Biologically Informed Disciplines:
A comparative analysis of terminology within the fields of bionics, biomimetics, and biomimicry.

by

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ABSTRACT

This thesis represents a stepping stone towards a complementary approach to research and education in biologically informed disciplines through the lens of bionics, biomimetics, and biomimicry terminology.

For the purpose of developing this approach, the author looks at past and current contexts in which the three fields have emerged and identifies three issues: an absence of common ground that unites the fields of bionics, biomimetics, and biomimicry while recognizing their contextual differences, a non-standardized use of the terminology that leads to ambiguity within the field of biologically informed disciplines, an incomplete and disorganized historical and contextual knowledge about the field that inhibits a common starting ground for collaboration, and confuses non-scientists who seek biological understanding that could provide them with an informed voice.

This thesis offers a fundamental understanding of the field of biologically informed disciplines from theoretical and practical perspectives by bringing together opinions of researchers and practitioners within the field, presenting experiments that illustrate practical applications of methodologies used in the field, and offering a comprehensive analysis of terms related to it along with suggestions for future research.

Keywords: Bionics, Biomimetics, Biomimicry, Interdisciplinary, Discourse, Biologically Informed Discipline

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CHAPTER 1

INTRODUCTION

It took half a century and the occurrence of scientifically, technologically, and socially important events before a separate field that can be described as a collaboration between natural sciences and applied sciences and arts began to be widely recognized outside of highly specialized expert communities. As a reader will find, one can assign these events to three different sets: 1) the refutation of certain principles in regards to self-replication of living and non-living matter 2) the recognition of functional and historical biology, and 3) the realization of the uniqueness of certain basic principles of biology that can inform nature-focused ethos and ultimately lead to sustainable practices. This section is devoted to an analysis of these three sets of developments in order to set the stage for the contextual analysis of the fields that continue to enjoy fruitful collaboration between biology and applied sciences and arts – the most prominent of which are *bionics* (Bernard & Kare, 1962), *biomimetics* (Schmitt, 1969), and *biomimicry* (Benyus, 1997).

1.1 The autonomy of biologically informed disciplines

Reproductive properties of animate and inanimate world

The nature of life, the property of being alive, has always been a puzzle for philosophers. Vitalism was a popular worldview that emerged in the early seventeenth century as a response to Descartes' radical mechanisms. It lost momentum in the early twentieth century, when methods of genetics and molecular biology were able to solve all the problems for which scientists traditionally had invoked the invisible force called Lebenskraft (Mayr, 2004).

At a time when cybernetics, defined by Norbert Wiener as "the scientific study of control and communication in the animal and the machine" (Wiener, 1948), was a burgeoning field, Heinz Von Foerster, Professor of Electrical Engineering at the University of Illinois at Urbana-Champaign, greatly contributed to the field by establishing the Biological Computer Laboratory (BCL) in 1958. The focus of research at the BCL was on systems theory, and generated many challenging questions that gave rise to the new field of bionics, a term coined by Jack Steele at the Wright-Patterson Air Force Base in Dayton, Ohio: "besides systems theory and self-organization, the buzzword 'bionics' was primarily responsible for attracting attention to the BCL research group. 'Bionics' was a general catchword that covered attempts to analyze biological processes, to formalize them and to implement them on computers." (Müller, 2007). Some of the research questions included: How can a machine replicate itself? How can a machine regenerate lost parts, as many kinds of organisms are able to do?

A few years later the Second Annual Bionics Symposium titled 'Biological Prototypes and Synthetic Systems' was conceived, in which "more emphasis was given to contributions from biological laboratories than has typically appeared in previous bionics meetings." (Bernard & Kare, 1962). There, Heinz Von Foerster introduced the topic of self-reproduction of synthetic systems, and the worlds of biology and applied technology became ever more concerted.

Vital difference between physical and biological sciences

When we try to address the challenge of the differences between physical and biological sciences in the context of this thesis, we find that biology consists of two individual fields: organismal (functional) biology and historical biology. Functional biology answers a question "how?" and deals with cellular processes and other physiology-related investigations of living organisms. "These functional processes ultimately can be explained purely mechanistically by chemistry and physics" (Mayr, 2004). Evolution, on the other hand, can only be explained by historical biology, in which "why?" is the most frequently asked question. It is this branch of biology that sets it apart from pure physical sciences (Mayr, 2004).

Otto Herbert Schmitt, an American biophysicist and originator of the biomedical engineering field, recognized the importance of both physical and biological sciences within the context of an engineering discipline. He officially coined the term 'biomimetics' (Schmitt, 1969) just eight years after the Second Annual Bionics Symposium took place, where Warren S. McCulloch – an American neurophysiologist and cybernetician – delivered a speech titled 'The imitation of one form of life by another – Biomimesis' (Bernard & Kare, 1962).

Schmitt laboured to unite biological and physical sciences using the lens of an engineer, while stating one major shortcoming of this collaboration: "Biophysics is not so much a subject matter as it is a point of view. It is an approach to problems of biological science utilizing the theory and technology of the physical sciences. Conversely, biophysics is also a biologist's approach to problems of physical science and engineering, although this aspect has largely been neglected" (Harkness, 2001). In his view, the communities of bionics and biomimetics were still dominated by engineers and physicists with little regard for biological sciences. However, the scale was tipped with the arrival of the living systems theory.

Biological science as a gateway to living systems theory and holistic thinking

Living systems theory, of course, is not new. It is the domain of biology, ecology, and any other discipline that incorporates systems thinking into its research and practice. McCulloch began the discussion during the Second Annual Bionics Symposium: "the structures which evolve are suited to the world in which they evolve" (Bernard & Kare, 1962), followed by published works of systems scientists Ervin Laszlo and Erich Jantsch, physicist Fritjof Capra, and biologist James G. Miller, among many others (Jantsch, 1980) (Laszlo, 1972) (Capra, 2010) (Miller, 1978). Scientific research was supplemented by the introduction of the Clean Air Acts (1956 & 1968) and the publishing of the Limits to Growth Report commissioned by the Club of Rome in 1972. This period coincided with strong public awareness of the environment: it was during this decade, that Greenpeace was founded (1971).

According to Daniel Wahl, an expert in Natural Design and Whole Systems Design, "during the 1970s, research at the 'New Alchemy Institute' began to explore how ecology, biology, and a bio-cybernetics system approach, could inform more sustainable solutions to meeting fundamental human needs" (Wahl, 2006). This research culminated in nine precepts of biological design and reflected holistic, living systems focused approach (Todd & Jack Todd, 1993) which spread worldwide during 80s, 90s, and 00s. The diverse movements sprouted and took forms of "biomimicry, ecological design, cradle-to-cradle design, industrial ecology, biophilic design, whole systems design, scale-linking design, bioregional design, salutogenic design" (Wahl, 2013).

Over many decades, the above described technological, scientific, and social advances enabled biologists, physicists, and ecologists to integrate biological research findings from diverse fields of applied sciences and arts. Today, the fields are dominated by several key institutes and universities that offer their contextual understanding of the role of biology in versatile applied disciplines. The Fermanian Business and Economic Institute of Point Loma Nazarene University has devised the Da Vinci Index, which measures research and industrial activities based on natural discoveries. The Index is compiled based on the number of patents issued, scholarly articles published, the number of grants issued by the National Science Foundation (NSF) and National Institutes of Health (NIH) in USA, and the value of those grants for any given period. The reading of 1052 in the third quarter of 2012 relative to the 100 Index level of 2000 indicates more than a tenfold expansion in the activity in the past twelve years (Fermanian Business & Economic Institute, 2012).

1.2 Statement of the Problem

Such dramatic growth illustrates that biological and applied technological research have indeed experienced extraordinary advances through the increasingly fruitful collaboration of biologists with applied sciences and arts researchers and professionals. Despite the potential that this creates, the challenge of advancing from identifying and channeling information on biological parts, to defining complex systems and informing systems design "is still well beyond current capabilities, and the barriers to advancement are similar at all levels from cells to ecosystems" (National Academy of Sciences, 2009). If this is an account of current capabilities of the discipline of biology through the lens of a scientist, it is only natural that a non-scientist can become overwhelmed by such challenges.

It is also evident that there is no standardization for the use of terms *bionics*, *biomimetics*, and *biomimicry* and little recognition of historical and contextual impact on the terms, creating disagreements among researchers of the community (Wahl, 2006), generating confusion and lack of confidence among young professionals entering the field of biologically informed disciplines. In his thesis, 'Biology as a Muse: Exploring the Nature of Biological Information and its Effect on Inspiration for Industrial Designers', Peter Wehrspann, a recent graduate of Carleton University points out that "biologically inspired design is a young field in which terms biomimicry, biomimetics, and biologically inspired design are used interchangeably" (Wehrspann, 2011). Having recognized the recent emergence of the field, it is also important to note that the ambiguity of terminology may hinder organized development of this burgeoning research domain.

Many young professionals, specializing in applied sciences and arts, and wishing to expand their set of skills to include a biological perspective, are already faced with the challenge of finding a common language with biologists and are overwhelmed with the possibilities the field has to offer. It is important to establish a common language that will unite various fields while recognizing their key differences. The following series of challenges currently experienced in the field guide the discussion of this thesis:

- *Since the field is mostly comprised of practical knowledge, very little time has been dedicated to the theoretical framework overarching the discipline. This causes ambiguity and confusion among researchers, leading to terminological disharmony and attempts at uniting disparate theoretical principals of the field's categories under the term 'biomimicry'. Simply put, how do the fields of bionics, biomimetics, and biomimicry differ from each other in a historical and cultural context?*

- *Over the decades, the fields have developed unique sets of principles and implementation strategies. Instead of recognizing these differences, researchers choose to describe various subcategories – such as biomimetics and biomimicry – as equivalent entities. This hinders the development of a standardized educational framework to prepare students for entering academic and professional fields of* *biologically informed disciplines. How do currently active experts perceive and define the fields of bionics, biomimetics, and biomimicry?*

- *Despite the immense benefits of bringing biological perspective into other disciplines* (Bonser & Vincent, 2007), *designers and biologists interested in pursuing this task, face daunting obstacles and disincentives. Some must deal with personal communication or 'culture' barriers, which are intensified by the ambiguity of terminology and principles to rely on. How can students and professionals studying and practicing biologically informed design begin to agree on terminology and principles used within the fields of bionics, biomimetics, and biomimicry?*

These challenges provide a compelling platform for discussion, and a robust framework upon which to organize conclusions. The essence of this thesis is to explore unique principles and historical contexts of existing biologically informed communities of engineers, designers, and other stakeholders and ultimately suggest a conception of a broader research community with a capacity to address a range of design, engineering, architecture, business, policy, and social problems. Integrating knowledge from bionics, biomimetics, and biomimicry, as well as other related and esteemed fields – i.e. biophilic design, salutogenic design, ecological design, etc. (Wahl, 2013) – will permit a deeper understanding of the field and will create more opportunities for enriching the academic experience of students and the contribution of new insights.

1.3 Purpose of the Study

This thesis represents a stepping stone for an additional, complementary research of history and theory in biologically informed disciplines. Purposefully organized around the analysis of terminology, this thesis offers a fundamental understanding of the name of field from a historical perspective, brings together opinions of researchers and practitioners with different experiences and expertise pertaining to the fields of bionics, biomimetics, and biomimicry, presents experiments that illustrate practical applications of methodologies used in the field and offers a comparative semantic analysis of the terms along with a suggestion for an umbrella term that unites the fields. The author presents proposed basic tools for communication of terminology and principles across the landscape of biologically informed disciplines, including design and engineering.

This thesis is not intended to replace or attenuate existing research in the fields of bionics, biomimetics, and biomimicry. That research, much of it driven by individual scientific and applied technology communities, is the foundation on which the discourse on historical and contextual meaning of terms will rely.

1.4 Research Questions

The main research question addressed in the study is:

How do the fields of bionics, biomimetics, and biomimicry differ from each other?

Which sets the stage for two sub-questions:

a. How do past and currently active experts perceive and define the fields of bionics, biomimetics, and biomimicry?

b. How do the fields differ in practical application? In the context of this thesis, how does the choice of field methodologies and principles affect the outcome of a project?

The answers to these questions are expected to make a contribution to the organization of the knowledge base of these rapidly developing fields and inform of applied sciences and arts students of its history and contextual nuances.

1.5 Significance to the Field

Science and technology alone cannot solve all the world's challenges. Political, social, economic, and many other factors have major roles to play in both setting and meeting goals in numerous areas of human systems.

This thesis presents a valuable addition to the body of work in the field of biologically informed disciplines. In order to achieve a sustained and organized development in all these fields, it is crucial to begin creating a theoretical foundation that will allow researchers and professionals to position themselves comfortably along the lines of their unique expertise, while enjoying access to the overarching community of wider biological enterprise with the scope and expertise to address a broad range of scientific, technological, and societal problems.

The following chapters present a fundamental understanding of the fields of bionics, biomimetics, and biomimicry from a historical perspective, bring together opinions of current researchers and practitioners within the field, walk the reader through experiments that illustrate practical applications of principles used in the field, and finally provide recommendations for shaping a common language for the field.

1.6 Scope of Thesis

An accumulation of body of knowledge over many decades has brought about the field of biologically informed disciplines to a point where rapid progress toward understanding its structure and theory is possible. Many of the essential ingredients are already in place. The overarching field of biologically informed disciplines is already emerging, but the interdisciplinary projects it encompasses fit uneasily within misinformed, ambiguous terminologies. This state of disorientation has been voiced by several researchers, including Julian Vincent, who was cited by J. Mlade in his thesis 'Bio-Inspired Design: Applying Nature's Genius to Buildings' (Mlade, 2005) and Peter Wehrspann of Carleton University in his thesis 'Biology as a Muse' (Wehrspann, 2011). Interactions with biologist Dr. Jeffery Dawson, industrial designer Bjarki Hallgrimsson, and applied linguist Dr. Graham Smart of Carleton University have helped to frame the topic of this thesis that now resides in the scope of terminological discourse within the fields of bionics, biomimetics, and biomimicry. Inspiring discussions with industrial designer

Brian Burns and chemist John Buschek of Carleton University influenced the researcher's decision to conduct experimental case studies, in which industrial design students interacted with environmental science, biology, and medical students to complete interdisciplinary projects exploring the methodologies of bionics and biomimicry.

CHAPTER 2

LITERATURE REVIEW

Immersion in any particular culture teaches humility about one's ability to understand the meaning of terms. Some terms are so intimately connected to human specific knowledge that their meaning cannot be understood independently of culture. The word *mimicry* provides an example. From a purely lexical approach, the term can be described in the field of biology as “the close external resemblance of an animal or plant (or part of one) to another animal, plant, or inanimate object” (Carpenter, 1933). As a mass noun, the term can be defined as “the action or skill of imitating someone or something, especially in order to entertain or ridicule.” (Oxford Dictionaries, 2013). With this guide, we could use the term correctly from a lexical perspective, modifying its form and pluralization as appropriate. Beyond this in the world of biologically informed disciplines, as it will be illustrated in Chapter Four, the term may be applied to a wide range of meanings, from “discovering ideas” to “emulating nature's strategies”. Thus, *mimicry* labels a category of meanings, which only partially overlaps with its formal encyclopedic definition.

These considerations led the author to study categories for terminological culture in biologically informed disciplines – words created and used by groups of experts in the fields of bionics, biomimetics, and biomimicry. A thorough investigation of literature was conducted to address the first sub-question raised by investigating patterns of the field: “How do past and currently active experts perceive and define the fields of bionics, biomimetics, and biomimicry?” A review has informed the author of the conventional knowledge and current debates within the field of biologically informed disciplines whilst establishing a base for research of terminological disharmony within the fields and, in particular, its effect on the practical applications of fields' methodologies. Primary sources and reference materials have helped to identify lexical and semantic disparity leading to terminological inconsistency within the field. The first section will discuss research related to lexical-semantic discourse, including a study of the meaning of the terms as it relates to language-internal notions and frame semantics. The second section will delve deeper into the semantic meaning of the terms *bionics*, *biomimetics*, and *biomimicry*. The third section will present two typical progressions of a project from biological templates to the final product, illustrative of the principles and historical context of the terms. Finally, the fourth section will introduce the concept of abductive reasoning within the context of biologically informed disciplines.

Literature review uses a discussion of each of these topics to set the intellectual case for comparative analysis of terminology used and the related confusion among the experts. The review illustrates the lexical, semantic, and practical differences of the terms *bionics*, *biomimetics*, and *biomimicry* within the disciplines of natural science and applied sciences and arts; and presents a method for analysis of such interdisciplinary terminology through discourse. The literature review concludes with a summary of the key problems that have been unearthed and an analysis of the terms within the scope of the first sub-question. These inform the terminology-driven argument within the scope of the field introduced in the beginning of this thesis.

2.1 Introduction to Charles Fillmore's frame semantics

This thesis strives to broaden the understanding of the field of biologically informed disciplines through study of the terms *bionics*, *biomimetics*, and *biomimicry* by employing a method of frame semantics. However, the theoretical interest of the work goes beyond this broadening to address the central problem of semantics and the issue of the relations between word meanings and the social, cultural, and temporal fabric in which they exist. This section answers the question "Can frame semantic study of the terms *bionics*, *biomimetics*, and *biomimicry* be done?"

In order to conduct a comprehensive analysis of these terms, it is important to study them within the context of the communities and culture of the people who have pioneered the fields, says Fillmore (Fillmore & Atkins, 1992). According to Fillmore (1985) a word's meaning can be understood only "with reference to a structured background of experience, beliefs or practices constituting a kind of conceptual prerequisite for understanding the meaning. Speakers can be said to know the meaning of the word only by first understanding the background frames which motivate the concept which the word decodes" (Fillmore & Atkins, 1992). As evident from this quote, Charles Fillmore believes that the meaning of a word is integrated in the mind to such an extent that it does not make sense to partition it into realms of encyclopedic and cultural knowledge.

According to Cliff Goddard, Professor of Linguistics at Griffith University in Australia, "Some linguists, including Fillmore, Langacker, and Lakoff, argue that it makes no sense to draw a rigid distinction between semantics – [meaning coded into linguistic form] –

and pragmatics – [inferences people make from how linguistic meanings are used in particular situations], just as it makes no sense to draw a rigid distinction between linguistic and [encyclopedic] knowledge" (Goddard, 2011). Thus, the author attempted to bridge the realms of both semantics (meaning encoded in the structure of the language) and pragmatics (meaning derived from how language is used in particular context) to integrate information about the terms' meanings, their grammatical properties, and knowledge about the world in which they were conceived.

The research studies reviewed indicated that there is an obvious disparity in expert opinions with regard to the terminology used within the fields. Such inconsistency leads to miscommunication within interdisciplinary teams and affects the outcome of a project. According to the research, the terms *bionics*, *biomimetics*, and *biomimicry* may be considered only partially equivalent within a context of a living language, because each one represents only part of the concept of a larger overarching community of biologically informed disciplines. Philosophical and knowledge base perspectives alter the selection of what is being expressed through the concepts of *bionics*, *biomimetics*, and *biomimicry*. Within the scope of this chapter, the author would like to further frame the terms in question against the background of experience, beliefs, and practices that "motivate the concept that [these terms] encode" (Fillmore & Atkins, 1992), drawing upon the brief introduction to the terms in Chapter One.

2.2 Semantic Discourse into the History of the Terms

2.2.1 Bionics

The term *bionics*, combined from the words *biology* and *technics*, was conceived by Jack Steele of the US Air Force Medical Division in 1960 (Bar-Cohen, 2006). Jack Ellwood Steele (1924 – 2009) studied General Engineering at the University of Illinois and the Illinois Institute of Technology before earning his medical degree from Northwestern University Medical School in 1950. According to Butsch and Oestreicher (1963), bionics aims to translate the information processing capability of living systems into design challenges. As mentioned in Chapter One, during the highly active times of the Biological Computer Laboratory (BCL), bionics served as a general catchword that covered attempts to analyze biological processes and to implement them using computers. Dr. Jack Steele, a prominent engineer and psychiatrist with emphasis on neuroanatomy, went on to co-organize the first Bionics Symposium, held at the Wright-Patterson Air Force Base in Ohio in 1960 (Gray C. H., 1995).

Three more symposiums were organized and sponsored by the United States Air Force, further popularizing bionics and proving it to be a fertile ground for military funding, "reported to be $100 million in 1963" (Heinley, 1963). The Second Annual Bionics Symposium held at Cornell University in 1961 served as a historical landmark that began to shift the focus of scientists from the physical sciences and mathematics to that of life sciences, namely biology (Bernard & Kare, 1962). The majority of papers focused on the theory of neural nets and self-organizing systems, experiments on sensory and neural recognition of animals and machines. These included "Bioelectric Patterns as Indicators of Behavioural Development in the Chick Embryo" by Joseph J. Peters and Charles J. Cusick, "Ultrasonic Interaction of Bats and Moths" by K. D. Roeder, and research on models for visual perception and hearing (Bernard & Kare, 1962). An abstract titled "Quantitative Aspects of the Problem of Shape in Biology" by W. R. Baum of Department of Mathematics at Syracuse University proposed a computable shape concept that may be used for evaluation of shapes in nature (such as volume, surface area, diameter, thickness, etc.).

Finally, Warren S. McCulloch of Research Laboratory of Electronics at MIT concluded the conference with the speech titled "The Imitation of One Form of Life by Another – Biomimesis", thus introducing a new term and positioning bionics within its scope:

> The full field of bionics opens up clearly within the general field of biomimesis, and it is not identical with cybernetics, nor a part of cybernetics. It is actually a broader field. It is concerned, I would say, primarily with an attempt to understand sufficiently well the tricks that nature actually uses to solve her problems, thus enabling us to turn them into hardware. The first hardware we need is the natural numbers because we must have a logically decent theory to work with. I think I know exactly what Jack Steele meant when he coined the word "bionics". It is not a new word; it is a word which was used many years ago for what is now called histology. It meant then what it primarily means now: the attempt to know the living unit.

Soon afterward, the focus of the term *bionics* was narrowed down to represent a "branch of science and technology" (Oxford Dictionaries, 2013) that deals with biologically inspired “design of electronic devices and systems” (Graf, 1962) to “replace or augment parts of the human body” (Oxford Dictionaries, 2013). The majority of participants of the symposiums were “focusing on the theory of neural nets and self-organizing systems, experiments on pattern and speech recognition in animals and machines” (Kline, 2009), with the minority of researchers studying “prosthetic devices and human augmentations, often to operate weapons systems” and, to a lesser extent, proposing medical aids (Kline, 2009). Finally, Henning E. Von Gierke, one of the pioneers of bionics defined its primary goal as an “extension of man's physical and intellectual capabilities by prosthetic devices in the most general sense, and to replace man by automata and intelligent machines” (Dario, Sandini, & Aebischer, 1991).

