem from section 5.5.7, PES hollow tubes must be continuous and under tension to maximize water flux.
5.7.6.2 Water removal from PEMFC

Figure 39: Water removal with a switchable humidifier

Figure 39 shows a sample apparatus to achieve water removal from the fuel cell. Two valves control the air inlet path: air can either be humidified by the wet PES hollow tubes by forced convection or air can be let into the fuel cell unmodified. Figure 39 shows a possible water removal method by forced convection and transpiration; other water removal methods, such as conduction (e.g. a sponge), are also applicable.

Table 10: Mapping from biological phenomena to redesign of PEMFC bipolar plate

<table>
<thead>
<tr>
<th>Biology Domain</th>
<th>Engineering Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xylem and water transport in plants</td>
<td>PES hollow tube for water removal</td>
</tr>
<tr>
<td>Ridged leaves</td>
<td>Machined micro-channels induce capillary action</td>
</tr>
<tr>
<td>Transpiration</td>
<td>Convection</td>
</tr>
</tbody>
</table>
5.7.6.3 Prototype

A simple prototype representing the flow field structure was created to expediently validate the proposed concept prior to application in a fuel cell. The prototype, shown in Figure 40 and Figure 41, was demonstrated on a test apparatus with low airflow rates and low inlet pressure. Preliminary results show total recovery from flow channel catastrophic flooding within seconds.

The prototype consists of a top cover, made of acrylic to aid visual inspection, side walls, made of machined aluminum 6061-T6 plates for providing clamping pressure for the silicon seals (not shown), and a prototype piece with integrated micro channels and PES hollow tube slots. The PES hollow tubes (0.26mm OD) are manufactured by Membrana, and used in a hemodialysis unit (Baxter Diapes PES-150). Figure 42 shows a cross section view of the PES hollow tubes that were cut by freezing with liquid nitrogen and cutting with a knife.

![Prototype detail](image)

Figure 40: Prototype detail
Figure 41: Physical prototype

Figure 42: PES hollow tubes from Diapes PES-150, Photo by Ian Pang

5.7.6.4 Test apparatus and experimental setup

Figure 43 illustrates the experimental setup. The test apparatus consists of the following components:
• Chromatography microsyringe – for water injection
• Side wall/top cover - cathode flow channel
• PES hollow tubes - water removal
• Prototype - flow channel with micro channels
• C-clamp - assists sealing
• Fan - simulates water removal by forced convection

![Experimental Setup Image]

**Figure 43: Experimental Setup**

### 5.7.6.5 Test procedure

The flow channel has the dimension of 1mm x 1mm x 40mm and a volume of 40µl. All machined parts are polished to ensure even sealing contact. Six PES hollow tubes, three on each side as shown in figure 10, are used in the prototype.

The prototype was tested nine times under each of the three fan settings: high speed, low speed, and off. The fan is located 40mm away from the water removal end of the PES hollow tubes. A chromatography syringe was used for water delivery of 10µl of water into the flow channel. Two time intervals were recorded for each experiment. The first time interval recorded was the water injection duration. This is important because if the water was injected too slowly, the injection
rate might be slower than the water removal rate. If the water was injected too rapidly, the injection pressure might undesirably aid in the water removal process. We waited 60 seconds between each test to let residual water from the previous test settle.

A total of 27 additional tests (nine for each fan setting) were performed to evaluate the water removal effect when the PES hollow tubes were nearing their maximum carrying capacity. Under this test, a much larger amount of water - 35µl - was injected into the flow channel continuously.

5.7.6.6 Experimental results

5.7.6.6.1 Correlation between injection rate and water removal rate

T-tests were performed to verify that there was no correlation between the injection rate and water removal rate for each test. The t-test results are 1.46, 8.47 and 21.13 with a degree-of-freedom of 16 for the three different fan settings. All tests indicate with a high confidence level that there was no correlation between water injection rate and water removal rate.

5.7.6.6.2 Time required to completely remove water from the flow channel

Figure 44 to Figure 46 show the time required (in seconds) for the test apparatus to completely remove 10µl of the injected water from the flow channel. Complete water removal is defined as no visible water in the flow channel. The average water removal time for the three fan settings are: high: 3.9s, low: 8.6s, off: 15.6s.
**Figure 44:** Water removal time (fan high)

**Figure 45:** Water removal time (fan low)
Figure 46: Water removal time (fan off)

5.7.6.6.3 Water removal flow rate

Figure 47 shows the water removal rate. As expected, the water removal rate is positively correlated with fan speed. For high fan speed, the water removal rate is 2.6µl/s, while the water removal rate is 0.6µl/s when the fan is off. Although there is a noticeably slower water removal flow rate when the fan is off, I believe that under normal fuel cell operations, the implementation of micro-channels and PES hollow tubes will help with water management in PEMFC with or without forced convection acting on the PES hollow tubes. No visible water droplets were observed during these tests.
Figure 47: Water removal rate (summary)

5.7.6.6.4 Water removal rate when PES are near maximum carrying capacity

Figure 48: Water removal time when the PES hollow tubes are nearing maximum carrying capacity
When the PES hollow tubes reach their maximum carrying capacity, water will not be able to move effectively from the flow channel to the PES hollow tube and water droplets are formed at the end of the PES hollow tubes. Water droplets fell from the PES hollow tubes when the droplets' size reached a critical dimension where gravity and air resistance overcame the droplets' surface tension acting on the PES hollow tubes.