As the decades advanced, bionics matured into a well-defined field in Europe (Wahl, 2006), while largely disappearing from North America. A German biologist Werner Nachtigall independently founded the field in 1960s and, along with Carmelo di Bartolo, Jurgen Hennicke and Gabriel Songel, formulated a set of principles that would guide bionics practitioners in their collaborative process (Nachtigall, 1997).

Table 1. Principles of bionics, as formulated by W. Nachtigall (Nachtigall, 1997)

1. Integrated instead of additive construction;
2. Optimization of the whole, rather than maximization of individual elements;
3. Multifunctionality instead of monofunctionality;
4. Fine-tuning adapted to particular environments;
5. Energy saving instead of energy squandering;
6. Direct and indirect use of solar energy;
7. Temporal limitation instead of unnecessary durability;
8. Total recycling instead of waste accumulation;
9. Networks instead of linearity;
10. Development through trial and error.

Furthermore, an Italian design educator Carmelo di Bartolo (Instituto Europo di Design di Milano) extended the applicability of the principles from engineering to industrial design and "urged a restructuring of the industrial design process that would better take into account environmental concerns" (Birkeland, 2002). He then developed a concept in the 1970s for a European set of requirements titled "Nature Oriented Design and Bionics". Daniel Wahl, an expert in natural design and founder of Sustainability Consultancy Innovation Education, mentioned in his paper 'Bionics vs. Biomimicry: from control of nature to sustainable participation in nature' that "Germany is currently taking a leading role in the field of bionics research" (Wahl, 2006) establishing the 'Society for Technical Biology and Bionics' and the 'Bionics Competency Network'. Wahl also took a radically different approach to the evaluation of the term *bionics*, describing it from the perspective of "nature-culture relationships" and indicating the deficiency of "salutogenic design approach that increases human, societal, and ecological health synergistically" (Wahl, 2006).

2.2.2 Biomimetics

Otto H. Schmitt, one of the key founders of the biomedical engineering field (Patterson, 2009), officially coined the term *biomimetics*, a derivative of Greek words *bios* (life) and *mimesis* (imitate) (Bar-Cohen, 2006), in his publication 'Some Interesting and Useful Biomimetic Transforms', which he presented at the Proceedings of Third International Biophysics Congress in Boston, Massachusetts (Schmitt, 1969). More than three decades earlier Schmitt developed a physical device that mimicked the electrical action of a nerve as part of his doctoral research (Schmitt, 1938), illustrating a similar trait to that of bionics: practice precedes theory. Schmitt (1913 – 1998) was a graduate of Washington University in the United States and of the University College London in England with degrees in zoology, physics, mathematics, and a post-doctorate degree in biophysics. That early emphasis on the interface between biological and physical sciences expanded and deepened through Schmitt's career as Professor of Biophysics, Bioengineering, and Electrical Engineering at the University of Minnesota. In his own words: ''Since 1935, my scientific and technical efforts have revolved about the conviction that a new major discipline of biomedical science and technology will arise through careful examination and reformulation of biological principles in algorithmic computer-manipulable form, generating new mathematical figures of thought as needed, and seeking technological and social analogies based on these biomimetic principles.'' (Geselowitz, 1998). From this quote, it becomes evident that Otto Schmitt's interest in biomimetics went beyond purely technological applications to include social and ethical domains.

A list of biomimetics applications has grown significantly since Schmitt's study of the neural impulse propagation in squid nerves and subsequent invention of the Schmitt trigger in 1934. According to Speck & Speck, seven subdivisions in biomimetic research can now be identified and continue to expand: optimization, architecture and design, lightweight constructions and materials, surfaces and interfaces, fluid dynamics, biomechatronics and robotics, communication and sensorics (Speck & Speck, 2008).

According to Bar-Cohen, "this science represents study and imitation of nature's methods, designs, and processes" (Bar-Cohen, 2006). He also underlines the importance of distant (imitation of structure and function) rather than local analogies (imitation of surface-level attributes, such as colour and shape) in the process of translation between biology and design for a truly successful outcome (Dahl & Moreau, 2002). Julian Vincent of the Centre for Biomimetic and Natural Technologies at the University of Bath, UK published a paper titled "Biomimetics: its practice and theory" (2006), in which he highlights major differences of organization in biology and engineering and proposes an adaptation of TRIZ (the Russian acronym of what can be loosely translated as 'Theory of Inventive Problem Solving', developed by Altshuller and Shapiro) to manipulate the process of information transfer from biology to engineering. Although useful for engineers, the BioTRIZ (a method of utilizing TRIZ and biology to solve engineering challenges) approach can be considered too rigid for designers, leaving little room for creative experimentation and interpretation, as this will be expanded in further detail in Section 2.4 of this chapter. Vincent also asserts that biomimetics is the original representation of "a relatively young study embracing the practical use of mechanisms and functions of biological science in engineering, design, chemistry, electronics, and so on" (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006) and points out that "people are inventing an increasing number of other words to label the area, thus giving them some sort of exclusivity" (Vincent, 2009).

The Oxford English Dictionary defines the term *biomimetics* as: "[the branch of science concerned with] the development and use of biomimetic materials, methods, etc." keeping in mind that the adjective 'biomimetic' is chiefly of chemistry origins, defined as "a synthetic method that mimics biochemical processes" (Oxford Dictionaries, 2013). This definition suggests that the encyclopedic meaning of the term largely ignores the contextual meaning of the term while not fully supporting Schmitt's view of seeking social analogies based on biomimetic principles, and were largely absent in the list of biomimetic capabilities formulated by Bar-Cohen in 2006. Unlike the general principles of biomimicry (see Section 2.2.3) and bionics (see Section 2.2.1), principles of biomimetics are based on nature's mechanical capabilities and are rooted in specific examples from nature (Bar-Cohen, 2006; Bar-Cohen, 2006):

Table 2. List of biomimetic principles (mechanical capabilities), as proposed by Yoseph Bar-Cohen (Bar-Cohen, 2006)

1. Fly with enormous maneuverability like a dragonfly;
2. Adhere to smooth and rough walls like a gecko;
3. Adapt to the texture, patterns and shape of the surrounding environment like a chameleon, or reconfigure their body to travel through very narrow tubes like an octopus;
4. Process complex three-dimensional (3D) images in real time;
5. Recycle mobility power for highly efficient operation and locomotion;
6. Self-replicate, self-grow using resources from the surrounding;
7. Chemically generate and store energy.

Bar-Cohen goes on to provide examples of mechanisms that were inspired by observing biology, noting that "some of the most important ones include the ability to operate autonomously in complex environments, perform multifunctional tasks and adaptability to unplanned and unpredictable changes" (Bar-Cohen, 2006). Such characteristics, Bar-Cohen states, can result in mechanisms that not only mimic, but surpass nature (Bar-Cohen, 2006).

2.2.3 Biomimicry

Janine Benyus (1958 –) is a graduate of Rutgers University with degrees in natural resource management and English literature and writing, is a natural sciences writer, innovation consultant, and author of six books, including 'Biomimicry: Innovation

Inspired by Nature'. The book opens with a quote by former president of the Czech Republic Václav Havel: "We must draw our standards from the natural world. We must honour with the humility of the wise the bounds of that natural world and the mystery which lies beyond them, admitting that there is something in the order of being which evidently exceeds all our confidence." (Benyus, 1997).

According to Benyus, the term *biomimicry* can be defined using three parameters of Nature: model, measure, and mentor. Thus, *biomimicry* does not just imitate or take inspiration from nature, but also uses an ecological standard to judge the appropriateness of an innovation and "introduces an era based not on what we can extract from the natural world, but on what we can learn from it" (Benyus, 1997). The youngest of the fields, biomimicry speculatively takes inspiration from natural design proposed by John Todd and his wife Nancy Jack-Todd in the 1970s (Todd & Jack Todd, 1993) (Jack Todd & Todd, 1984), which "offered a list of [nine] principles for ecologically or biologically informed design" "augmented by a tenth precept that was added more recently" (Wahl, 2006).

Table 3. A list of natural design principles, formulated by Nancy Jack Todd and John Todd (Jack Todd & Todd, 1984)

1. The living world is the matrix for all design;
2. Design should follow, not oppose the laws of life;
3. Biological equity must determine design;
4. Design must reflect bioregionality;
5. Projects should be based on renewable energy sources;
6. Design should be sustainable through the integration of living systems;
7. Design should be co-evolutionary with the natural world;
8. Building and design should help heal the planet;
9. Design should follow a sacred ecology;
10. Everyone is a designer!

Later expanded on by Fritjof Capra – a prominent physicist and founder of Center for Ecoliteracy – these principles of ecology transformed into "the language of Nature" (1994) and caused a perceptual shift in "the link between ecological and human communities" (DeKay, 2011).

Table 4. A list of ecology principles by Fritjof Capra (Capra, 2010)

1. *Cycles:* members of an ecological community depend on the internal and external exchange of resources in continual cycles.
2. *Networks:* all living things in an ecosystem are interconnected through networks of relationship, depending on this web for survival.
3. *Nested Systems:* each individual system is an integrated whole and – at the same time – part of larger systems.
4. *Flows:* each organism needs a continual flow of energy to stay alive.
5. *Development:* all life – from individual organisms to species to ecosystems – changes over time, developing, learning, adapting, evolving, and co-evolving.
6. *Dynamic Balance:* ecological communities act as feedback loops, so that the community maintains a relatively steady state that also has continual fluctuations, providing resiliency in the face of ecosystem change.

The principles of biomimicry are also experiencing continuous evolution. The 2009 version, which the author of this thesis learned about during a biomimicry workshop in Costa Rica (Biomimicry 3.8, 2011), has undergone several changes and was introduced as a reworked set of principles at the 2011 at Biomimicry Education Summit in Ohio, Cleveland, which the author attended. The latest version of biomimicry principles is offered by The Biomimicry Institute, Montana, USA and is "the most comprehensive tool and the most important and influential component of biomimicry" (Biomimicry 3.8, 2011).

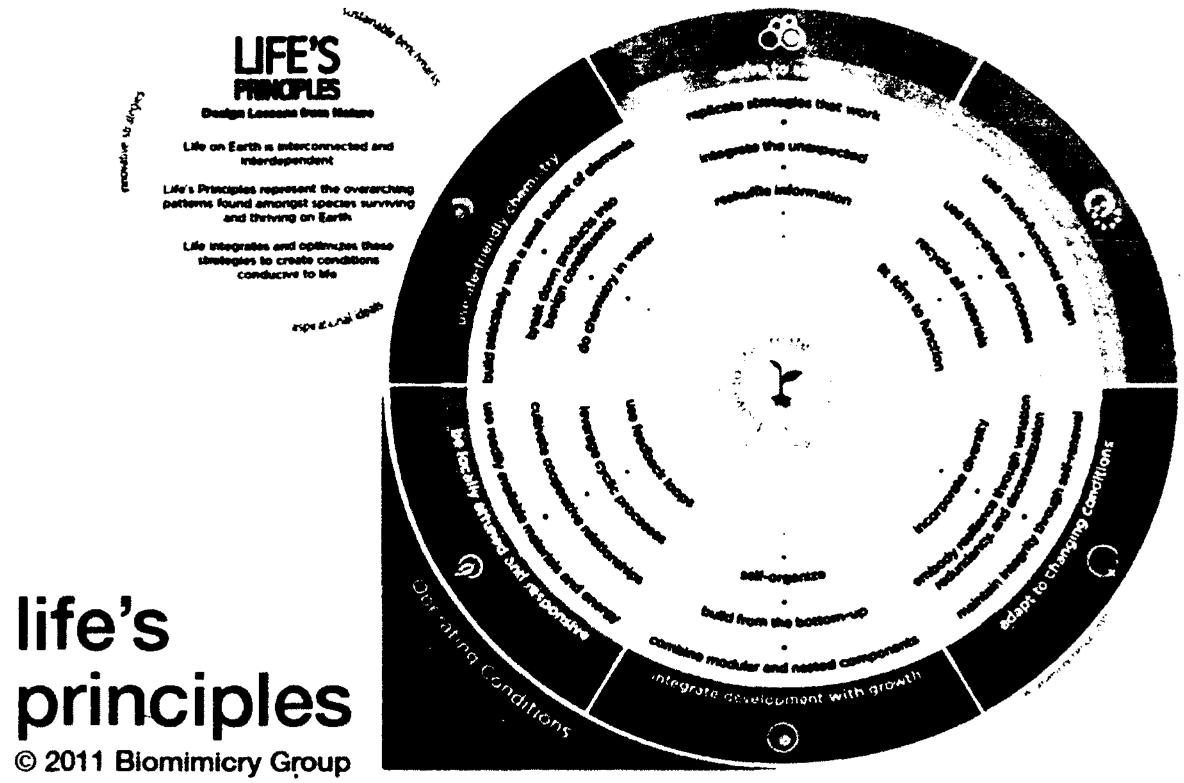


Figure 1. One of the versions of Life's Principles by The Biomimicry 3.8. The six main categories are: use life-friendly chemistry; evolve to survive; be resource (material and energy) efficient; adapt to changing conditions; integrate development with growth; be locally attuned and responsive (Biomimicry 3.8, 2011). Reproduced with permission from Dayna Baumeister, Biomimicry 3.8

Founders of the Biomimicry Institute identify a successful mimicry of nature through emulation of natural forms, processes and systems (The Biomimicry Institute, 2010). Similarly to the field of bionics and biomimetics, biomimicry identifies the importance of the emulation of natural forms to perform specific functions (multifunctionality, fit form to function, etc.) as well as processes that are informed by manufacturing methods in nature that are conducive to life (self-assembly, biodegradability, the use of water as solvent, etc.). Furthermore, biomimicry asserts a context-dependent view, in which the form and process are successfully implemented only if the final design fits into a given context and encourages solutions that are part of a larger system (a shared view with principles of bionics 'fine-tuning adapted to particular environments', natural design 'design must reflect bioregionality', and Fritjof Capra's language of Nature 'nested systems').

Passino (2005), however, in his book "Biomimicry for optimization, control, and automation" takes a radically different approach, stating "biomimicry uses our scientific understanding of biological systems to exploit ideas from nature in order to construct some technology" (Passino, 2005), bringing the concept closer to the realm of the encyclopedic definition of bionics and biomimetics. Finally, the Oxford English Dictionary equates the term biomimicry to the earlier biomimetics and points out the combined nature of the word (bio + mimicry) (Oxford Dictionaries, 2013).

Today, biomimicry spans various fields of human systems: from reimaging the way we feed ourselves to how we conduct business and make things (Benyus, 1997) with great emphasis on sustainability, promoted by The Biomimicry Institute.

2.3 Information transfer from biological template to final product

Technological advances in a number of fields outside of biological sciences have made it possible to begin conducting quantitative and qualitative analyses of biological systems. These applied fields are diverse, and include computer science, information technology, engineering, and design. In most instances, tools and methods developed for specific applications in their respective fields have been adapted for use in understanding biological systems and facilitating information transferability from biological to applied sciences. In bionics, biomimetics, and biomimicry cases such tools, developed by experts in respective fields, attempt to systematize the progress of a project from the biological templates to the final product using two approaches that have different names, depending on the field, but employ similar methodologies. Currently there is no standard approach in place to assist this transfer and instead it is typically derived from analogies (Vincent, Bogatyreva, Bogatyrev, Bowyer, & Pahl, 2006). However, various individual methodologies have been developed, some of which are described below.

2.3.1 Bionics: Inductive and Deductive Approaches

One of the first discussions on the subject of information transferability between biologists and engineers was introduced by Warren S. McCulloch during his speech at the Second Annual Bionics Symposium in 1961 (Bernard & Kare, 1962):

> The difficulty with every field like this is that it tends to require an increasing number of people who know two scientific disciplines. Engineering is, in this sense, a scientific discipline, though it differs from the physical sciences, being much more like biology. One has to have a reasonable knowledge of both engineering and biology in his own head, and there is no use in having in one room what should be in one head. This has been a standard failure. As a result, what you generally must have is close team play over the years between a youngster in biology and a youngster from engineering, until each knows both disciplines. This is about the only way it happens.

Decades later, as the field of bionics matured and transcended continents, settling down in Europe, many industrial design educators began implementing two approaches – inductive and deductive – into their courses. This allowed the students to collaborate on biologically informed projects (Birkeland, 2002). "The inductive approach begins with an observation of living nature, which is then documented, pending some application of the principles abstracted from the natural subject matter. The deductive approach is a reversal of this and begins with a design problem or design brief before extending to a search through nature for a solution or an appropriate response." (Birkeland, 2002). Birkeland goes on to demonstrate this approach using two case studies drawn from the University of Canberra and the Instituto Europo di Design industrial design courses. Students were asked to complete a biologically informed project using an inductive approach and then a deductive approach with a biological template of a caridoid escape reaction, also known as lobstering or tail-flipping.

In the case of inductive approach, students researched a particular specimen exhibiting this function, abstracted bio-mechanical principles and then proceeded to create a multifunction gripping and cutting tool. In the case of a deductive approach, students were first given a brief to design a more efficient clasping hand-tool and then were asked to research and abstract principles found in nature (Birkeland, 2002). Although creatively unique, the results of the studies yielded criticism and raised a discussion on the subject of lack of "the breadth of criteria brought to the design table" (Edmonds, 1994) and lack of research into "the complex interactions between a species and its environment and the role of these interactions in the development of any biophysical structure" (Birkeland, 2002).

2.3.2 Biomimetics: Bottom-up, Top-down, and Extended Top-Down Processes

In the field of biomimetics inductive and deductive approaches are known as bottom-up and top-down processes respectively with an addition of an extended top-down process. It is useful to introduce these concepts through the research outlined by T. Speck & O. Speck in their paper for The 4th International Conference on Comparing Design in Nature with Science and Engineering Design, titled "Process Sequences in Biomimetic Research" (2008). In this paper Speck & Speck differentiate the three processes according to their sequences (as also evident in inductive and deductive approaches): "The starting point for a biomimetic development in the bottom-up process is the fundamental research of biologists" that can later be applied to numerous design challenges if the abstraction of principles has been successful. The process also takes longer to be implemented due to the time needed for alignment between a recognized biological principle and a need for innovative biomimetic product.

The top-down process, similar to a deductive approach in bionics, begins with a design brief rich with technical constraints and recommendations. An engineer or a designer then works with a biologist to seek biological templates for solving his or her particular technical problem. The time needed in a top-down process is significantly less than for a bottom-up one and innovative leaps are rare.

Finally, the extended top-down process is characterized by the insertion of one or several iterations of basic research cycles. This process can generate great innovative leaps but take longer than top-down process, comparable to those in the bottom-up process (Speck & Speck, 2008).

It is evident that the process makes use of the analysis of biological forms, processes, and systems using methodological approaches from engineering sciences, "established by Werner Nachtigall as a complimentary item to biomimetics (bionics)" (Nachtigall, 1997). Such analysis allows for the abstraction and transferability of ideas from biology to technical applications in the course of biomimetic projects (Speck & Speck, 2008).

2.3.3 Biomimicry: Biology-to-Design and Challenge-to-Biology Design Spirals

Janine Benyus, together with Dayna Baumeister co-founded the Biomimicry Institute and Biomimicry Guild (Biomimicry consulting company). The Biomimicry Institute devised two approaches similar to those of bionics and biomimetics, differing in how the field integrates Life's Principles into the final stage as well as iterations throughout the entire spiral. The two approaches, known as 'design spirals', include Biology-to-Design – comparable to inductive approach in bionics and bottom-up and extended top-down processes in biomimetics – and Challenge-to-Biology – comparable to deductive approach in bionics and top-down and extended top-down processes in biomimetics.

The Biology-to-Design methodology prompts a designer to first discover a natural model; then abstract the deep principle used; brainstorm potential applications; emulate nature's strategies through mimicking form, process, and/or system; and finally evaluate the final design against Life's Principles identifying further ways of improving the final result (The Biomimicry Institute, 2010).

Challenge-to-Biology methodology implies a more challenge-focused approach, in which designer first identifies the problem by employing a function-focused mind-set; interprets the design brief by biologizing the question and defining operating parameters; discovers natural models through connection with nature, literature review, collaboration with biologists; abstracts design principles by identifying the core design concept; emulates design strategies by mimicking the form process, and/or system and finally evaluates final product against Life's Principles (The Biomimicry Institute, 2010).

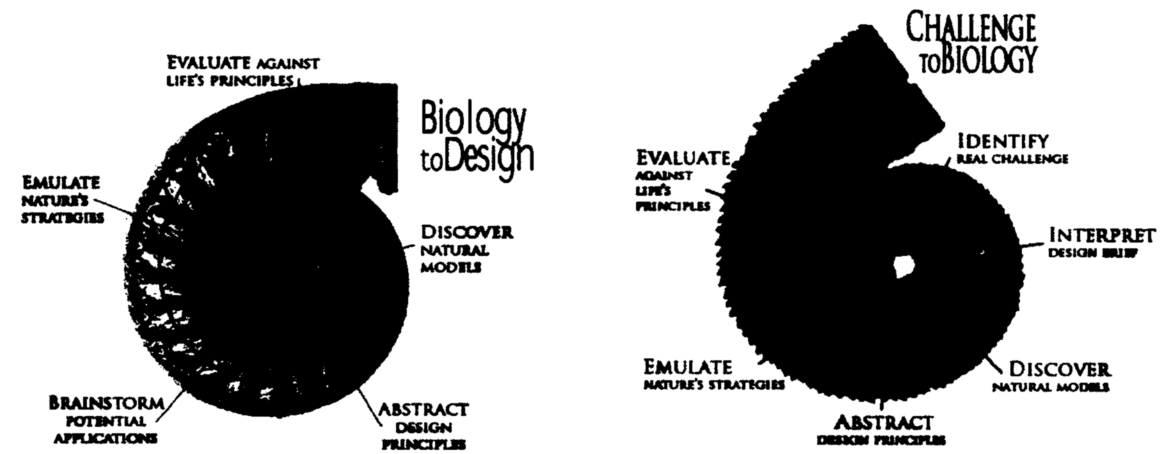


Figure 2. Biomimicry: Biology-to-Design and Challenge-to-Biology Design path proposed by The Biomimicry Institute (The Biomimicry Institute, 2010). Reproduced with permission from Dayna Baumeister, Biomimicry 3.8

These variations of Biomimicry Thinking paths (2013) called 'Design Spirals' differ from those of bionics and biomimetics, because they encourage the designer to constantly evaluate and re-work the sustainability of their design against Life's Principles and allow the designer to recognize sustainability as a continuous goal to strive toward, unless or until time or budget constraints take over.

2.4 Abductive reasoning and emerging methods in Biologically Informed Design

According to Atocha Aliseda, a philosopher of science and logician at National Autonomous University of Mexico, "abduction is a reasoning process invoked to explain a puzzling observation" and, according to Charles Peirce, is essential for acquiring new ideas (Aliseda, 2006). In comparison to methods of bionics, biomimetics, and biomimicry stated in Section 2.3, which may be characterized as related to inductive – from the specific to the general – and deductive – from the general to the specific – reasoning, abduction can be taken as "a distinctive kind of inference that follows this pattern: "D is a collection of data (facts, observations, givens); H explains D; No other hypothesis can explain D as well as H does. Therefore, H is probably true." (Josephson & Josephson, 1994). Thus, the purpose of abductive logic "is not to declare a conclusion to be true or false", but "to posit what could possibly be true" (Martin, 2009).

Charles Pierce, an American philosopher and a scientist, known as "the father of pragmatism" (Aliseda, 2006), states in notes for a conference titled "Pragmatism – Lecture VII" that "the question of pragmatism [the doctrine that every conception is a conception of conceivable practical effects] is nothing else than the logic of abduction" (Aliseda, 2006).

One such example of a direct link between experimental corroboration and explanatory hypothesis, related to the research in biologically informed disciplines, can be found in many interdisciplinary projects involving design discipline. Abductive reasoning allows for complex problems to be approached in an emergent fashion, causing often ill-defined problems to become clear in the process of design. This thesis written by Peter Wehrspann titled 'Biology as a Muse: Exploring the Nature of Biological Information and its Effect on Inspiration for Industrial Designers' as part of his Masters studies in School of Industrial Design of Carleton University studied transferability of biological information to industrial designers for the purpose of inspiration, using a toolkit that designers can interact with and be inspired by in their design process (Wehrspann, 2011). Variations of such toolkit are a common method, employed by Dr. Jeanette Yen of Center for Biologically Inspired Design (Wehrspann, 2011) and The Biomimicry Institute in Montana (The Biomimicry Institute, 2010). These toolkits emphasize pragmatic conduct of biologists and designers and may be essential introductory tools into abductive methodology of biologically informed disciplines.

2.5 Final Research Synthesis

The analysis of frame semantics literature; history surrounding the terms bionics, biomimetics, and biomimicry; methods of information transfer from biological template to final product as they evolved based on the field in question and an overview of abductive approach to problem solving partially cover the scope of the overarching question: How do the fields of bionics, biomimetics, and biomimicry differ from each other?

This question can now be answered from a historical perspective by addressing a section of the first sub-question: "How do experts, that founded and actively participated in the fields of bionics, biomimetics, and biomimicry as they evolved, perceive and define the fields?" It became evident from research that the meanings of terms depend on a whole set of interconnected notions, including educational and professional backgrounds of the founders; Jack Steele received a medical degree and worked in the US Air Force Medical Division, Otto Schmitt earned a degree in biophysics and worked as a Professor of Bioengineering at the University of Minnesota as well as at Wright-Patterson Air Force Base in Dayton with Jack Steele and Janine Benyus earned a degree in natural resource management and English literature and writing, eventually co-founding The Biomimicry Institute in Montana. Many theoretical advances of the early 20th century in physical sciences led to applications of their theories and technologies for studying biological sciences that gave rise to the fields of bionics and biomimetics. As the biological sciences advanced during the 20th century, the fields of bionics and biomimetics evolved almost simultaneously to tackle the complex subsystems of cells (neurons), tissues (muscles), organs (heart, brain, etc.), and organ systems (nervous system, cardiovascular system, etc.). Although it was understood on a conceptual level that the organizational levels are tightly interlocked (as evident from quotes by Otto Schmitt and principles of bionics), most researchers focused on a single system in great detail (for example, nervous system in the case of bionics and biomimetics).

As time progressed, however, biologists began gaining the capability to go beyond the interactions of components within a single system (National Academy of Sciences, 2009). As microbiologist and evolutionist Carl Woese said over 30 years ago, "Our task now is to resynthesize biology; put the organism back into its environment; connect it again to its evolutionary past … The time has come for biology to enter the nonlinear world" (Woese & Fox, 1977). As the fields of bionics, biomimetics, and biomimicry are now developing almost in parallel, the sheer volume of knowledge generated in each of these fields makes it increasingly difficult for researchers who study a nervous system (such as experts in the field of bionics) to keep up with the progress being made by researchers studying ecosystems (such as experts in the field of biomimicry).

It is time to highlight not only the differences, but also the connections between the fields of bionics, biomimetics, and biomimicry. This will hopefully provide an opportunity for experts to combine their different skills and perspectives and to accelerate the development of theoretical and practical approaches in biologically informed disciplines. For example, methodologies discussed in Section 2.3 arose within individual fields but resemble the principles of all three. These methodologies, processes and approaches share similar traits and will be examined in greater detail in Chapter Three. However, discovering and understanding the features that make these fields unique and similar will bring about a productive acceleration to the development of bionics, biomimetics, and biomimicry.

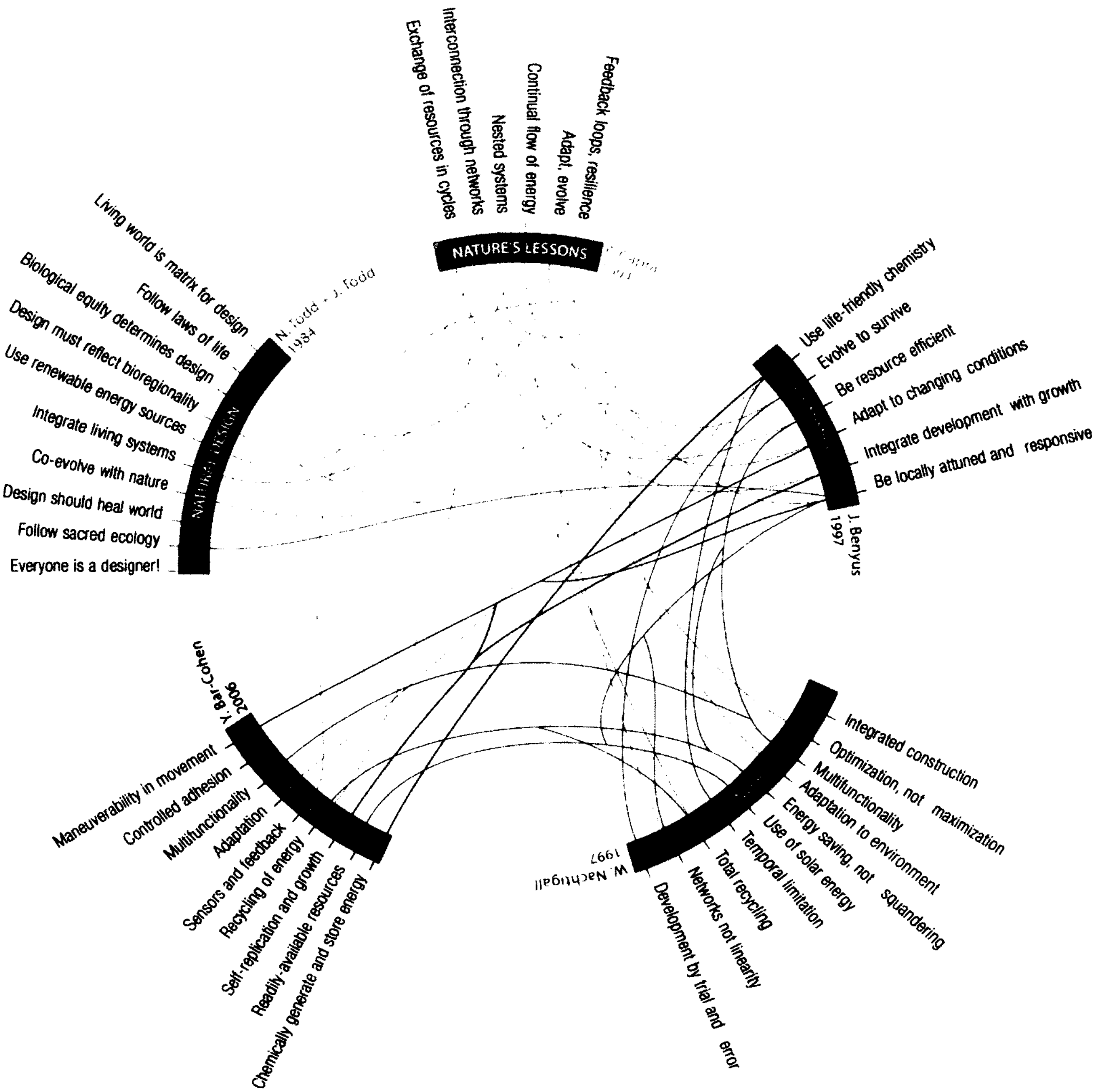


Figure 3. Diagram of comparative interconnections between the principles of bionics, biomimetics and biomimicry, supplemented by those of 'natural design' by Nancy and John Todd and 'the language of Nature' by Fritjof Capra. The authors of the principles and the year of their publications are written in corresponding colours (Iouguina, 2013).

2.6 Chapter in Review

Several patterns begin to emerge through the analysis of the roots, methodologies, and principles of the fields of bionics, biomimetics, and biomimicry.

The fields of bionics and biomimetics exhibit similarities in their origins of biophysics and cybernetics, while biomimicry stems from such disciplines as ecology and environmental sciences. The fields of bionics and biomimetics were both conceived in the 1960s following the rise of numerous scientific studies of control and communication in the animal and the machine. The field of biomimicry arose in the 1990s, as a resulting synthesis of other fields that were studying and incorporating living systems theory into their thinking as early as 1970s. The diverse movements took forms of natural design in the 1970s, industrial ecology in 1980s, resulting in the field of biomimicry in the late 1990s. Research into the origins of the fields, as shown in Section 2.2, illustrates that bionics and biomimetics have similar roots, whereas biomimicry differs.

Information transfer methodologies proposed by the educators in the fields of bionics, biomimetics, and biomimicry exhibit similar characteristics of inductive and deductive reasoning. Formal inductive and deductive approaches were introduced into the field of bionics as the field matured in Europe and began its integration into the curriculum of educational institutions in the 1970s and the 1980s. Thomas Speck and Olga Speck introduced bottom-up, top-down, and extended top-down methods to the field of biomimetics in the year 2006, with the intent of transferring scientific findings from biology to technical applications by means of biology push and technology pull. Finally, experts at The Biomimicry Institute proposed Biology-to-Design and Challenge-to-Biology Design Spirals in the first decade of the 21^{st} century, modifying the appearance of methods from a spiral to a circle early this year. It is interesting to note, that only in the case of bionics and biomimicry, the methodologies were developed in close consultation with one of the founders of the fields, Werner Nachtigall and Janine Benyus respectively. Research into the educational tools of the fields, as shown in Section 2.3, illustrates that bionics, biomimetics, and biomimicry have strong similarities in information transfer methodologies.

The principles of bionics, biomimetics, and biomimicry have experienced transformation throughout the years, which is evident in the evolution of the fields. Although, the field of bionics began as a scientific study of control and communication in the animal and the machine, its principles have evolved into those, closely resembling the field of biomimicry, as evident in Figure 6 of Section 2.5, due to the introduction of the principles by W. Nachtigall in 1997, an independent founder of the field of bionics in Germany. Yoseph Bar-Cohen, a physicist and one of the prominent experts in the field of biomimetics, formulated a set of principles in 2006, which focused on the mechanical capabilities of biological prototypes and largely ignored nature-focused ethos, evident in the principles of bionics and biomimicry. Research into the latest principles of the fields, as shown in Sections 2.2 and 2.5, illustrates that bionics and biomimicry are evolving toward similar goals of informing sustainable participation in the natural process, whereas the field of biomimetics differs in its specific focus on technological capabilities informed by nature.

CHAPTER 3

METHODS

The overarching objective of this thesis was to determine how the fields of bionics, biomimetics, and biomimicry differ from each other through the terminology, methods and principles. To address this objective, two questions were posed in Introduction:

a) How do current experts define the fields of bionics, biomimetics, and biomimicry?
b) How do the fields of bionics, biomimetics, and biomimicry differ in practical application?

To answer both these questions, the author constructed an online survey that was sent to experts in the field, and used two experimental case studies from which direct observations and semi-structured interviews were completed. All data gathered from participants was collected with permission from the participants and in full compliance with Carleton University Ethics Board guidelines (Project #13-1232).

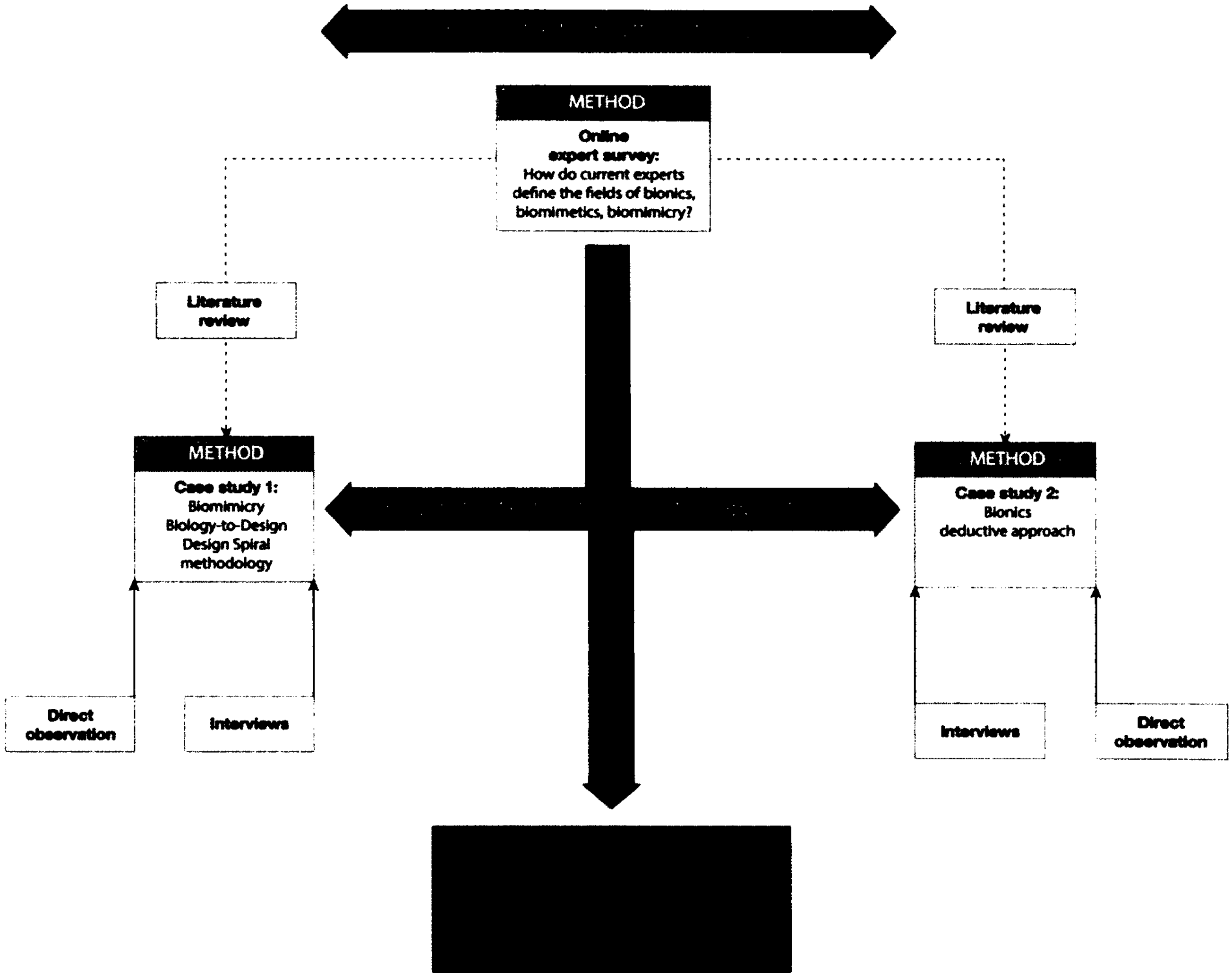


Figure 4. Depiction of research questions and methods that allow the researcher to study theoretical and practical differences between the terms bionics, biomimetics, and biomimicry. These include two experimental case studies from which direct observations and semi-structured interviews were completed and an expert survey (solid arrow lines). Both methods were enriched by Literature Review (dashed line) (Iouguina, 2013).

The researcher chose a qualitative research approach, because it allowed her to gain a greater understanding of a designer's and biologist's use and conception of, and/or their experiences with, principles and methodologies within the fields of bionics, biomimetics, and biomimicry. According to Merriam, "Qualitative researchers are interested in understanding the meanings people have constructed, that is, how they make sense of their world and the experiences they have in the world" (Merriam, 1998). Qualitative research offered an opportunity to explore the directions that the participants and their experiences took and to gain deeper understanding through natural interaction. "Being open to any possibility can lead to serendipitous discoveries" (Merriam, 1998).

3.1 Online Expert Survey

Following the review of historical context of terms bionics, biomimetics, and biomimicry, based on how they evolved through time, the author chose to gather the opinions of current experts. An online survey was conducted between February 19th and February 27th of 2013 using Fluidsurveys as a platform (fluidsurveys.com). Approximately 20 individuals, whose distinguishing characteristics included their recognized knowledge and experience in the field of biologically informed disciplines, were recruited personally by email. Several experts provided contacts for their colleagues, as they recognized the importance of the research, increasing the number of participants to twenty-five people. Key participants were identified based on their reputation in the field through their publications and their position with key organizations. Those who agreed to participate were provided with information and assurances of confidentiality, in the form of a letter from the researcher about the terms of participation in full compliance with Carleton University Ethics Board guidelines (Project #13-1232).

The link to the survey was sent to 25 respondents by email along with the information about the research being conducted for this thesis. All 25 persons completed the survey, which represented a participation rate of 100%. According to the defined opportunities discovered through literature review and case studies, the following topics for questions were chosen:

- *Identifying a presence of disparate opinions in the field of biologically informed disciplines.* This was revealed by asking participants to compare the terms bionics, biomimetics, and biomimicry; identify the meaning of the word mimicry; choose the term that describes the process of being inspired by nature to solve human problems best; and agree or disagree with the need to make a clear distinction between the meanings of the terms.

- *Identifying the present use of the terms in the field of biologically informed disciplines.* This was accomplished by the researcher analyzing and prioritizing responses of participants through tabulating similar answers and colour-coding key words and phrases that contributed to the identification of trends in responses.

- *Identifying educational and professional background of respondents.* This was accomplished by asking participants to share their educational background, field of work, and a number of years they were involved in the field of biologically informed disciplines.

3.2 Semi-structured interviews and direct observations using case studies

Two case studies were formed to investigate the sub-question: "How do the fields of bionics, biomimetics, and biomimicry differ in practical application". Using qualitative research techniques, the researcher conducted interviews with experts relevant to the focus of case studies and observed interdisciplinary interactions between students participating in case studies.

Challenges for case studies were chosen according the principles the fields have proposed and the researcher has reviewed in Chapter Two. The teams for the case studies were selected according to the scope of the challenges. In the case of the first challenge the researcher approached participants who would closely correlate with a typical composition of a team that would be interested in living systems and holistic thinking based projects. In the case of the second challenge the author reached out to potential participants who were affiliated with military and medical fields.

The objectives of each case study along with the procedures and the methods used to fulfill such objectives were summarized in Table 5.

Table 5. Case studies and corresponding methods (Iouguina, 2013).

	Case study 1: Biomimicry Biology-to-Design Design Spiral methodology	Case study 2: Bionics deductive approach
Aim	To investigate practical applications and effects on the outcome of the project of various methodologies proposed by the fields of bionics and biomimicry.	
Objectives	To investigate a Biology-to-Design methodology proposed by the field of biomimicry and explore interactions between biology and design students as they complete a challenge informed by biological prototypes.	To investigate a deductive approach methodology proposed by the field of bionics and explore interactions between medical and design students as they complete a challenge informed by biological prototypes.
Procedures	• Locate a challenge appropriate for the biomimicry Biology-to-Design methodology. • Locate students appropriate for the challenge: two industrial designers (with eco-literacy ethos) and one environmental scientist. • Interview experts in biology, design, and biomimicry. • Observe the process of the project from beginning to end, acting as a facilitator between the students of industrial design and environmental science. • Document the process, including sketches, brainstorming sessions, nature walks, etc.	• Locate a challenge appropriate for the bionics deductive approach methodology. • Locate students appropriate for the challenge: two industrial designers (with engineering approach) and one medical student. • Interview experts in medicine, military field, and bionics. • Observe the process of the project from beginning to end, acting as a facilitator between the students of industrial design and medicine. • Document the process, including sketches, brainstorming sessions, etc.
Methods	• Semi-structured interviews • Direct observation	

3.2.1 Case study 1: Biomimicry Biology-to-Design Design Spiral methodology

This case study was undertaken at Carleton University, to benefit from the close-knit nature of a university community. Two industrial design students and one environmental science student were selected for the study. The biomimicry Biology-to-Design methodology driven case study was conducted between October 1st and December 21st (three months) of 2011 as part of an online competition organized by The Biomimicry Institute, a nonprofit organization based in Missoula, MT. This case study enabled the researcher to use two research methods: semi-structured interviews and direct observation. Moreover, to understand the whole aspect of methodology proposed by The Biomimicry Institute, it was essential to examine the role of each team member and their impact on the outcome of the project.

Two industrial design students and one environmental science student were selected for the case study and the researcher took on a role of facilitating the study and transferring communication between scientists and designers. The main rationale behind selecting a student of environmental science was to replicate the context, in which the field of biomimicry originated with eco-literacy ethos in mind. Participants were contacted using a poster that gave a brief introduction about the competition and asking the respondent to take part in the case study. The poster was distributed in the department of the Institute of Environmental Science and School of Industrial Design at Carleton University.

The project's design brief was broad enough for the application of a Biology-to-Design method and challenged participants "to create a technology, product, service, or process that would reduce greenhouse gas emissions by: (1) improving energy efficiency, or (2) improving energy storage, or (3) reducing energy consumption within a defined system." (Biomimicry Institute, 2011). The institute requested for the entry to have "a clear connection between a biological mechanism, process, pattern, or system, and the technological solution submitted; i.e., the solution must emulate a natural model(s)." (Biomimicry Institute, 2011) (See Appendix B).