This observation can partially explain the variability displayed in Figure 48 between each test's water removal times. When plotted in a graph, the water removal times for all three fan settings result in a repetitive pattern as shown in Figure 48, where the water removal time steadily increases and then decreases. The increase in water removal time corresponds to the water buildup (e.g. droplet forming) in the PES hollow tubes, and the decrease in water removal time corresponds to the water removal (e.g. droplet dropped due to gravity) from the PES hollow tubes. The dotted line in Figure 48 represents a 5th order polynomial fit for the water removal time when the fan is off, the local maximum represents when the PES has reached its carrying capacity.

When we analyze the standard deviation of the water removal time, we found that when the fan is on, the standard deviation is 6.02, compared to 9.94 when the fan is off. I believe the difference in the standard deviation is due to the forced convection method of water removal being a relatively continuous process when compared to the water removal process when the fan is off, which mainly relies on gravity. The difference in water removal mechanics is directly observed in the experiments, where water droplets detach from PES hollow tubes more frequently. The droplets are also observed to be physically smaller when the fan is on.
### Photos of the experiment

![Water Position](image)

**Time:** -2 sec

**Time:** 0 sec

**Time:** 17 sec

**Time:** 24 sec

**Time:** 35 sec

**Time:** 40 sec

**Figure 49: Frame capture of a video of the experiment**

Figure 49 shows six frames of a video that demonstrates the water removal capabilities of the prototype. At time = -2 seconds, the flow channel is empty with a needle ready to inject 20 ul of water. At time = 0 seconds, water is being injected into the flow channel. After 17 seconds, water started to evacuate the flow channel.

To improve visibility of the water-air interface, the water position bar above the individual images represents the location of the water-air interface in the photo.
5.7.6.7 Discussion and future work

Water removal rates from the test rig show that the new bipolar plate design can passively prevent flooding and recover from catastrophic flooding. This could result in lower air stoichiometry by eliminating the need for using excess airflow to remove water. Despite the advantages of this design, we must note the following drawbacks:

- Manufacturability of the current design is under investigation. Strict tolerances and miniaturized components of the new bipolar plate add to the manufacturing and assembly cost of a PEMFC.
- Durability of the PES hollow tubes limits viable applications of the current design (i.e. automotive applications are not currently feasible due to potential damage caused by vibration).
- Added complexity to the PEMFC might not justify the increase in performance using the new bipolar plate design.

Due to the dynamic nature of fuel cell water transport phenomenon, performance in an actual fuel cell might differ from the anticipated performance increase described in this paper. Future work includes implementing the current design into a fuel cell to comprehensively evaluate the performance impact.

I am also working on improving the manufacturability of this design by simplifying the components. A new concept was generated that utilizes the surface texture of GDL to replace the machined micro channels.

6 Conclusion

Biology is a good source of analogies for engineering design. One approach of retrieving biological analogies is to perform keyword searches on natural-language sources such as books, journals, etc. This thesis describes several methods that organize a large group of diverse biological information into meaningful and categorized viewing format. This organization functionality improves designer’s ability to search, identify and apply relevant biological phenomena to their intended design objective.
The present thesis described the application of a biomimetic search approach augmented with the following main improvements to develop engineering solutions based on biological phenomena:

- Categorization of search results
- POS identification
- Sense disambiguation
- Abstract object identification

This chapter will summarize my research efforts by describing the improvements individually first, and then I will conclude with my case study design efforts; I will end with future work and recommendation.

### 6.1 Categorization

By incorporating the categorization of search results into the existing biomimetic search tool, users can quickly filter out results that do not contain relevant biological phenomena to the design problem, thus simplifying navigation through a potentially large number of matches. This thesis also described how the category structure is extracted from Wikipedia and WordNet ontology. In addition, I also described methods to detect and insert the search results into relevant categories. Search results are displayed in three stages: the category stage, the excerpt stage and the section stage. Each stage increases the depth of the information content but narrows the field of information. Using these display stages as well as increasingly specific categorization levels, users can progressively narrow their search results to identify relevant biological phenomena.

### 6.2 POS identification, sense disambiguation and abstract object identification

The purpose of implementing POS, word sense disambiguation, and abstract object identification is to address two challenges associated with natural-language search for biological phenomena. The first challenge is that a large number of results may exist for a particular search. Therefore, the user may need to process a large amount of information to identify the most suitable analogies. The second challenge is that not all results are relevant; for example, irrelevant results may include keywords with an undesired POS, incorrect word sense, or keywords acting on
abstract nouns. Identifying the word POS, sense and phrase groups in the corpora improves the precision and recall of the biomimetic search tool.