Semi-structured interviews. Three interviews were conducted with a biologist, a polymeric design specialist, and an expert in biomimicry as part of the case study. A list of questions was developed in advance and is included in Appendix D. At the beginning of each interview, the author explained the aim of the case study and introduced the team members. Most of the questions asked were open-ended in nature. All respondents exhibited diverse experience in the topic of the case study. The interviews with a biologist and a polymerics designer took place within the interviewees' departments and lasted between 30 – 45 minutes; the interview with the biomimicry expert was conducted online. All interviews were either written down or audio-recorded with a permission of each participant.

Direct observation. During the course of the case study the researcher observed interactions between the students of design and environmental science; their communication patterns through sketches, conversations, and during inspirational walks in nature. The researcher watched for challenge points and break-downs in communication as well as success-points, which allowed the project to jump forward. The photographs that were taken during the observation were beneficial in highlighting the crucial points in the flow of the project and complementing the information gathered during interviews with the expert biologist and a designer.

3.2.2 Case study 2: Bionics deductive approach

The bionics deductive approach driven case study was conducted between January 20th and February 18th of 2011 (one month) at Carleton University as part of a competition organized by Innocentive and sponsored by the US Department of Defense (see Appendix C). The researcher located participants through a Facebook post that gave a brief introduction to the competition. Two industrial design students and one student of medicine were selected for the study and the researcher took on the role of facilitating the study and transferring communication between scientists and designers.

This case study allowed the researcher to use semi-structured interviews and direct observation as research and data collection methods. Moreover, it was essential to examine the role of each team member and their impact on the outcome of the project in order to understand the whole aspect of methodology proposed by the field of bionics. The main rationale behind selecting a student of medicine was to replicate the context in which the field of bionics originated.

The team was required to "submit a design or blueprint-style sketch for a transportation device that can be carried into a hostile site by a single rescuer, that is quickly unpacked to load the injured person, and used to safely evacuate an injured or deceased person away from the hostile activity and into a helicopter" (see Appendix C). The project's design brief was highly specific and driven by constraints and technical requirements, rendering it a perfect scenario for a deductive approach.

Semi-structured interviews. Three online interviews were conducted with Jill Steele Mayer, the daughter of Jack Steele, as well as an infantryman and a medic as part of the case study. The purpose of the interviews was to clarify the methodology used by Jack Steele to communicate the concepts discovered in nature that resulted in solutions transferred from biology to design and to understand priorities and communication strategies in regards to biological prototypes used in case studies. The interviews were conducted by email, are included in the Appendix D, and are discussed in Chapter Four.

Direct observation. During the case study the author observed interactions between a student of medicine and students of design and noted their communication pattern during brainstorming sessions. The researcher watched for challenge points, break-downs in communication and success-points, which allowed the project to jump forward. Photographs that were taken during the observation were helpful with highlighting crucial points in the flow of the project.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents and discusses the results obtained from an online survey of experts working in self-described fields of bionics, biomimetics, biomimicry, bio-inspired engineering, biologically inspired design, biophilia, biotectonics, and natural design and case studies of bionics and biomimicry driven methodologies. This chapter begins with a discussion of current views and attitudes toward the fields of bionics, biomimetics, and biomimicry that were uncovered through the online survey, followed by participant formulated definitions of the terms *bionics*, *biomimetics*, and *biomimicry* within the context of their historical and current use. The chapter continues with the exploration of a practical approach to the fields of bionics and biomimicry through their methodologies and principles introduced in the Literature Review of this document.

4.1 Triangulation of Research Methods

Triangulation is a strategy that can be used to strengthen the confidence of research findings (Arksey & Knight, 1999). Decrop indicated that triangulation can reduce and/or eliminate personal and methodological biases and increase the probability of generalizing the findings of a study as the data is gathered from different angles and by different methods (Decrop, 1999). Denzin identified multiple triangulations that can be used in the same investigation, of which the author chose the following (Denzin, 1970):

- Methodological triangulation – the use of multiple methods to collect data.
- Data triangulation – the use of a variety of data sources in a study in terms of person, time and space.

Methodological and data triangulations had been accomplished through collecting the data from different sources and by using multiple methods, including: expert surveys, semi-structured interviews, and direct observation. All these are supplemented by extensive Literature Review:

1. Expert survey that included researchers and professionals working in self-described fields of bionics, biomimetics, biomimicry, bio-inspired engineering, biologically inspired design, biophilia, biotectonics, and natural design.
2. Semi-structured interviews with experts in the fields of biology, design, and biologically informed disciplines.
3. Direct observations of case study participants, including documentation of participant artifacts (sketches, mind-maps, prototypes, and final products).

Direct observations, semi-structured interviews, and an online survey were useful for obtaining an insider, perspective regarding the issues being studied. The interaction between researcher and participant through surveys, interviews, and observations was, "designed to help bridge the gap between what [the researchers] think [they] know about [participants] and who they really are" (Kuniavsky, 2003). This chapter analyzes and discusses research methods employed by the author to address an overarching question "How do the fields of bionics, biomimetics, and biomimicry differ from each other?"

4.2 Online Expert Survey

This section aids in formulating distinct definitions of the fields bionics, biomimetics, and biomimicry based on how they evolved through time and their current use. The researcher conducted an online survey of experts to find out more about the current cultural context of the fields and learn diverse perspectives of the leading experts that research and practice bionics, biomimetics, and biomimicry today. This methodology concentrated on the qualitative value of responses, because it provided more detailed answers and demonstrated diversity of perspectives in a more comprehensive way than a simple scale questionnaire alone. Furthermore, not the amount of data but the quality of information was relevant in order to address the research question of the study.

The link to the survey was sent to 25 respondents by email along with the information about the research. All 25 persons completed the survey, which represented a participation rate of 100%. The respondents identified themselves to be biologists, physicists, designers, architects, engineers, and artists working in the fields of biologically inspired design, bioinspiration, biomimetics, and bio-inspired engineering, with the majority of respondents identifying themselves with the field of biomimicry (48%), creating a bias in the results. Levels of experience varied considerably (from nine months to thirty-two years). Therefore, it was important to utilize the information obtained from the survey in conjunction with research from other sources, such as case studies, especially since the survey was concerned with how the researchers and practitioners perceive the fields in purely theoretical form.

4.2.1 Variations of the term 'mimicry' within biology and design

The researcher introduced the term *mimicry* in Chapter Two with the intention of providing an example of analyzing the term from the perspective of frame semantics within a context of the Literature Review. This section introduces the term *mimicry* within a wide range of meanings, from "discovering ideas for the purpose of innovation" to "resembling a pattern to enhance survival". Thus, *mimicry* labels a category of meanings, which only partially overlaps with an encyclopedic definition. The researcher organized responses to the question "How do you interpret the term mimicry within the fields of biology and design?" into a colour-coded table that yielded a trend illustrated in Table 6.

Following this analysis, a biologist might define the term as follows:

Mimicry is an imitation/copy/resemblance of form, pattern, or behaviour to enhance survival of an organism.

Experts, involved in the biologically informed disciplines appeared to have had a more diverse choice of meanings for the definition of mimicry. In fact, any one of the key words could have been used to manipulate the intention of the term, some of which included, but were not limited to:

Definition 1: Mimicry is an abstraction of nature's principles in order to create innovation.

Definition 2: Mimicry is an imitation of nature's function in order to benefit human technologies.

Definition 3: Mimicry is an emulation of nature's ideas in order to create sustainable designs.

Table 6. Analysis of Q1 "How do you interpret the term mimicry within the fields of biology and design?" where the definition of mimicry is broken down into the following structure: **[ACTION]** of ■ in order to ■ and numbers in square brackets [# > 1] represent the frequency of more than one of occurrence in responses (Iouguina, 2013).

	Biology	
[ACTION]	■	■
Mimic	Form	Enhance survival
Copy	Shape	
Resemble	Pattern	
Imitate	Behaviour	
	Design	
[ACTION]	■	■
Emulate [6]	Principle	Engineering
Understand	Ideas [3]	Sustainability [2]
Apply	Strategies	Innovation
Discover	Adaptations	Human technology
Abstract	Function	
Imitate	Pattern	
Translate	Process [4]	
Copy [2]	System	
Mimic	Form	

It was interesting to note that biologists identified an encyclopedic meaning of mimicry as an imitation of an external appearance, shape, and behaviour of a model to enhance survival. For designers, engineers, and architects mimicry surpasses encyclopedic definition and gains a new meaning of "understanding", "discovering", and "abstracting" for the purpose of "innovative", "sustainable" designs that surpass form and focus on function, process, and system. As a result, biologists and designers that choose to collaborate on a project may face obstacles in their communication due to the misalignment of these definitions. The biologist may view the goal of a project as an imitation of a form found in nature, while a designer may be more interested in understanding and translating the principles behind the function. Thus, practitioners of biomimicry and biomimetics need to be aware of this misnomer and make their intentions clear in the beginning of the project.

4.2.2 Bionics ≠ Biomimetics ≠ Biomimicry

The experts were then asked to give their personal opinions on the comparative equability of the terms *bionics*, *biomimetics*, and *biomimicry*. The three questions aimed at revealing how the experts evaluated terminology of biologically informed disciplines in general, and in particular, how the role of each term was seen compared to the others. Firstly, the researcher asked the following question "In your professional opinion, does biomimicry = biomimetics = bionics? Why or why not?"

Response	Chart	Percentage	Count
Yes		8%	2
No		92%	23
		Total Responses	25

Figure 5. Q2 and Q3 responses: "In your professional opinion, does biomimicry = biomimetics = bionics?" (Iouguina, 2013)

The responses indicated that none of the participants thought that biomimicry was equal to bionics. However, eight experts responded that bionics matched the meaning of biomimetics, and eleven experts responded that biomimetics was identical to biomimicry (equality is represented by corresponding coloured cells), illustrating a difference of understanding of the terms, illustrated in Table 7.

Table 7. Responses to Q2-3: "In your professional opinion, does biomimicry = biomimetics = bionics? Why or why not?" categorized according to the term and assigned a number (bionics – 1; biomimetics – 2; biomimicry – 3) and a letter according to the participant's response (Iouguina, 2013).

1	[redacted]	2	[redacted]	3	[redacted]
a	[redacted]	a	[redacted]	a	Design focus, business, organizational development, architecture, etc.
b		b		b	Places the greatest emphasis on sustainability
c		c		c	More accessible to general public
d	[redacted]	d	[redacted]	d	Very context dependent and has methodology: form, system, process.

e	Myopic view that looks to nature for innovation for innovation's sake	e		e	Holistic view that generates innovation to be more like nature in sustaining and generative way
f	Nature-inspired robotics and mechanics	f	Nature's strategies copied for design and technology	f	Nature's strategies copied for design and technology with ecosystem in mind
g	Uses Earth operating principles, but not Life principles	g	[redacted]	g	[redacted]
h	Emulates superficial level of function with 'gee whiz factor' [shows off a technical skill or a sensational design, but really has no useful purpose]	h	[redacted]	h	[redacted]
i	Design innovation alone	i	[redacted]	i	[redacted]
j	[redacted]	j	[redacted]	j	Follows "life creates conditions conducive to life" and aims for more energy, resource efficient, and non-polluting innovations
k	Term created by engineer, to describe mechanical devices based on biology	k	Term used by contemporary material scientists	k	Term [created] by an educator, to describe a philosophy of learning from nature to solve human problems.
l	Field related to robotics or complex mechanical technologies that simulate or replace biological functions	l	[redacted]	l	[redacted]
m	[redacted]	m	[redacted]	m	More broad interpretations
n	[redacted]	n	[redacted]	n	Learns from nature, connects with nature, and finds ethos about how people fit into natural world
o	The product of attempting to mimic biological systems in mechanical/electrical form	o	[redacted]	o	[redacted]
p	[redacted]	p	[redacted]	p	More nature-focused with an ethos and "earth-systems component" that is carried throughout the design

q	A more scientific connotation that focuses on how nature can support human system systems, without regard for ["life principles"]	q	[redacted]	q	[redacted]
r	Mostly associated with medical industry and robotic engineering	r		r	
s	Study and design of engineering systems and modern technology	s		s	
t	[redacted]	t		t	Has environmental sustainability objective
u	A hybrid of human and non-human design = cyborg: putting something synthetic into something organic	u		u	[redacted]
v		v		v	
w		w		w	
x	[redacted]	x		x	
y	Innovation inspired by nature, does not necessarily include sustainability	y		y	Refers to the intersection of innovation, sustainability, and an ethos of collaborative work to reach a sustainable future.

The researcher then posed a statement "Making a clear distinction between the meanings of the above terms is, or could be, very useful" prompting the experts to reflect on the relevance of the study, revealing the following results as shown in Figure 6.

Response	Chart	Percentage	Count
Strongly disagree		**4%**	**1**
Disagree		**8%**	**2**
Undecided		**12%**	**3**
Agree		**44%**	**11**
Strongly agree		**32%**	**8**
		Total Responses	**25**

Figure 6. Results of Q5 "Making a clear distinction between the meanings of the above terms is, or could be, very useful" indicating a clear need for organization of terms (Iouguina, 2013).

Aside from a clear need for an organized terminology in the field of biologically informed disciplines, the responses illustrate some of the different components that comprise the terms in question. Using this, it is possible to redefine each of the terms as follows:

Bionics

Experts position bionics within disciplines of biology (1e, 1f, 1k, 1l, 1o, 1q, 1u, 1y) and engineering (1a, 1m, 1k, 1m, 1r, 1s, 1t), more specifically the industries of "robotics" (1f, 1l, 1o, 1r), "mechanics" (1f, 1k, 1l, 1o, 1p, 1t) and "medicine" (1r). Bionics employs "physics principles" (1f, 1q) with the end-goal of creating "innovative" (1e, 1h, 1i, 1y) "functional products" (1h, 1j, 1k, 1l, 1p, 1t) with no regard for "ecology" (1d, 1g, 1j, 1n, 1p, 1q, 1x, 1y).

The first four components categorize bionics into an amalgam of biology and engineering disciplines, conceptualized primarily as a sub-field of engineering, focused primarily in robotics and mechanics. The 'purpose' component centers on the final outcome of innovative functional products that may incorporate synthetic design with organic matter. It is interesting to notice that the 'context' component is defined in relation to sustainability or ecology. This kind of focus is an evidence of bias among respondents, the majority of whom relate themselves to the field of biomimicry (52%).

Biomimicry

Experts position biomimicry mainly within the disciplines of design (3a, 3f, 3i, 3o, 3p, 3r, 3w), business (3a), architecture (3a, 3r) and a general field of philosophy (3k, 3n) with a broad subject field (3a, 3m, 3d, 3v, 3w) that allows for a greater accessibility to a general public (3c, 3l), whose main interest is "form, process, systems" design (3f, 3p, 3v, 3w), nature-focused ethos (3i, 3n, 3p, 3w) and environmental sustainability (3b, 3e, 3f, 3h, 3i, 3j, 3t, 3w, 3y).

Responses detail that, although mostly focused in the field of design, biomimicry carries much broader interpretations and presents less technical complexity than bionics, rendering it a general philosophical approach to "how people fit into the natural world" (3n). Many references to the connection between sustainability and human-nature connection leads to a conclusion that this is the Institute's main public declaration of intentions. Some of the evidence in support of the above components comes in the form of phrases and sayings such as: "Learns from nature, connects with nature", "Holistic view that generates innovation to be more like nature in sustaining and generative way".

In further support of a nature-focused ethos, a member of the Biomimicry Institute asserts in the survey: "It differs in that it incorporates Ethos, Emulate, and (Re)Connect with nature, what we at Biomimicry 3.8 are calling the Essential Elements. The Ethos piece is about seeking sustainable designs, [...]. The Emulate piece is about learning from the organism or system how it meets its challenge or function, then applying the abstracted design principle to the design. (Re)Connect means remembering that we humans are part of nature, not separate from it." The Emulate component may be equally applied to definitions of all three terms, yet it is the Ethos and (Re)Connect components that set biomimicry apart and allow for greater public accessibility, while diverting the focus of those in the field from technical complexity.

Biomimetics

Biomimetics is best described through comparative semantic analysis, because the majority of experts (76% of respondents) equate the term to either bionics or biomimicry. In fact, 8 experts think that biomimetics equals bionics. Thus, biomimetics can be defined as equal to bionics in its engineering focus (2a, 2f, 2j, 2m, 2p, 2t) lacking sustainability component (2d, 2j, 2x) and nature-focused ethos (2n).

However, 11 experts think that biomimetic(s) is congruous with biomimicry. The first and most lexically interesting point is that four experts only view biomimetics as an adjective (biomimetic), the role of which is to describe the process (2v) or solutions with traits (2h, 2o, 2v, 2w) of biomimicry. In fact, one expert states: "Unfortunately, there's no good adjective to go with biomimicry, so we often refer to biomimetic design when we refer to a design that meets our definition of biomimicry. I think that's part of the confusion for some."

Moving on, it became evident that at least 7 experts thought that the term biomimetics was congruent with biomimicry in its human-nature ethos (2w) and sustainability (2g, 2h) focus, while only one expert differentiated the term from the other two by positioning it exclusively in the discipline of material science (2k).

In the analysis stated above for bionics, biomimicry, and biomimetics, the initial component includes "innovation" (1e, 1i, 2i, 3e, 3i, 3j, 3y) and "nature-inspired or mimicked or copied or learned" (1e, 1f, 3y, 1n, 1q, 2f, 2n, 2q, 3e, 3w, 3f, 3k, 3n, 3p) concepts, thereby establishing their position at a certain level of hierarchical ranking. What then are *innovation* and *nature* in the eyes of the experts as well as a variety of action verbs that attempt to describe the channeling of ideas from nature to innovation? Further research is needed to answer these questions.

4.2.3 Biomimicry and Biologically Inspired Design are the most popular among experts

The majority of respondents identified themselves to be associated with the field of biomimicry (52%), thus demonstrating a clear affinity for the term biomimicry in order "to describe the process of being inspired by nature to solve human problems".

Response	Chart	Percentage	Count
biomimicry		52%	13
biomimetics		4%	1
bionics		0%	0
bio-inspired engineering		0%	0
biologically inspired design		12%	3
biophilia		8%	2
Other, please specify...		24%	6
		Total Responses	25

Figure 7. Results of Q8 "Which best describes your field of work" revealing a bias in the study. The majority of respondents identified themselves to be associated with the field of biomimicry (52%) (Iouguina, 2013).

Response	Chart	Percentage	Count
bionics		0%	0
bio-inspired engineering		4%	1
biomimicry		48%	12
biologically inspired design		24%	6
biomimetics		4%	1
Other, please specify...		20%	5
		Total Responses	25

Figure 8. Results of Q4 "If you could use only one of the following terms to describe the process of being inspired by nature to solve human problems, which would you use?" with biomimicry in majority (48%) followed by Biologically Inspired [Design] (32%), including "other" (Iouguina, 2013).

It is interesting to note, that although the researcher used the word *inspired* in the formulation of the question, respondents still gravitated toward the term biomimicry.

Additionally, several experts indicated their preference for *bio-inspiration* rather than Biologically Inspired Design, demonstrating that the word *design* may be limiting.

4.2.3 Innovation and sustainability are two main drivers of the fields

Lastly, the researcher posed a question "In your opinion, why should designers learn from nature?" to uncover additional keywords and trends relevant to the fields of biologically informed disciplines.

Response	Chart	Percentage	Count
To practice sustainable design		64%	16
To apply to cybernetics and systems design		24%	6
To achieve technological innovation in the field of biomedical engineering		16%	4
To produce synthetic materials and products that mimic natural ones		20%	5
Other, please specify...		72%	18
		Total Responses	25

Figure 9. Results of Q6 "In your opinion, why should designers learn from nature?" which (with "other" responses included) indicate that innovation and sustainability are two main drivers of biologically informed disciplines (Iouguina, 2013).

Experts indicated that the main goal of learning from nature should be "to break out of patterns that currently dictate our mode of problem solving" to "push innovation" and "practice design with a firmly grounded sense of life sustaining principles".

4.3 Case Studies

The two case studies, used in the research, were bounded by two major contexts, the students themselves and their experiences and educational background. Through qualitative research techniques and the resulting interdisciplinary interactions between students and mentors, principles guiding the project and their influence on the final outcome of the study were uncovered. These experiences, principles, and an initial design brief facilitated the outcome of the project to be driven either by inductive (according to the field of bionics), bottom-up (according to the field of biomimetics), biology-to-design (according to biomimicry) or deductive, top-down, or challenge-to-biology methodologies as defined by the fields (see Chapter 2).

The results of the case studies are presented in narrative form to provide the reader of this thesis with insight into and an understanding of the design process as implemented by an interdisciplinary group of students. The outcome of a narrative text describing the experience of the students was dependent on organized, flexible, and careful data collection.

The idea for experimental case studies arose from the Literature Review, during which the author investigated the fields and its methods which were developed by experts in the fields of bionics, biomimetics, and biomimicry and complimented by insights drawn from semi-structured interviews that occurred during the progress of the studies. It became evident that all three fields exhibited differences historically and principally, and were also driven by a loose framework which attempts to guide the progression of a project from a biological template to the finished product, as described in the Literature Review.

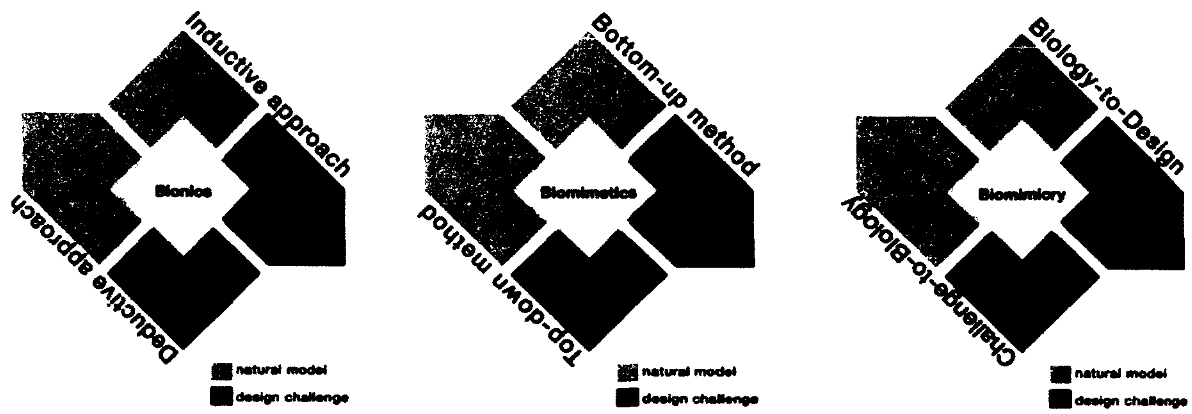


Figure 10. Simplified diagrams of methodologies in the fields of bionics, biomimetics, and biomimicry. The legend reads: [yellow: natural model], [blue: design challenge] (Iouguina, 2013).

As a result, the second set of sub-questions arose: If the author were to replicate the original conditions in which projects were conceived in the fields of bionics, biomimetics, and biomimicry, how would the results differ? In the context of the presented methodologies, how does the choice of inductive/bottom-up/biology-to-design vs. deductive/top-down/challenge-to-biology approaches affect the outcome of the project, in combination with the unique principles of the fields? The author decided to investigate the fields of bionics and biomimicry, because both defined set of strict set of principles, as illustrated in the Literature Review, and both were conceived by a community of either driven by engineers and physical scientists or biologists and environmental scientists. Thus, the following parameters were chosen:

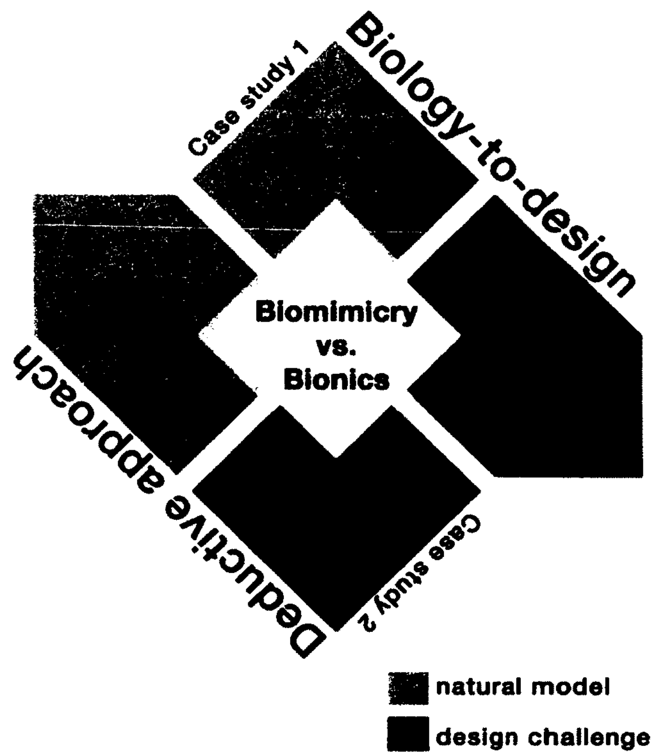


Figure 11. Diagram of two methodologies of progression of a project investigated in this thesis through two case studies: Biology-to-Design (biomimicry) vs. Deductive (bionics) (Iouguina, 2013).

The reason for choosing a deductive approach in bionics and Biology-to-Design Design Spiral in biomimicry was to investigate the effects of methodologies, driven by principles, which became an important distinction that influenced the overall interaction patterns between research participants and the final outcome of the projects. The researcher evaluated these choices as situated on opposite sides of the spectrum and expected these methodologies to guide the teams toward two principally different solutions.

The teams were chosen according to the scope of the projects. In the case using a biomimicry Biology-to-Design methodology the researcher recruited participants who would closely correlate with a typical composition of a team that would be interested in living systems, holistic thinking based projects. In the case using a bionics deductive approach the researcher recruited participants who were affiliated with military and medical fields to replicate the context in which the majority of the early bionics projects were completed. More precisely, for the Biology-to-Design (biomimicry) driven project the researcher recruited two industrial design students and one environmental science student, while for the deductive (bionics) driven project two industrial design students and one medical science student were selected.

4.3.1 Semi-structured Interviews

As part of case studies the researcher conducted six semi-structured interviews that informed the flow of the projects and aided in gaining a deeper understanding of the methodologies driven by the fields of bionics and biomimicry.

The first interview was conducted with Jill Steele Mayer, the daughter of Jack Steele, to bring insight to the transfer of knowledge from the biological template to the final product of bionics.

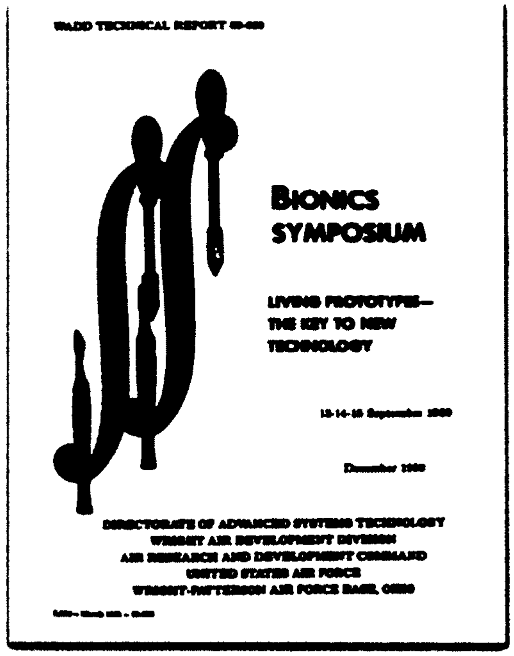


Figure 12. Poster from the Bionics Symposium organized by the United States Air Force, Wright Air Development Division showing the 'symbol' of Bionics developed by Jack Steele, 1961 (Kline, 2009). Reproduced with permission from Jill Steele Mayer.

Dad designed the symbol for bionics, which is shown on the cover of the symposium report you have pictured on your website. (I could find no other example or explanation of the bionics symbol on the Internet. The proper symbol is in color, and is slightly tilted to the right just as the mathematical integral sign is tilted.) Bionics combines the fields of biology, mathematics, and engineering. A design problem that has already been solved in nature is analyzed, and then the solution is recreated into a new engineering design through the language of mathematics. The three disciplines are represented by 3 separate elements in the bionics symbol. The scalpel (at the bottom left of the symbol) represents the field of biology and also the process of analysis (or understanding by cutting apart into smaller pieces). The welding iron at the top right represents engineering and the process of design and creation (putting together concepts into a new form). The mathematical integral symbol connecting the scalpel and welding iron represents mathematics which integrates the fields of biology and engineering. Mathematics is

> also used as a language to communicate the concepts discovered in nature's solutions, and to describe the new design in a way it can be synthesized, manufactured, or built (Steele-Mayer, 2012).

The interview partially guided this thesis, acting as a valuable supplement that bridged the Literature Review and case study methods. By focusing on the description of a visual symbol that, according to Jack Steele, perfectly represented the meaning of the term *bionics*, and outlining the importance of the mathematical integral symbol as an important tool that bridged biology and engineering, Jill helped inform the author's methodology of the case study, driven by deductive approach and heavily informed by mathematical models of the natural world.

The second interview was conducted with an expert from The Biomimicry Institute to inform the author about the Biology-to-Design methodology and its application in a design project. The researcher spoke with Sherry Ritter, an expert from The Biomimicry Institute, known as a Biologist at the Design Table, whose role is "to create a bridge to biological understanding. That is, to translate science language in such a way that a designer can easily make a link to their design challenge" (Ritter, Biomimicry Workshop: Costa Rica, 2010). Sherry informed the team working on the biomimicry challenge about the methodology employed at The Biomimicry Institute and encouraged the students to follow Biology-to-Design Design Spiral "to achieve successful results" (Ritter, Case Study 1: Biology-to-Design Methodology, 2011). Having an expertise in wildlife ecology, Sherry sees "biomimicry as a way to develop positive solutions to today's most challenging human problems" (Ritter, Biomimicry Workshop: Costa Rica, 2010).

A second set of interviews with a biologist and a naturalist, Professor Michael Runtz of Carleton University and a mechanical technologist and polymerics designer, Hans Koopman of E. I. DuPont Canada Co., was conducted at the very beginning of the first case study. The interviews contributed to a general understanding of two very different thinking patterns: one driven by a biologist and another driven by an engineer, creating a platform for testing the two approaches introduced in Chapter Three.

Two interviews were conducted at the end of the second case study with an infantryman of the Royal British Army and a doctor of emergency medicine at The University College London Hospitals. Similar to the interviews with Michael Runtz and Hans Koopman, they contributed to the flow of the case studies and, through this process, informed the researcher of priorities and approaches both experts chose while advising on biologically informed design projects. The second and third set of interviews will be discussed in greater detail in the following section.

4.3.2 Direct Observations: Case Study 1 Biology-to-Design Methodology

The biomimicry Biology-to-Design methodology driven case study was conducted between October 1st and December 21st of 2011 as part of a competition organized by The Biomimicry Institute. The project's design brief was broad enough for the application of the Biology-to-Design method and challenged participants "to create a technology, product, service, or process that would reduce greenhouse gas emissions by: (1) improving energy efficiency, or (2) improving energy storage, or (3) reducing energy consumption within a defined system." (Biomimicry 3.8, 2011). The institute required the entry to have "a clear connection between a biological mechanism, process, pattern, or system, and the technological solution submitted; i.e., the solution must emulate a natural model(s)." (Biomimicry 3.8, 2011).

Having been quantitatively dominated by industrial designers (a ratio of 2:1 excluding the researcher), the team naturally gravitated toward a Challenge-to-Biology method, despite a recommendation from The Biomimicry Institute to use a Biology-to-Design method. Members of the team began by brainstorming various challenges within the field of industrial manufacturing (since this is the educational background of industrial designers graduating from the Carleton School of Industrial Design) and settled on greenhouse gas emissions produced by the process of injection molding. This statement of the problem positioned the project within social, economic, and technological scope driven by biological prototypes that now needed to be identified.

The team decided to speak with two experts from the fields of biology and engineering respectively. The first interview was conducted with Michael Runtz, one of Canada's highly respected naturalists, nature photographers, and natural history authors. A birdwatcher since the age of five, he "has lived, breathed and worked with nature all his life" (Runtz, 2011). The team prepared several questions, included in the Appendix D with one highlighted below due to its importance in bringing insight into subsequent steps taken in the project (Runtz, 2011):

> **Q: The reason there are molds in injection molding is to make duplicates of a form. Are there any examples of such need in nature?**

> A: I'm not sure. In nature you don't think from the perspective of a mold. Hmm, that's a really good question, I really can't think of anything. Perhaps, a wasp's nest? But no that's more free-forming. A spider extrudes a thread, but that's extrusion. I really can't think of an example!

The conversation with Michael Runtz fell apart at this point, but the team extracted one valuable lesson: engineers and biologists think differently. After this interview, the team went on to speak with Hans Koopman, whose expertise included injection molded and blow molded polymeric applications. A conversation with Hans featured numerous technical details and examples of existing products and processes that employ injection molding in manufacturing industries successfully. However, the conversation was of no interest to the environmental science student who was part of the team due to an abundance of technical terminology and very specific knowledge. Industrial designers could relate to Hans' expertise very well and engaged in a discussion readily, however, the conversation produced no insights in regards to biological prototypes. It stayed within the realm of manufacturing technology of human systems (Koopman, 2011).

These interviews created a sense of confusion and the team decided to return to square one. The author, who was part of the team, steered the students back to the brief, articulated by The Biomimicry Institute and it was decided that instead of researching a challenge in the field of design, it was important to first look into the issue of greenhouse gas emissions.

The team began with a very broad challenge of reducing the emissions and went on to explore strategies in nature that addressed similar scenarios. Various organisms and processes were researched and cursory information was brought together from the various sources, including interviews with biologists from The Biomimicry Institute, literature reviews, and nature walks.

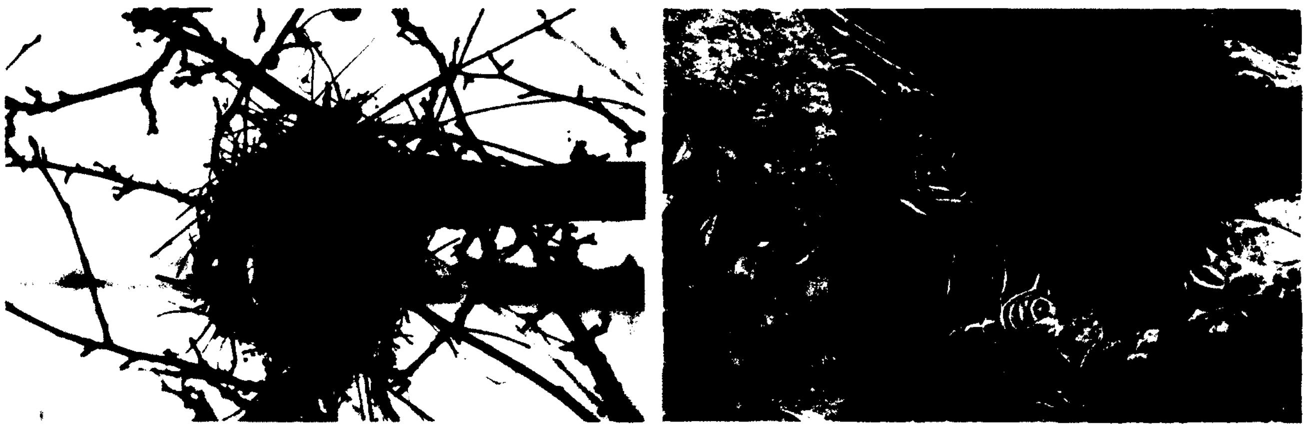


Figure 13. Nature walk as part of the design process during Case Study 1 [Biology-to-Design methodology within the scope of biomimicry project]: Cedar waxwing nest and flow lines discovered and documented (Iouguina, 2011).

During one of the meetings the team spotted a spider in the Master of Design studio, where the gatherings took place. The environmental science student mentioned that spiders have glands that secrete protein containing molecules, which are dissolved in a water-based solution inside these glands: "while in the gland, the solution is viscous, but upon being drawn through spinnerets they become insoluble and ten times denser than the fluid state" (Environmental Science student, 2011). One industrial design student became excited about this information and mentioned the process of plastics extrusion, which is a high volume manufacturing process in which raw plastic material is melted and formed into a continuous profile. Another industrial design student stressed the importance of localized production and on-demand manufacturing as an inspiration from a spider. After much discussion, the team settled on the biological prototypes, which began with an inspiration of form and propagated into higher-level systems thinking by continuously evaluating the concept against Life's Principles (Biomimicry 3.8, 2011).

The next step in the process was to abstract the principles of the biological prototypes, identifying areas in human systems and processes that can benefit from such strategies, thereby producing some representation of the biological prototype in the context of the challenge. The team recognized an opportunity to move away from high-volume production and embrace the use of low-energy processes, decentralization, and diversity in the industry of injection molded polymers: strategies informed by nature. The translation process of biological prototypes took the most amount of time and caused the project to run for much longer than the one driven by deductive approach.

Table 8. A table of biological prototypes and their translation into the language of design within the scope of Biology-to-Design biomimicry challenge (see Appendix B for details) (Iouguina, 2013).

Biological prototype		**Life's Principles**	**Final Design**
Form	Spinneret of a spider	Integrate development with growth	Injector head to inject various types of polymer bases, depending on the resulting mechanical properties of the final product that builds from bottom up.
	Cedar waxwing nest building process	Be resource (material and energy) efficient; integrate development with growth	Inspiration for material sourcing. The bird's nest was spotted during one of nature walks, and team members were amazed at how resourceful this bird was in finding local materials (including synthetic fibers) for the construction of its home.
Process	Phenotypic plasticity in aquatic buttercup	Evolve to survive	Process of a polymer product formation. Just as the buttercup readily produces dissected or entire leaves as a plastic response to growing in water or above it, the team has decided to adopt the same strategy for product design.
System	Mycelial network	Use-life friendly chemistry, regions and also maintains its integrity in the face of damage. Adapt to changing conditions, and be locally attuned and responsive	System of manufacturing was inspired by how the network both transports nutrients between spatially separated source and receiving

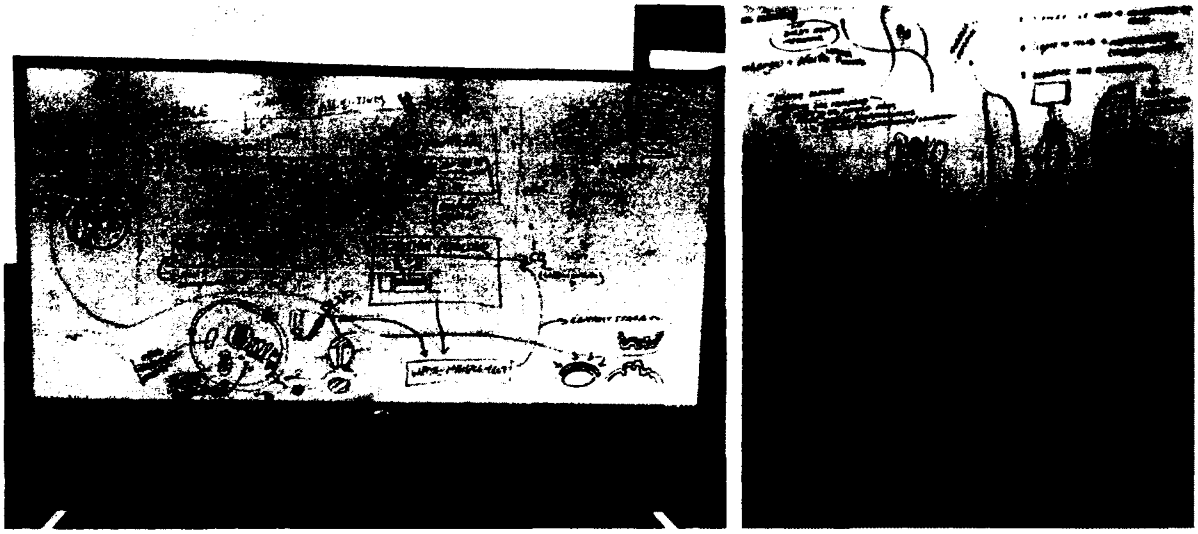


Figure 14. A rough diagram of biological prototypes abstraction and brainstorming of potential applications within the scope of Biology-to-Design biomimicry challenge. The drawings show a cell producing energy and a concept of an injection molding equipment that takes inspiration from mitochondrion (Iouguina, 2011).

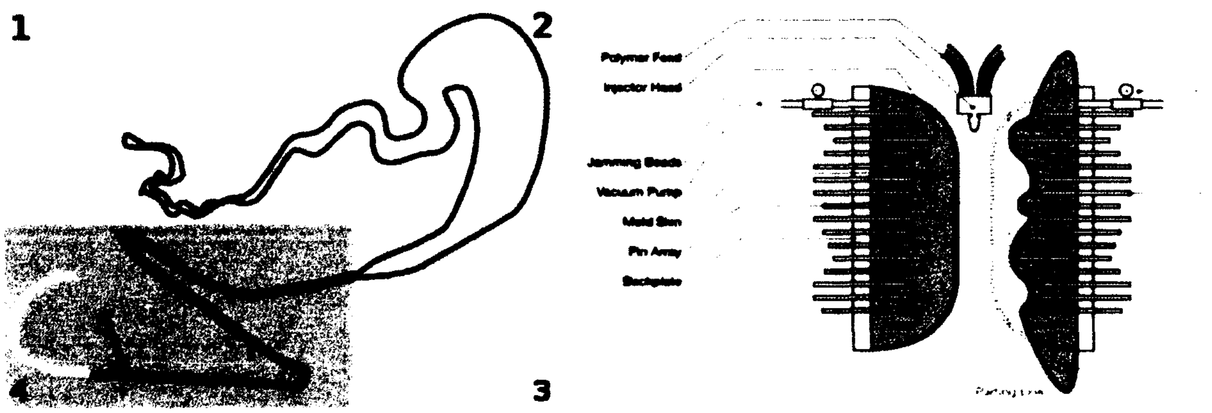


Figure 15. An example of communication between an environmental science student and an industrial design student. An environmental science student explained the function of a spider's spinneret through a sketch, which was then translated into a design of a biopolymer extruder by industrial designers (see Appendix B for enlarged version). The team addressed the form and process of the challenge (Environmental Science student and Industrial Design student, 2011).

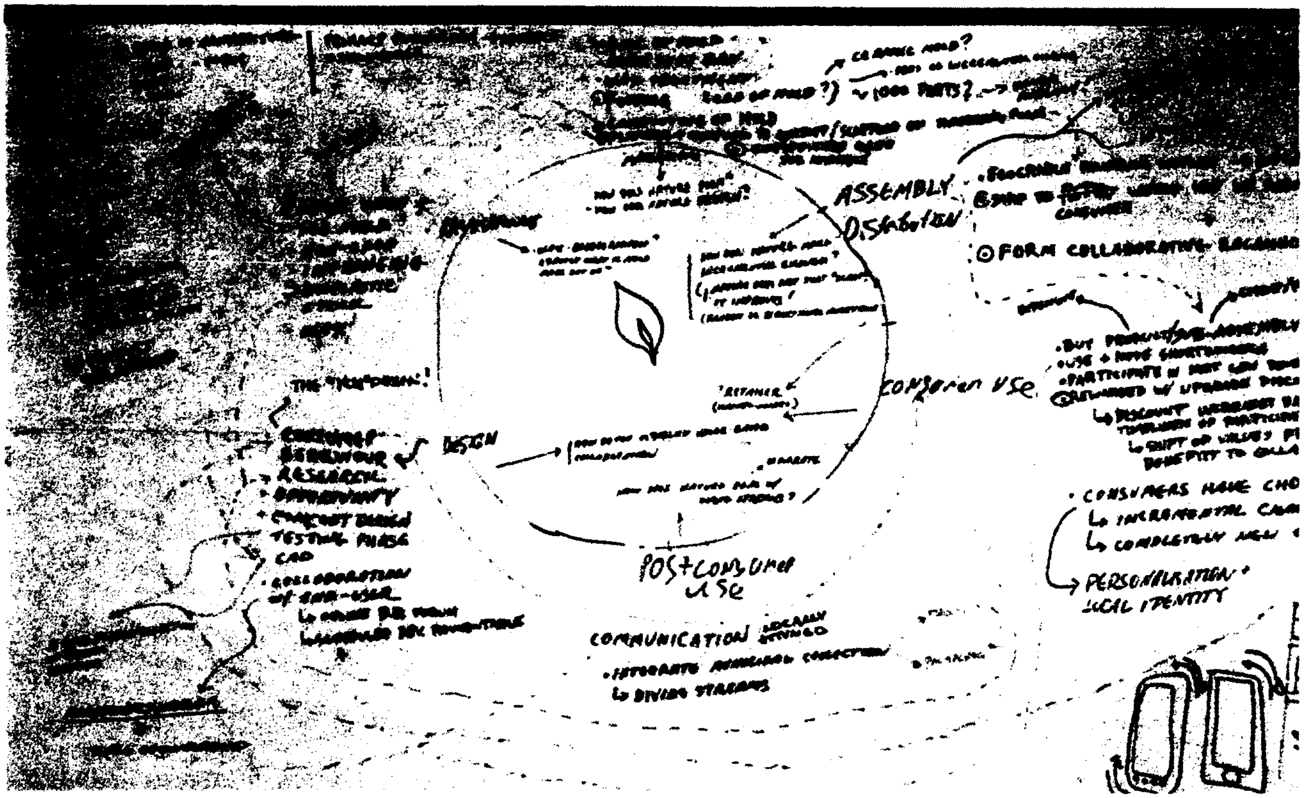


Figure 16. A rough diagram of systems design solution following the emulation of nature's strategies within the scope of the Biology-to-Design biomimicry challenge. The drawing depicts early stages of Life's Principles assessment (see Appendix B for more details).The team went further to address the system of the challenge (Iouguina, 2011).