6.2.1 Separate results by search keyword POS and sense

Search keywords in the verb POS may locate biological phenomena that perform related functions. In contrast, search keywords in the adjective POS may locate biological phenomena relevant to desired qualities. After specifying the intended search word POS, users can further narrow down search results by showing only result excerpts that also use the intended search word sense.

6.2.2 Remove results where keywords act on abstract nouns

Since mechanical design usually involves physical objects, we can also choose to remove matches that contain search keywords acting on abstract nouns. The introduction of POS, word sense and phrase group identification enables this task to be done automatically by identifying grammatical objects that are abstract entities.

Initial efforts reveal a positive outlook for the present approach. Qualitatively, by choosing to limit results to those that contain matches to keywords in specific POS, users can choose to display results related to desired functions or desired qualities. Also, tagging phrase groups with WordNet lexicographer metadata enables users to omit search results that have search keywords acting on abstract versus physical nouns.

6.3 Case study: PEMFC water management system design

Proper water balance is a consistent challenge in PEMFC development. The unique technical requirements serve as excellent motivation to use biomimetic design methodology to aid in the design of a PEMFC water management system. I believe that biology is a good source of design analogies for the PEMFC water management system; biological systems have many characteristics that might benefit fuel cell designs including efficient use of materials and energy, environmental sustainability, and the ability to self-regulate.
Using biomimetic design methodology, I identified several biological phenomena as good stimuli for design concepts. After several design sessions, I have created several prototypes that can passively remove water from parallel flow channels. One successful design was discussed in detail that combines micro-channels and PES hollow tubes for water removal, similar to the capillary action inducing physical features of nontraceophytes and the cohesion-tension phenomenon in xylems.

Several prototypes based on the identified biological phenomena demonstrated promising results. One successful prototype in particular was discussed in detail. The prototype was able to passively remove water at 0.6µl/s from a single channel plate with a 1mm x 1mm cross section. The prototype was able to recover from a simulated catastrophic flooding in seconds with stagnant inlet flow and no inlet pressure.

Ongoing research is focused on creating a comprehensive prototype to better integrate my concepts into an actual fuel cell. Future designs will also focus on the cost reduction and manufacturability of our concept. In addition, future work includes applying the biomimetic design methods to solve other fuel cell issues including membrane design, fuel storage and cell durability.

6.4 Future work and recommendation

The work presented in this thesis is a valuable contribution to the field of DTM and fuel cell design. The experimental results from BioSearch have demonstrated the usefulness of viewing the search results in a meaningful and categorized fashion. However, as current BioSearch is only about 70% accurate at identifying word sense and 97% accurate at identifying POS, it is perhaps useful to improve word sense disambiguation.

As mentioned in the present thesis, it is difficult to differentiate the sense of a word in a corpus, especially in a fine-grained polysemy lexical dictionary such as WordNet. Therefore, future work involves finding a suitable coarse-grained homograph level lexical dictionary for word sense disambiguation.

The current word sense disambiguation algorithm is a dictionary-based method based on the hypothesis that words used together in text are related to each other and the relationship can be
extracted based on the definitions of the words and their senses (Pedersen, Patwardhan, & Banerjee, 2005). Future work might include using content specific dictionaries (e.g., biological dictionaries, assuming the corpus is within the biology domain) to increase the WSD accuracy.

The categorization method described in this thesis is based on two ontologies: WordNet lexical dictionary and Wikipedia Ontology. There are drawbacks for both ontologies, WordNet lexical dictionary is too domain general and the senses are too fine-grained. Wikipedia Ontology is difficult to use due to various noise-categories. Future work should improve the categorization ontology, possibly using the intersecting categories of the WordNet and Wikipedia ontology.

Finally, the graphical user interface should be redesigned to enhance the efficiency and ease of use. The current GUI was not designed with any functional requirement analysis and usability testing. Future work should include a carefully designed GUI to enhance the usability of BioSearch.

My fuel cell design experiments were primitive but have promising results. Several designs were able to prevent catastrophic flooding in a controlled environment; perhaps enhancing some of these prototypes, such as deploying the prototype in an actual fuel cell, would help validate my designs and provide feedbacks to help future designs.

Overall, this thesis advances the capability of BioSearch by enhancing the search function and the reviewing process, thus increasing understanding of biological stimuli for the support of more creative and innovative concept generation.
Bibliography


Appendices

A. Full categorized results

Nodes with boxes indicate categories, nodes without boxes indicate sections; please use the electronic version to zoom in.

1. Results for Splice:
3. Results for Extract:

4. Results for Trap:
5. Results for Delete:
6. Results for Degrade:
7. Results for Beat:
8. Results for Separate:
9. Combined results (removing redundant categories):