The team then proceeded to create a solution for the City of Ottawa that included product design and manufacturing, distribution, use, feedback, and post-use in a holistic closed-loop system for all polymer-based goods.

The project followed the guidelines for Biology-to-Design methodology proposed by The Biomimicry Institute and leaned heavily on the expertise of an environmental scientist and biologists from The Biomimicry Institute, who led online sessions with the team. The final solution was titled 'Phenomold: Re-imagining the system of manufacturing', in which the challenges of form, process, and system were addressed adequately enough so that the project went on to compete internationally in the finals of the competition. Janine Benyus, the founder of the field of biomimicry, commented upon the completion of the project that the team's work with principles of the biomimicry field was "well done", confirming the team's adherence to the principles and methodology of the biomimicry field. It is also interesting to note that Janine Benyus used the phrase "biomimetic blueprints", an evidence that The Biomimicry Institute employs a use of the term biomimetics in its adjective form "to describe design that meets the definition of biomimicry", as it was later expressed by another expert in the online survey. However, Thomas Speck, an expert in biomimetics explicitly states that "biomimetics is not a blueprint from nature, but a creative transfer from biology to technics, i.e. a 'new invention' inspired by nature" (Speck & Speck, 2008).

Although most of the experts deemed the solution to be interesting and innovative, they were concerned with "generic application" of biomimicry principles and analogies being "too distant", classifying the result as "high-level" with insufficient focus on form, and is unlikely to be implemented in its entirety into the existing manufacturing system (Experts at The Biomimicry Institute, 2012).

4.3.3 Direct Observations: Case Study 2 Deductive Approach

The bionics inductive approach driven case study was conducted between January 20th and February 18th in 2012 (one month) as part of a competition for the InnoCentive Challenge sponsored by the US Department of Defense. The team was required to "submit a design or blueprint-style sketch for a transportation device that can be carried into a hostile site by a single rescuer, that is quickly unpacked to load the injured person, and used to safely evacuate an injured or deceased person away from the hostile activity and into a helicopter" (InnoCentive, 2012). The project's design brief was highly specific and driven by constraints and technical requirements, rendering it a perfect scenario for an inductive approach investigation.

The case study followed the guidelines of deductive approach proposed by the field of bionics to design a medical transportation device for combat rescue. While the example of a Biology-to-Design method described earlier concluded with a high-level solution to a challenge that provided vague design brief, this deductive case was much more explicit in terms of the desired final product. The team relied heavily on the expertise of the infantryman and industrial designers, and benefited from the knowledge supplied by a medical student and a doctor of emergency medicine. It was natural for the team to follow a deductive approach, because the educational background of designers allowed them to understand the language of a design brief and technical requirements for a proposed solution. The challenge began with researching medical stretcher systems currently in use and their shortcomings and advantages.

After several days of research, the team quickly settled on three biological prototypes that were used in the design of a final product: a lobster tail, snake muscle cords, and the coating of an intertidal fish. Individual species were further investigated if they seemed likely to provide useful information that could directly inform the designer. After evaluation, the strategies were translated into analogies, illustrated in Table 9.

Table 9. A table of biological prototypes and their translation into the language of design within the scope of bionics deductive approach (see Appendix C for more details) (Iouguina, 2013).

Biological prototypes	Function of biological prototype	Final design
Lobster tail	"All crustaceans have an exoskeleton made of the protein chitin and calcium. This external shell, in addition to being protective, gives rigid support for the attachment of the muscles. The exoskeleton is made of separate plates connected by thin membranes. This segmented exoskeleton creates joints, allowing the crustacean to move its body and appendages." – Information provided by the medical student team member	Segments of device that are protected by a hard plate and held together by flexible membrane
Snake muscle cords	"Snake musculature is very complicated, consisting of many different individual muscles and muscle cords. It is the coordinated interaction of the muscles which gives snakes their smooth gliding motion. Three pairs of long muscle cords run along the backbone, connecting the vertebrae, and these are responsible for the smooth curving of the body. There are numerous muscles on the vertebral processes, which, when contracted, bring about the tight curves or loops in the snakes body." – Information provided by the medical student team member	Allows the device to collapse and deploy
Intertidal fish	"The skin of intertidal fishes is generally tough, and so it can withstand repeated scraping against the substratum. Some of the fishes (such as blennies and clingfishes) have no scales; in others (such as gunnels and pricklebacks) the scales are greatly reduced and in still others (the gobies) they are attached very firmly. Many of the fishes secrete large amounts of mucus, which may provide lubrication in confined spaces." (AskNature.org, 2012)	System of layers that decreases friction

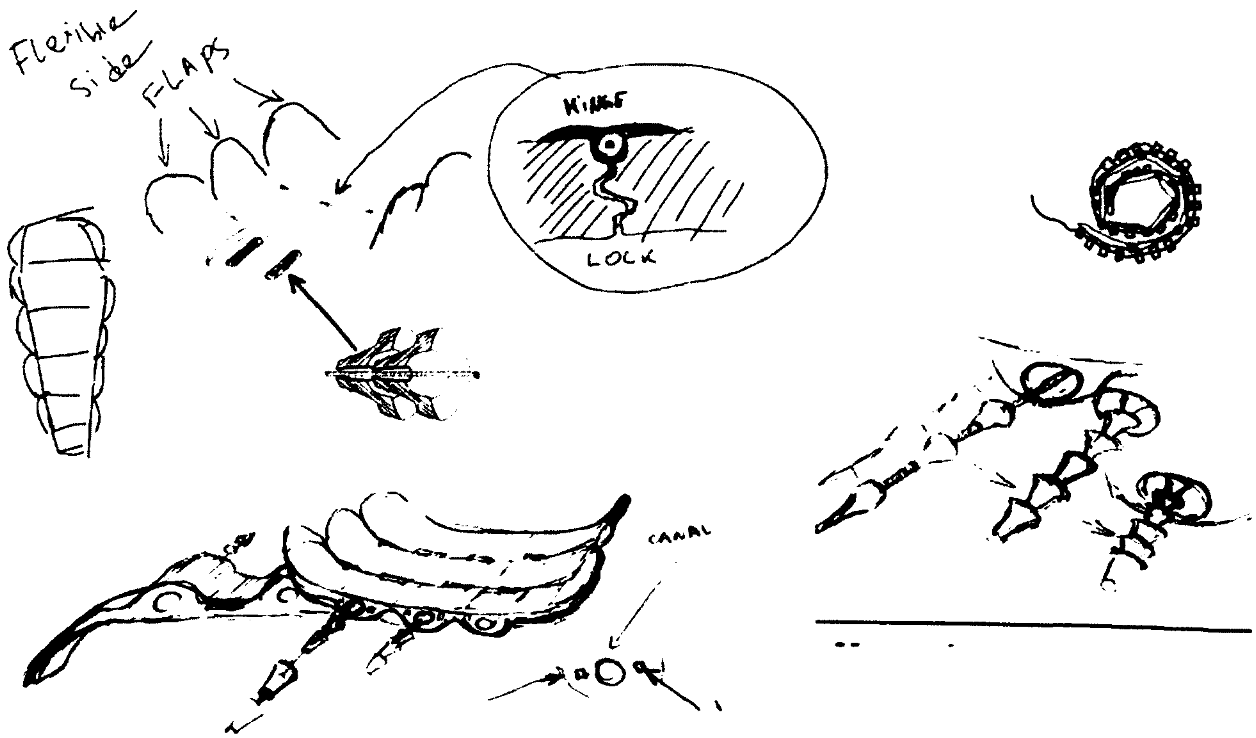


Figure 17. Medical student communicating the analogy of lobster tail plates connected by thin membranes and the subsequent brainstorming session of all team members translating the biological prototype into a design concept (Student of medicine, 2011).

As someone who was well informed in the fields of industrial design, engineering, and biology, the researcher took on the role of facilitator to bridge biological prototypes with design concepts. Industrial design students and a medical student mainly concerned themselves with various technical requirements needed for the design, including slide sheets, spinal and pelvic support, etc. Very little attention was paid to biological prototypes beyond their functionality once they had been established.

The team separated into groups. Designers focused on addressing engineering details including hinges, straps, materials, and locks while the medical student concentrated on resolving issues dealing exclusively with anatomical knowledge, including the amount of segments needed to comfortably arrange an injured person and situations dealing with amputees.

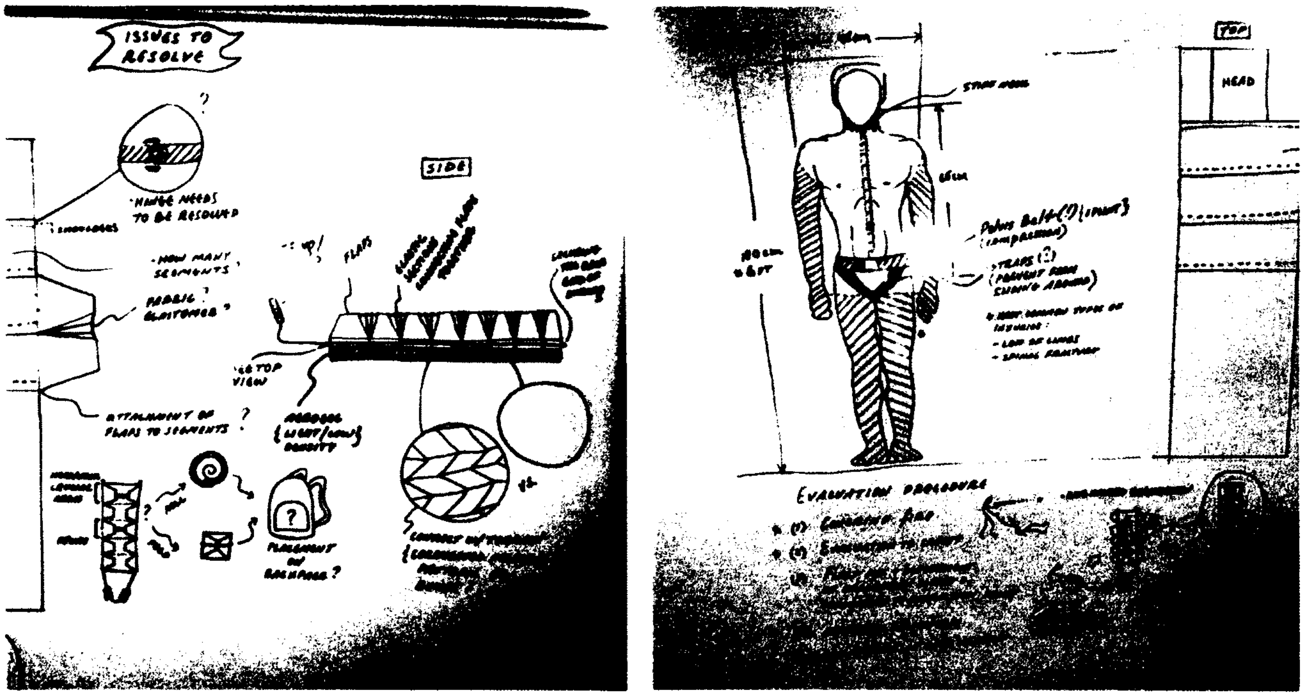


Figure 18. Diagram of translation from design brief to biological prototypes to design concept. Image on the left illustrates one example of a biological prototype that never made it into a final design (a corrugated folding pattern of Hornbeam leaves). Image on the right shows priorities chosen by the medical student (requirements for comfort of the patient) and informed by the infantryman (evacuation procedure from the line of fire) (Iouguina, 2012).

In the final stages of design the researcher conducted two interviews with an infantryman of Regular British Army and with a doctor of Emergency Medicine introduced in the previous section. The experts informed the team of any final details that were missing from the design, such as “integral pelvic splint”, “extendible distal segment”, as well as offered their opinion on the project. Although, the researcher asked for their opinion on the biological prototypes used in the design, both interviewees expressed their interest solely within the context of the final product.

Case studies allowed for investigation of practical applications of methodologies and principles of biologically informed design, namely a Biology-to-Design Design Spiral of biomimicry and a bionics-based deductive approach. The case studies have illustrated a clear divide between the two approaches supplemented by the principles of the fields, which led to two very different results.

4.4 Biomimicry driven project yields different results from bionics driven one

Using experimental case studies introduced in the previous section, this section compares a Biology-to-Design methodology originated from The Biomimicry Institute to the deductive approach proposed by The Instituto Europo di Design. Variations are explained as effects of expertise and educational background.

The author expected two major factors to affect the outcomes of projects: the methodology (deductive vs. Biology-to-Design) and the principles (bionics vs. biomimicry). Expertise would be expected to correlate with educational background and field experience. For example, industrial design students would be more familiar with deductive approach, driven by a design brief; environmental science and medical students with a Biology-to-Design method. The author began the case studies without any hypothesis as to how expertise would affect the design process – the experiment was to test about differences between bionics and biomimicry principles and methodologies.

The researcher took on the role of balancing the two methodologies depending on where the process might lead the team. Having become comfortable with establishing a design brief early on in the project, designers began with lists of requirements and limitations during both case studies. In Case Study 1, designers naturally gravitated toward establishing a challenge, despite recommendations of The Biomimicry Institute, and introduced a design brief early on in the project. In Case Study 2, one designer immediately took on a role of managing functional requirements for the project and designed the following diagram, as shown in Figure 19.

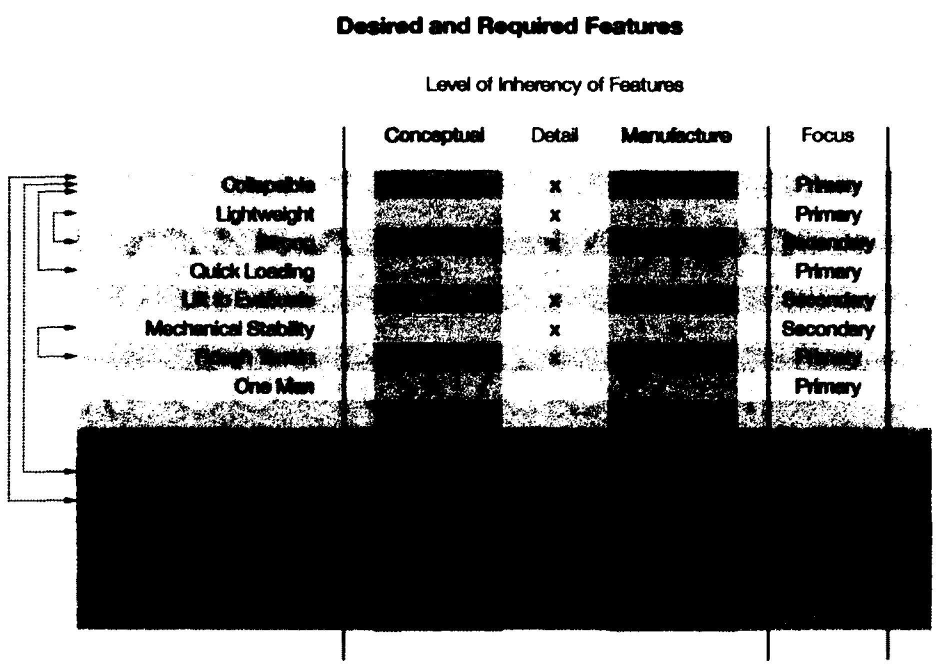


Figure 19. Industrial design student developed an illustration of design requirements for Case Study 2, prior to seeking biological prototypes (Industrial Design student, 2012).

After an unsuccessful attempt at employing a deductive method in the Case Study 1 challenge, the team was guided back by the researcher to the statement of the problem and biomimicry principles and methodologies. Although the team could have continued on the same path with successful results, it would not have been able to achieve such a high-level solution as it did, possibly concluding with the first level of biomimicry (form and function inspired by nature).

By the time the team was getting ready to clarify some questions in regarding to the project with Sherry Ritter (Biologist at the Design Table) of the Biomimicry Institute, the project manifested into an exploration and design of a holistic system for polymer product manufacturing, focusing on all levels of production, distribution, and consumer/post-consumer use.

Experts at The Biomimicry Institute expressed a clear affinity toward biology-focused questions rather than challenge-focused ones. For example, when asked "Are there any analogies to "molding" plastics in nature? That is, creating (and duplicating) form using external elements, such as in injection molding process?" the question was quickly rephrased by the expert into "How does nature manufacture polymer shapes?" This instance reminded the author of the interview with Michael Runtz, described in the previous chapter, in which communication between biology and design were hampered by the lack of common language. Such pattern of communication presents a preference by the experts at The Biomimicry Institute for Biology-to-Design method. Although, Challenge-to-Biology method also exists in the portfolio of the institute, it does not appear to be as popular with the experts, the majority of whom have a biological sciences background. Therefore, the author asserts that the latter methodology is not as well supported by The Biomimicry Institute, possibly due to the disciplinary bias rooted in the lack of understanding of how designers and engineers operate.

In Case Study 2, since the design brief was known to the members of the team from the beginning, it was only natural for the team to employ a deductive approach to the solution of the challenge. There was a lack of focus on biological prototypes, which the author attempted to mediate with no success – once the design brief was established, there was no room for inductive or Biology-to-Design approach. Instead, problem statement drove the progress of the project, while biological prototypes took on a secondary role as an inspiration for form and function. A student of medicine provided expertise within a context of requirements informed by the knowledge of human anatomy. Industrial design students took on a role as experts in technical requirements, creative conceptualization, and user-centered approach.

As mentioned in the previous section, the students settled on biological prototypes much more quickly than students in Case Study 1 did and moved on to solve technical problems. This instance reminded the author of the interview with Hans Koopman, described in the previous chapter, in which discussion of biological prototypes and existing manufacturing systems was predominantly leveraged on the technical side. This pattern of communication illustrates a strong preference by designers for a deductive or

Challenge-to-Biology approach while working on a project within a context of biologically informed design.

In the first case study, industrial designers were catalysts for pushing the project in the direction of a Challenge-to-Biology method, while an environmental scientist was more concerned with directing the project toward a Biology-to-Design approach. In the second case study, the design process was more accelerated, because both medical and industrial design students were focused on the design brief and requirements presented to the team at the beginning of the project. Discussion about the appropriateness of biological prototypes was scaled to a minimum, while addressing technical issues of the design was elevated to the highest priority. The deductive approach appeared to work well in the context of improving an already existing technical product, while it failed to inspire in the case of the biomimicry challenge. Based on new insights in biological functions, structures, processes, and systems, a Biology-to-Design methodology can be applied to a large number of problems if the principle is understood and the abstraction has been successful.

Both case studies informed the author of clear differences between practical applications of bionics and biomimicry, driven by methodologies and principles proposed by the fields of bionics, biomimetics, and biomimicry. There appears to be a need for a more active presence of designers in the field of biomimicry and a more active presence of biologists in the field of bionics, as well as a need for a mediator, who is well informed in both disciplines of biology and design. To understand the methodology of the field of biomimetics, more research needs to be conducted.

4.5 Chapter in Review

In respect to the present research, data and methodological triangulations were accomplished through collecting the data from different sources and by using multiple methods, including: online expert survey, semi-structured interviews, and direct observation to answer the research question: "How do the fields of bionics, biomimetics, and biomimicry differ from each other?"

The fields of bionics and biomimicry differ in context and objective. The researcher established through the online survey that the main difference between the fields lies in their intent. The primary purpose of bionics is to promote creative problem solving and push innovation in the industries of robotics and mechanics by mainly employing physics principles, while the goal of biomimicry is to promote a firmly grounded sense of life sustaining principles through reconnection with nature in the fields of design, business, and architecture, by employing principles of biological sciences. Thus, it can be generalized that the field of bionics is primarily dominated by functional biologists and engineers, while the field of biomimicry is more welcoming of ecologists, environmental scientists, designers, architects, and economists. The field of biomimetics was found to be the least concrete in its broad context and objective, however it differentiates itself by specializing in the materials science and its focus on mechanical capabilities.

The fields of bionics and biomimicry differ in the way of reasoning. Through the semi-structured interviews the researcher established thinking patterns in the fields of bionics and biomimicry. It was uncovered that the experts in the field of bionics – driven by engineers – employ largely a quantitative deductive approach of applying scientific knowledge and mathematical analysis to the solution of practical problems, while experts in the field of biomimicry – driven by biologists – prefer a qualitative inductive approach of observing, recording, analyzing and abstracting, before introducing a practical problem.

The fields of bionics and biomimicry differ in resulting solutions. Through observation the researcher established that biology-driven project yielded vastly different result than a design-driven one. A biology-driven project resulted in a solution firmly grounded in life sustaining principles, yet lacked real-world applicability, while a design-driven project resulted in an applicable mechanically innovative solution that lacked in sustainability focus. A biology-driven project naturally gravitated toward a combination of inductive and abductive approaches, while a design-driven project focused on a deductive approach.

As a result of these findings, the researcher was able to conclude that the field of bionics is primarily suitable for biologists and designers interested in technical complexity of projects with a focus on technological innovation, whereas the field of biomimicry is more appropriate for biologists and designers driven by nature-focused ethos and seek minimal technical complexity. Finally, the researcher confirmed that an abductive approach may be beneficial as a design tool in the field of biomimicry.

CHAPTER 5

CONCLUSIONS & SUGGESTIONS FOR FUTURE RESEARCH

5.1 Discussion of Terminology within the Fields

Using the responses from the online survey and information from the Literature Review, it became possible to answer the question "How do past and currently active experts perceive and define the fields of bionics, biomimetics, and biomimicry?" In some of the definitions presented in the survey and literature review there are indications that the applied fields of biologically informed disciplines could be considered a subclass of sustainable design. However, the term sustainable design is excessively vague, general, and cuts off applicability within the fields of biomimetics and bionics to be entirely meaningful.

It is clear that all three fields are highly interdisciplinary in nature, yet they collaborate with one unifying discipline biology. As a result of analyzing the definitions presented by experts, it became clear that the core meaning component of the overarching term that the author introduces in this thesis comprises the following structure:

Biologically Informed Discipline is: the informed interpretation of [X] in order to address [Y] for the purpose of [Z].

The common denominator for [X] is 'biological research' and for [Y] is 'human challenges', thus formulating the definition for Biologically Informed Discipline as follows:

Biologically Informed Discipline is the informed interpretation of biological research in order to address human challenges for the purpose of innovation that may or may not result in sustainable solutions.

Thus, as evident from the definitions of bionics, biomimetics, and biomimicry, one structuring factor of Biologically Informed Discipline is the end goal of finding a solution. Depending on the context of the biologically informed field and the discipline within which biological knowledge is applied (industrial design, engineering, architecture, economics, etc.), different results are produced.

5.2 Discussion of Methodology within the Fields

As a result of case studies supplemented by the Literature Review, it is now possible to answer the question "How do the fields of bionics, biomimetics, and biomimicry differ in practical application?" As discussed throughout this thesis, two fundamentally different methodologies can be distinguished in the fields of bionics, biomimetics, and biomimicry.

Although the field of biomimetics has introduced an extended top-down process and The Biomimicry Institute proposed a Design Spiral as its primary methodology, both exhibit overwhelming characteristics of deductive and inductive reasoning. Is there a place for abductive reasoning in biologically informed disciplines? Brian Burns, former Director of School of Industrial Design and present Director of Environmental Science Institute, once quoted Wim Gilles, the founder of School of Industrial Design at Carleton University:

"Design is never a proven process. It's a matter of trial and error. Eventually, you will discover if it doesn't work."

"Whether they realize it or not, designers live in Peirce's world of abduction; they actively look for new data points, challenge accepted explanations, and infer possible new worlds" (Martin, 2009). The author proposes that perhaps this is why design is a suitable discipline for bridging biology with applied sciences and arts. By posing the question "What is the process behind the end result?" it can be asserted that evolution works in precisely the same way as design.

5.3 Conclusions and suggestions for further research

Several questions about the fields of bionics, biomimetics, and biomimicry brought the author to this thesis. When the author began to study the terms used to describe the fields, she discovered that her attempt to find a general understanding of bionics, biomimetics, and biomimicry was ineffectual due to disparate definitions and general confusion dominating the field of biologically informed disciplines. Volumes of studies of historical accounts and principles of the fields of bionics, biomimetics, and biomimicry were not balanced by equally thorough research into their contemporary state, as seen through the eyes of experts researching and practicing bionics, biomimetics, and biomimicry. This thesis contributes a study of terminology through extensive reading, listening, and doing. The findings obtained through primary research (experimental case studies, an online survey of experts in the field of BID, and casual conversations with experts), in combination with secondary research findings (literature review) allow movement toward a general understanding of the differences and similarities between the fields of bionics, biomimetics, and biomimicry.

As designers begin to embrace and incorporate concepts and ideas from nature and biology, more extensive interaction between designers and biologists is inevitable. For effective communication and interdisciplinary collaboration, a common understanding of certain terms is essential. Key elements of discourse that become integral and familiar to practitioners is shaped by both history and the culture of the various disciplines. Language evolves, it is plastic, fluid, and profoundly knowledge creating. Language can also be isolating and inhibitory to interdisciplinarity when terms 'familiar' to both parties have acquired different meaning. The objective of this thesis was to critically review and research the historical and contemporary use of the terms 'bionics', biomimicry' and 'biomimetics'.

Finally, within the scope of collaboration between biologists and designers, the author suggests that the term *biologically informed design* has a potential utility, as an umbrella term, in interdisciplinary discourse. The term has a potential to embrace all the tennets of bionics, biomimetics, and biomimicry, thereby incorporating additional value from the three fields into the field of biologically informed disciplines.

BIBLIOGRAPHY

Aliseda, A. (2006). *Abductive Reasoning: Logical Investigations into Discovery and Explanation.* Springer.

Arksey, H., & Knight, P. (1999). *Interviewing for Social Scientists.* London: Sage Publications, Ltd.

AskNature.org. (2012). *Skin, Mucus Prevent Abrasion: Blennies.* Retrieved from AskNature: A Project of the Biomimicry 3.8 Institute: http://www.asknature.org/strategy/29fcad0e5fcd3fcae96d66ca3fbbfc89

Bar-Cohen, Y. (2006). Biomimetics - Using Nature to Inspire Human Innovation. *Bioinspiration and Biomimetics*, 1-12.

Bar-Cohen, Y. (2006). *Biomimetics: Biologically Inspired Technologies.* Taylor & Francis Group, LLC.

Benyus, J. (1997). *Biomimicry: Innovation Inspired by Nature.* New York: HarperCollins.

Bernard, E. E., & Kare, M. R. (Eds.). (1962). Biological Prototypes and Synthetic Systems: Proceedings of the Second Annual Bionics Symposium. New York: Plenum Press, Inc.

Biomimicry 3.8. (2011). *The Biomimicry Institute Student Design Challenge.* Retrieved from http://2011.biomimicrydesignchallenge.com/

Biomimicry 3.8. (2013). *Biomimicry 3.8: Resource Handbook.* Retrieved from Biomimicry 3.8: Two Organizations, One Canopy: http://biomimicry.net/educating/professional-training/resource-handbook/

Biomimicry 3.8. (2013, May). *Download DesignLens.* Retrieved from Biomimicry 3.8: Two organizations, one canopy: http://biomimicry.net/about/biomimicry/biomimicry-designlens/download-designlens/

Birkeland, J. (2002). *Design for Sustainability: A Sourcebook of Integrated Eco-logical Solutions.* London: Earthscan Publications Ltd.

Bonser, R. H., & Vincent, J. F. (2007). Technology trajectories, innovation, and the growth of biomimetics. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 221*, 1177-1180.

Capra, F. (2010). Ecology and Community. Center for Ecoliteracy. Retrieved February 2012, from www.ecoliteracy.org/essays/ecology-and-community

Carpenter, H. G. (1933). *Mimicry.* London: Methuen & Co. Ltd.

Cross, N. (2006). *Designerly Ways of Knowing.* London: Springer-Verlag London Ltd.

Dahl, D. W., & Moreau, P. (2002). The Influence and Value of Analogical Thinking During New Product Ideation. *Journal of Marketing Research*, 47-60.

Dario, P., Sandini, G., & Aebischer, P. (Eds.). (1991). Robots and Biological Systems: Towards a New Bionics? *Proceedings of the NATO Advanced Workshop on Robots and Biological Systems.* Springer-Verlag Berlin Heidelberg.

Decrop, A. (1999). Triangulation in Qualitative Tourism Research. *Tourism Management*, 157-161.

DeKay, M. (2011). *Integral Sustainable Design: Transformative Perspectives.* London and Washington, DC: Earthscan.

Denscombe, M. (1998). *The Good Research Guide for Small-scale Social Research Projects.* Buckingham: Open University Press.

Denzin, N. K. (1970). *The Research Act in Sociology: A Theoretical Introduction to Sociological Methods.* London: Butterworths.

Duane, P. T. (1998). *Shaping the Sierra: Nature, Culture, and Conflict in the Changing West.* Los Angeles: University of California Press.

Edmonds, E. (1994). Support for Collaborative Design: Agents and Emergence. *Communications of the ACM 37*, 41-47.

Experts at The Biomimicry Institute. (2012). Evaluation of Case Study 1. (A. Iouguina, Interviewer)

Fermanian Business & Economic Institute. (2012). *The Da Vinci Index & Biomimicry.* Retrieved from Point Loma Nazarene University: http://www.pointloma.edu/sites/default/files/filemanager/Fermanian_Business__Economic_Institute/Da_Vinci_Index_2012_Q3_final.pdf

Fillmore, C. J., & Atkins, T. S. (1992). Towards a frame-based lexicon: The semantics of {RISK} and its neighbors. In *Frames, Fields and Contrasts: New Essays in Semantics and Lexical Organization* (pp. 75-102). Hillsdale: Lawrence Erlbaum Associates.

Geselowitz, D. B. (1998). In Memoriam: Otto H. Schmitt. *Annals of Biomedical Engineering, 26*(5), 739-740.

Goddard, C. (2011). *Semantic Analysis: A Practical Introduction.* New York: Oxford University Press Inc.

Graf, F. R. (1962). *Modern Dictionary of Electronics.*

Gray, C. H. (1995). An Interview with Jack E. Steele. In *The Cyborg Handbook* (pp. 61-69). New York & London: Routledge.

Gray, D. E. (2004). *Doing Research in the Real World.* Thousand Oaks: Sage Publications Ltd.

Harkness, J. M. (2001). A lifetime of connections – Otto Herbert Schmitt, 1913–1998. *Phys. Perspect.*

Heinley, D. R. (1963). The Role of Biology in Instrumentation Industry. *American Institute of Biological Sciences Bulletin*, 35-37.

Huberman, A. M., & Miles, M. B. (1983). Drawing Valid Meaning from Qualitative Data: Some Techniques of Data Reduction and Display. *Quality and Quantity, 17*(17), 281-339.

InnoCentive. (2012, January). *Blueprint a Medical Transportation Device for Combat Rescue.* Retrieved from InnoCentive.

Jack Todd, N., & Todd, J. (1984). *Bioshelters, Ocean Arks, City Farming.* San Francisco: Sierra Club Books.

Jantsch, E. (1980). *The Self-Organizing Universe: Scientific and Human Implications of the Emerging Paradigm of Evolution.* New York: Pergamon Press.

Josephson, J. R., & Josephson, S. G. (1994). *Abductive Inference: Computation, Philosophy, Technology.* Cambridge: Cambridge University Press.

Kline, R. (2009). Where are the Cyborgs in Cybernetics? *Social Studies of Science, 39*(3), 331-362.

Koopman, H. (2011, October). Interview with Hans Koopman. (A. Iouguina, Interviewer)

Kuniavsky, M. (2003). *Observing the User Experience: A Practitioner's Guide to User Research.* Morgan Kaufmann Publishers.

Laszlo, E. (1972). *The Systems View of the World: The Natural Philosophy of New Developments in the Sciences.* New York: George Braziller.

Martin, R. (2009). *The Design of Business: Why Design Thinking is the Next Competitive Advantage.* Boston: Harvard Business Press.

Mayr, E. (2004). *What makes biology unique? Considerations on the Autonomy of a Scientific Discipline.* Cambridge: Cambridge University Press.

MBDC. (2013). *C2C Framework.* Retrieved from MBDC: http://www.mbdc.com/cradle-to-cradle/c2c-framework/

Merriam, S. B. (1998). *Qualitative Research and Case Study Applications in Education* . San Francisco: Jossey-Bass Publishers.

Miller, J. G. (1978). *Living Systems.* New York: McGraw Hill.

Mlade, J. (2005). Bio-inspired Design: Applying Nature's Genius to Buildings. Colorado State University.

Müller, A. (2007). A Brief History of the BCL: Heinz von Foerster and the Biological Computer Laboratory. In A. Müller, & K. Müller (Eds.), *An Unfinished Revolution? Heinz von Foerster and the Biological Computer Laboratory (BCL), 1958-1976* (pp. 279-302). Vienna: Edition Echoraum.

Nachtigall, W. (1997). *Vorbild Natur: Bionik-Design für Funktionelles Gestalten.* Berlin: Springer Verlag.

National Academy of Sciences. (2009). *A New Biology for the 21st Century.* Washington, D.C.: National Academies Press.

Oxford Dictionaries. (2013). *Biomimetic: Definition. Oxford Dictionaries.* Retrieved from Oxford Dictionaries: The world's most trusted dictionaries: http://oxforddictionaries.com/definition/english/biomimetic?q=biomimetic

Oxford Dictionaries. (2013). *Biomimicry: Definition. Oxford Dictionaries.* Retrieved from Oxford Dictionaries: The world's most trusted dictionaries: http://oxforddictionaries.com/definition/english/biomimicry?q=biomimicry

Oxford Dictionaries. (2013). *Bionics: Definition. Oxford Dictionaries.* Retrieved from Oxford Dictionaries: The world's most trusted dictionaries: http://oxforddictionaries.com/definition/english/bionics

Oxford Dictionaries. (2013). *Mimicry: Definition. Oxford Dictionaries.* Retrieved from Oxford Dictionaries: The World's Most Trusted Dictionaries: http://oxforddictionaries.com/definition/english/mimicry

Passino, K. M. (2005). *Biomimicry for Optimization, Control, and Automation.* Springer.

Patterson, R. (2009). Otto Schmitt's Contributions to Basic and Applied Biomedical Engineering and to the Profession. *Conference Proceedings: Annual International Conference of the IEEE Engineering in Medicine and Biology Society.*

Ritter, S. (2010, March). Biomimicry Workshop: Costa Rica. (A. Iouguina, Interviewer)

Ritter, S. (2011). Case Study 1: Biology-to-Design Methodology. (A. Iouguina, Interviewer)

Runtz, M. (2011, October). Interview with Michael Runtz. (A. Iouguina, Interviewer)

Schmitt, O. H. (1938). Cathode Ray Oscillograph for the Investigation of Nerve Action Potentials. *Journal of Scientific Instruments.*

Schmitt, O. H. (1969). Some interesting and useful biomimetic transforms. *Third International Biophysics Congress of the International Union for Pure and Applied Biophysics,* (p. 297). Cambridge.

Speck, T., & Speck, O. (2008). Process Sequences in Biomimetic Research. In C. A. Brebbia (Ed.), *Fourth International Conference on Comparing Design in Nature with Science and Engineering* (pp. 3-11). Boston: WIT Press.

Stake, R. E. (1994). Case Studies. In N. K. Denzin, & Y. S. Lincoln (Eds.), *Handbook of Qualitative Research.* CA: Sage Publications.

The Biomimicry Institute. (2010). Innovation Inspired by Nature: Biomimicry and Design. In *Biomimicry Resource Handbook: A Seed Bank of Knowledge and Best Practices.* The Biomimicry Institute.

Todd, J., & Jack Todd, N. (1993). *From Eco-Cities to Living Machines: Principles of Ecological Design.* Berkeley: North Atlantic Books.

Van der Ryn, S., & Cowan, S. (1996). *Ecological Design.* Island Press.

Vincent, J. F. (2009). Biomimetics — a review. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine,* (pp. 919-939).

Vincent, J. F., Bogatyreva, O. A., Bogatyrev, N. R., Bowyer, A., & Pahl, A.-K. (2006). Biomimetics: Its Practice and Theory. *Journal of the Royal Society Interface, 3*(9), 471-482.

Wahl, D. C. (2006). Bionics vs. Biomimicry: From Control of Nature to Sustainable Participation in Nature. In C. A. Brebbia (Ed.), *Design and Nature III: Comparing Design in Nature with Science and Engineering* (Vol. 87). WIT Press.

Wahl, D. C. (2013, February). Design Inspired by Nature: Survey on Terminology. (A. Iouguina, Interviewer)

Wehrspann, P. (2011). Biology as a Muse: Exploring the Nature of Biological Information and its Effect on Inspiration for Industrial Designers.

Wiener, N. (1948). *Cybernetics, or Communication and Control in the Animal and the Machine.* Cambridge: MIT Press.

Wiener, N. (1948). *Cybernetics, or Communication and Control in the Animal and the Machine.* Cambridge: MIT Press.

Wilson, E. O. (1984). *Biophilia: The Human Bond with Other Species.* USA.

Woese, C. R., & Fox, G. E. (1977). Phylogenetic structure of the prokaryotic domain: the primary kingdoms. *PNAS,* 4576-4579.

Yin, R. K. (2003). *Case Study Research: Design and Methods.* Thousand Oaks: Sage Publications, Inc.

GLOSSARY

Abductive Reasoning	"Is a form of inference that goes from data describing something to a hypothesis that best explains of accounts for the data. [It] is a kind of theory-forming or interpretive inference." (Josephson & Josephson, 1994)
Bioregionalism	"Is concerned with 'home' regions defined according to physical and biological interactions that describe ecosystem dynamics" (Duane, 1998)
Biophilia	"The innate tendency to focus on life and lifelike processes [...] in which instinct is aligned with reason" (Wilson, 1984)
Cradle-to-Cradle Design	Is the kind of design that embraces the following principles (MBDC, 2013): *Material Health:* Value materials as nutrients for safe, continuous cycling *Material Reutilization:* Maintain continuous flows of biological and technical nutrients *Renewable Energy:* Power all operations with 100% renewable energy *Water Stewardship:* Regard water as a precious resource *Social Fairness:* Celebrate all people and natural systems
Cybernetics	"Is a scientific study of control and communication in the animal and the machine" (Wiener, 1948)
Design	In the context of this thesis, design is a discipline that "develops innate abilities in solving real-world, ill-defined problems, sustains cognitive development in the concrete/iconic modes of cognition, and offers opportunities

	for development of a wide range of abilities in nonverbal thought and communication." (Cross, 2006)
Ecological Design	"Is any form of design that minimizes environmentally destructive impacts by integrating itself with living processes" (Van der Ryn & Cowan, 1996)
Frame Semantics	Is a subset of semantic theory, which states that "the meaning of a word can only be understood against a background frame of experience, beliefs, or practices that 'motivate the concept that the word encodes'" (Goddard, 2011)
Living Systems	Are "open biological systems rich in emergent properties [...] and endowed with capabilities such as reproduction, metabolism, replication, regulation, adaptedness, growth, and hierarchical organization" (Mayr, 2004)
Pragmatism	In connection to abductive reasoning, pragmatism is "a method of reflection with the aim at clarifying ideas and guided at all moments by the ends of the ideas it analyzes" (Aliseda, 2006)

APPENDIX A
SURVEY

How do you interpret the term 'mimicry' within the fields of biology and design?

In your professional opinion, does 'biomimicry' = 'biomimetics' = 'bionics'?

- Yes
- No

Why or why not?

In reference to the previous question.

If you could use only one of the following terms to describe the process of being inspired by nature to solve human problems, which would you use?

- bionics
- bio-inspired engineering
- biomimicry
- biologically inspired design
- biomimetics
- Other, please specify...

Making a clear distinction between the meanings of the above terms is, or could be, very useful.

- Strongly disagree
- Disagree
- Undecided
- Agree
- Strongly agree

Making a clear distinction between the meanings of the above terms is, or could be, very useful.

- Strongly disagree
- Disagree
- Undecided
- Agree
- Strongly agree

In your opinion, why should designers learn from nature?

- To practice sustainable design
- To apply to cybernetics and systems design
- To achieve technological innovation in the field of biomedical engineering
- To produce synthetic materials and products that mimic natural ones
- Other, please specify...

Which of the following best describes your educational background?

- Interdisciplinary
- Sciences
- Design and Architecture
- Engineering
- Arts and Humanities
- Other, please specify...

Which best describes your field of work?

- biomimicry
- biomimetics
- bionics
- bio-inspired engineering
- biologically inspired design
- biophilia
- Other, please specify...

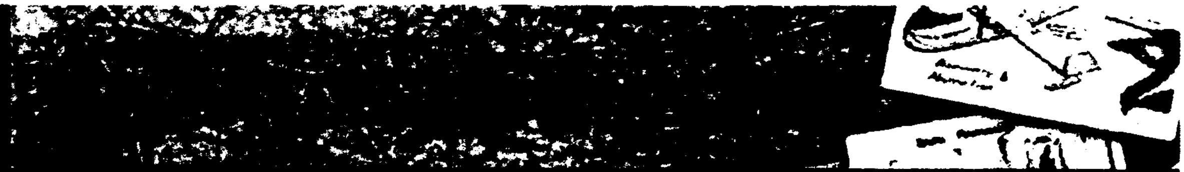
How long have you been involved in your field?

Submit

APPENDIX B

PRODUCT OF CASE STUDY 1

BIOMIMICRY 3.8



RULES & ELIGIBILITY

Eligibility

Updated 26 November 2011

1. The entry must involve a technology, product, service, or process that will reduce greenhouse gas emissions by: (1) improving energy efficiency, OR (2) improving energy storage, OR (3) reducing energy consumption within a defined system (e.g., your local transportation network or your college campus).
2. The entry must show a clear connection between a biological mechanism, process, pattern, or system, and the technological solution submitted; i.e., the solution must emulate a natural model(s).
3. Eligible teams may submit only one entry per team.
4. Entries must describe an entirely new solution. Projects within existing businesses are NOT eligible for entry.

Team Membership

1. Because this Challenge is a combination of a class (so teams can effectively apply biomimicry to their entries) and a competition, each team is required to pay a $25 registration fee. Once registered, teams will have access to a wealth of Resources from The Biomimicry Institute. Prior to registration, anyone may see the list of available resources but not the resources themselves.
2. A team must be comprised of a minimum of two individuals and a maximum of eight individuals.
3. Students are strongly encouraged to form interdisciplinary teams and to include at least one team member who is a biologist.
4. Students are eligible to participate only on a single team.
5. At the time of submission all team members must be enrolled in a degree program at a university. Team members may include Undergraduates, MBAs, MD candidates, JD candidates, other Masters candidates, PhD Candidates, and individuals in University Postdoctoral positions.
6. Students who graduated in the preceding academic year are not eligible to participate.
7. Faculty and external mentors are encouraged to serve as team advisors. Faculty may serve as advisor to more than one team.
8. Teams may designate a specific faculty mentor during the registration process. Once a team designates a faculty mentor, he or she will have access to the full Resources.
9. Each team must designate a Team Manager who will be responsible for managing the team presence online and submitting the bulk of required materials.
10. Only team members can present the team's work and answer questions from the judging panels.
11. Biomimicry Group staff and Board of Directors, Biomimicry Institute staff and board members, and members of the judging panel for the Biomimicry Student Design Challenge (BSDC) are not eligible to serve as individual team advisors. However, designated Biomimicry Institute staff will be available to answer questions and provide guidance to Challenge participants as a whole.
12. BSDC program staff reserve the right to make a final determination of a team's eligibility.

As a result of our research, it has become evident that a change on systems level in the design and manufacturing of products will yield greatly reduced carbon emissions. Our overall aim is to re-imagine product design, manufacturing, distribution, use, feedback, and post-use in a holistic closed-loop system for all polymer-based goods.

We realized that the design of a product (as represented by CAD data) is equivalent to the DNA (or genotype) of the product and the mold is the physical manifestation (or phenotype) of this information. By viewing products as organisms in their own right, we were able to envision a sustainable future for product design in general.

By expanding on Smart Mold technology researched by MIT Media Lab's *Mediated Matter* group, we cut wasteful and expensive steel tooling out of the typical polymer manufacturing process. The fact that smart molds can be driven directly from CAD with no intermediary, opens up a number of exciting possibilities for a revolution in product manufacturing:

Polymer products are currently limited by the shape of their steel mold, which has only ever changed once the profit of adapting the product outweighs the exorbitant cost of tooling a new mold. With Smart Mold technology, the form of parts can be changed on the fly, even in the middle of a production run, by simply modifying the driving CAD. This allows products to be subject to a more natural evolution: one of continuous iteration.

Also, the mold will allow parts to be formed in a series of overmolded layers, each with their own structural qualities as required. The material injected would be mixed on demand, similar to how a spider mixes silk from a variety of spinnerets or how cedar waxwing sources its materials for nest building. Each of the various material components would provide a different mechanical property, which could be fine-tuned by varying the combination ratios.

Crucial to our process is the fact that all the component materials are locally sourced, biodegradable biopolymers and additives. After the product is past its use phase, the materials are composted and returned to the material stream from which new parts are produced.

Biodegradable, breakaway packaging can be molded around parts as part of the main fabrication process. A foamed polymer could encase the part for safe transportation without the need for another external process.

We have investigated the flow of products and compost streams, energy management at the plant and in participation with the municipal programs in Ottawa area, and the user feedback cycle that allows products to become more and more appropriate with each iteration.

FIGURE 1 ■■■ MOLD DESIGN

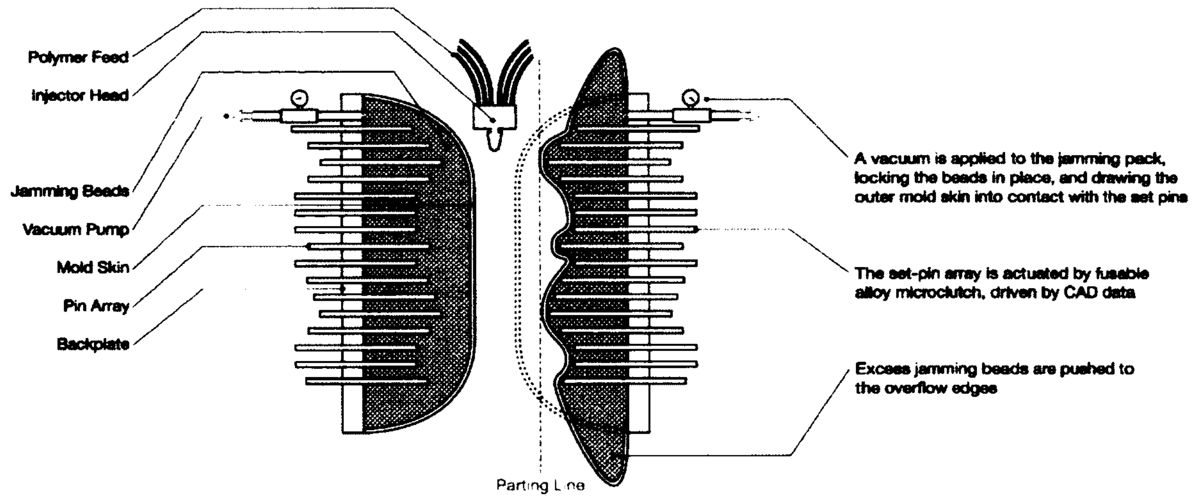
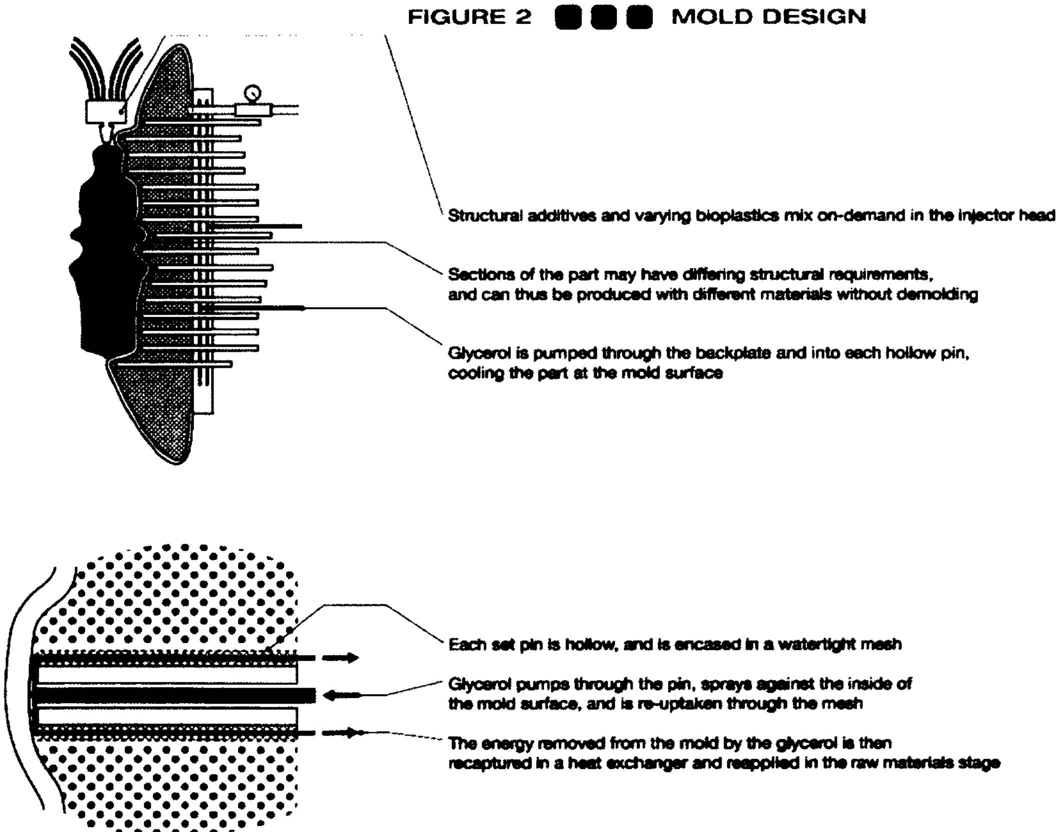


FIGURE 2 ■■■ MOLD DESIGN



ECOSYSTEM OF MANUFACTURING

LIFE CYCLE ASSESSMENT

BASIC STRUCTURE

Vascular system has been chosen to represent the LCA of manufacturing process. From perfusion of materials and energy within the manufacturing phase to a continuous flow of information between the user and the designer

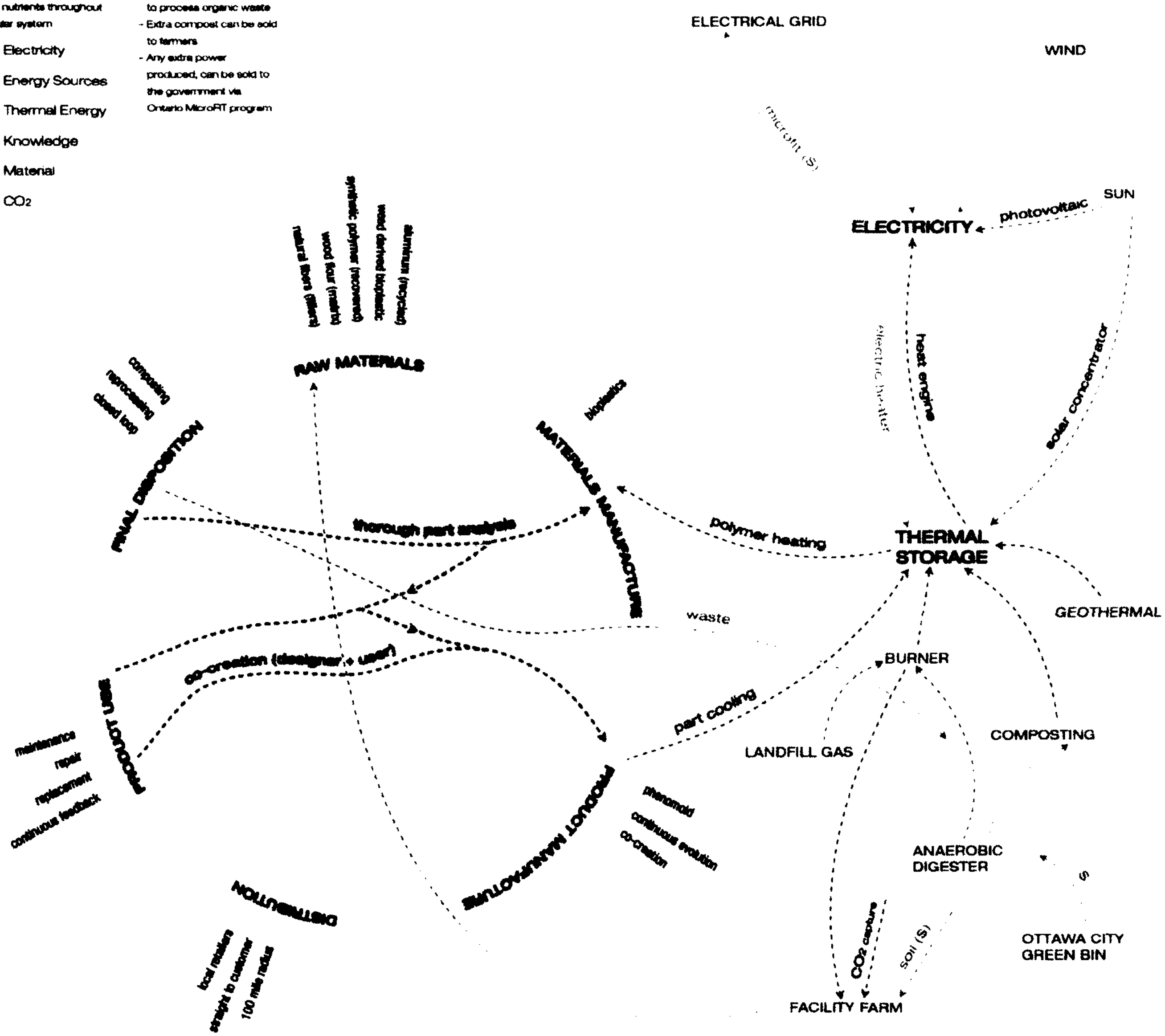
COLOURS

Each path shows the flow of particular nutrients throughout the vascular system

- - - → Electricity
- - - → Energy Sources
- - - → Thermal Energy
- - - → Knowledge
- - - → Material
- - - → CO_2

$ EXTRA INCOME

- City of Ottawa pays facility to process organic waste
- Extra compost can be sold to farmers
- Any extra power produced, can be sold to the government via Ontario MicroFIT program



NATURE LESSONS	RESEARCH LESSONS	DESIGN REQUIREMENTS
Evolve to survive	**Existing manufacturing system of polymer products is rigid and does not encourage dynamic design processes**	**Must create a dynamic manufacturing process that will allow incremental changes in design and manufacturing strategies, and encourage continuous flow of information between consumers, designers, and manufacturers**
Replicate strategies that work	Co-creation at the front end of the design process will require companies to have new attitudes and mindsets about the people formerly known as "customers" as well as broader perspectives on the meaning of "value".	Success of a designed product lies in its evolution and continuous incremental improvements. The system must employ co-creation as a strategy that will ensure a continuous connection with the end-user, and incremental innovation.
Integrate the unexpected	Existing manufacturing system does not integrate product failure into the process. Mistakes made during the design and manufacturing stages are often discovered after thousands versions of a product are already shipping around the world. This results in mass or individual product recalls, extended development stage, loss of capital.	Designer, Manufacturer, and User are closely interconnected through the "vascular" system. Mistakes must be resolved incrementally without major overhaul, as the dynamic mold allows, and as information about product malfunctions is being uploaded into a local database. This leads to a new paradigm, where mistakes are solved quickly and effectively, with minimal cost, while fostering a trust relationship with the customer.
Reshuffle information	Polymer product manufacturing does not have to be divided or limited to existing processes, such as injection molding, vacuum forming, blow-molding, etc. These processes are limited by available tooling.	The proposed system must no longer distinguish between manufacturing processes, but rather alter its state depending on the process. The reshuffling takes into account necessary mechanical properties of designed product and the shape of the mold.

NATURE LESSONS	RESEARCH LESSONS	DESIGN REQUIREMENTS
Be resource efficient	**Production of polymer products through various manufacturing processes (mainly, injection molding) is extremely widespread. However, the existing system is highly wasteful (energy and materials), globally oriented (offshore production), and relatively static (few improvements)**	**Production process must take advantage of Ottawa resources: naturally derived plants for polymer production and the most effective energy source for the geographical location. It also benefits from fostering relationships with local stakeholders**
Use multi-functional design	An opportunity to combine manufacturing processes exists within the sector of polymer products production.	Smart mold must address versatile design forms and packaging options, wooden mold incorporates texturing abilities, waste is used as energy source, mold cells are used for forming and cooling.
Use low energy processes	Raw material extraction, compounding, and transportation are phases of life cycle assessment in polymer products manufacturing that require the most energy.	The system must employ principles of low energy use by localizing production (manufacturing on demand, reduced transportation); minimizing the use of non-renewable resources; employing recycled aluminum; re-designing compounding stage to decrease energy consumption; and using waste as an energy source.
Recycle all materials	Presently, polymer products manufacturing is dominated by cradle-to-grave approach: from extraction of non-renewable resources (e.g. oil) to disconnect between the producer and the customer, leaving the end user responsible for disposal of the product.	The system must adopt a cradle-to-cradle approach: malfunctioning or end-of-useful-life products can be sent to a local manufacturing plant for parts analysis or composted in the garden. Further recycling can be achieved upon using post-consumer recycled plastics in place of virgin polymer matrices for composites. These can be obtained through collaborative relationship with local businesses.
Fit form to function	The tools and cores for injection molding are generally machined from either aluminum or tool steel. The tools are very complex parts of the process and are virtually impossible to modify, once machined.	The system must modify the shape of the mold based on need. CAD software acts as a genotype of the final product, and mold employs phenotypic plasticity in response to continually evolving design.

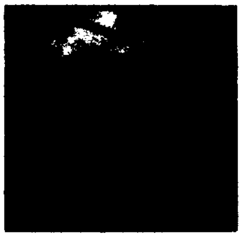
NATURE LESSONS	RESEARCH LESSONS	DESIGN REQUIREMENTS
Adapt to changing conditions	**Respond to Ottawa's present economic challenges, governmental presence (active involvement in policy making), abundance of renewable natural resources, densification of city core**	**The facility must embrace a collaborative model by actively participating in the community and cooperating with local businesses. It must reduce its dependance on oil extraction to the minimum and rely on renewable bio-resources local to Ottawa region.**
Maintain integrity through self renewal	Present system encourages passive involvement of the customer within the design process, which leads to the feeling of frustration (evidenced by DIY websites, hacker communities). Such model hinders the seamless and incremental evolution of the manufacturing sector.	The proposed system must employ a dynamic interaction between customers, designers, and manufacturers. Users have access to the facilities for tours, can send in their suggestions for improvement. The principles of operation of the facilities are transparent to the customer. Such model will allow the customers to send in their broken parts for repair, replacement, or analysis to further improve the product.
Embody resilience through variation, redundancy, and decentralization	Polymer product manufacturing model is largely operating offshore. This introduces product quality, supply chain, payment, and communication risks.	Ottawa production must be more cost effective than manufacturing overseas and eliminate the risks of offshore sourcing. Although, it should be tied into the global network, the system can establish on-demand production through decentralization and will allow for sustainable renewal of natural resources. Variation must be introduced through smart mold design, and redundancy must be employed through various information flows between producers and costumers.
Incorporate diversity	Although, diversification is taking place in the world of injection molding (as an example of polymer products manufacturing), the tooling, cores, and static temperatures and pressures within the process are limiting the innovation in the design stage. Additionally, the facilities rarely take advantage of the expertise of local producers.	The system must employ the principles of interdisciplinary approach to manufacturing, bringing in the diversity of suppliers, producers, and users to meet the design, manufacturing, and human factors criteria. The manufacturing process must accommodate the experimentation with emerging natural materials early in the product's development, and exploration of versatile markets for implementing these materials.

Integrate development with growth	**The majority of present polymer products manufacturing systems targets growth, and favours unsustainable development**	**The system must invest into renewable resources, collaborative models, cradle-to-cradle principles, localized production, and on-demand manufacturing. Finally, the design of the mold allows for growing complexity as technology permits.**
Combine modular and nested components	Although, several advancements in mold manufacturing are taking place, including retractable cores, and multishot injectors, the overall structure can be thought of as monolith.	The proposed smart mold must be composed of progressively complex layers: from a silicone cover to the selective cooling system and computer aided molding process.
Build from the bottom up	Present system does not allow for dynamic part manufacturing. The most adaptive process can be considered overmolding	The part is built layer by layer, not unlike in natural systems
Self-organize	Present system of polymer products manufacturing does not allow for dynamic interaction within the components, whether it is mold and part, or manufacturer and customer.	The proposed design of a mold will allow for continuous interaction with the part: selective cooling will allow diversely functional sections within a part (integral hinges, packaging perforation), embedded texture, overmolding. The design of the overall system will allow for dynamic interaction between the customer and manufacturer leading to continuous innovation.

NATURE LESSONS	RESEARCH LESSONS	DESIGN REQUIREMENTS
Be locally attuned and responsive	**Respond to Ottawa's present economic challenges, governmental presence (active involvement in policy making), abundance of renewable natural resources, densification of city core**	**The facility must embrace a collaborative model by actively participating in the community and cooperating with local businesses. It must reduce its dependance on oil extraction to the minimum and rely on renewable bio-resources and solar panels (manufactured in Ontario) local to Ottawa region.**
Use readily available materials and energy	Oil, virgin aluminum extraction, and steel production sectors have stated that they intent to cut back on production and expansion plans will go into conservation mode. Nearly all of Canadian steel is now owned by foreign markets, making the manufacturing of steel molds costly and inefficient.Ontario province possesses the highest number of farms in comparison to the provinces and territories, with roughly 59,728.	The facility must collaborate with local farms, sustainably harvest forests for wood (through partnership with FSC), support solar panel production through partnership with Grasshopper Solar, and wind power generation through partnership with Trillium Power Wind Corporation (Ontario is one of the leading producers of renewable wind power in Canada). Solar concentrators and geothermal, energy for heating.
Cultivate cooperative relationships	Social sustainability is at the heart of Ottawa's character. Collaborative relationships are being continually established in academic, industrial, and public sectors. One of the advantages of Ottawa is the presence of government and a strong academic base, densified city core, and closely-knit community. The opportunity for cooperation is immense.	The system must establish partnerships with renewable energy sectors, midscale farms, local businesses, organizations, waste management sector, human resources, and policy-making departments.
Leverage cyclic processes	The present polymer product manufacturing system generates discharges and waste along the entire life cycle of the product (from raw materials to final disposition).	The material and energy systems must return to their original state after completing a series of changes.The proposed system closes the loops by integrating synthetic polymers back into the cycle through scrap management, and natural polymers through composting. The design cyclic process begins with initial iteration, follows into production, analysis, and feeds back into the design phase.
Use feedback loops	The existing system employs a passive feedback loop, which delays the reaction significantly.	The proposed system actively engages all stakeholders within the information flow, increasing the effectiveness of design and manufacturing process. For example, waste management of all produced goods is integrated within the facility. This allows customers to bring/send parts in for repair and analysis, and make design decisions accordingly.

APPENDIX C

PRODUCT OF CASE STUDY 2



Blueprint a Medical Transportation Device for Combat Rescue

TAGS: Physical Sciences, Engineering/Design, Life Sciences, Tec^Edge (Air Force), Theoretical-licensing

STATUS: **Awarded** | ACTIVE SOLVERS: 1751 | POSTED: 12/28/11

Deliver a concept/design for a next-generation medical transportation device that enables a rescuer to quickly and safely transport an injured person away from an active combat site

This Challenge requires only a written proposal.

Source: InnoCentive **Challenge ID:** 9932705

Challenge Overview

This Challenge is seeking innovative designs for a transportation device that can be carried into a combat site by a single rescuer, quickly unpacked to load an injured or deceased person, and used to safely evacuate the injured or deceased person away from the combat zone and into a helicopter.

The current design is a collapsible medical stretcher that uses straps to secure the patient, but straps are too slow to deploy in the field. Any design is acceptable as long as it meets all requirements; detailed Technical Requirements are available in the full description. Key improvements over existing systems are: quick/simple loading of an injured person, ease for a single rescuer (on foot) to safely transport the injured person across difficult terrain, ability to support/stabilize the body's vital functions, and overall elegance/simplicity of the design. The Seeker expects to prototype winning designs; successful Solvers may be invited to engage in the design/prototyping process.

This is a Theoretical Challenge that requires only a written proposal to be submitted. The Challenge award will be contingent upon theoretical evaluation of the proposal by the Seeker. To receive an award, Solvers will not have to transfer their exclusive IP rights to the Seeker. Instead, they will grant to the Seeker ***non-exclusive license*** to practice their solutions.

Team **Share** **Referral: $1,500 USD**

INTRODUCTION

HexaPereon |hexa – peh – reh – on|
n. hexa- is a prefix from the Greek word for 'six' and *pereon-* is from the Greek present participle peraion, meaning to 'carry across' or 'transport'. It is the thorax or the seven metameres comprising the thorax of some crustaceans (such as a lobster).

HexaPereon is an easy to operate, collapsible, and quick loading rescue stretcher for war affected terrains. The device includes (among other features) a deployable head-and-neck and spinal support. It can also accommodate additional rescue devices such as a pelvic splint or a cervical collar (not included).

The device facilitates multiple methods of transpiration, including handling by single or multiple rescuers. It has a lift-to-evacuate system for attachment to a helicopter winch. The invention has particular advantages in a military environment as it allows for a one-man operation and requires less than 14 seconds for deployment. This lightweight, yet robust, stretcher can be operated hands-free by a single carrier. It is designed to traverse effectively through a rough terrain, while providing shock absorption and thermal insulation as well as protection for the injured. The device can be easily folded for transportation and reuse.

BACKGROUND

The introduction of Tactical Combat Casualty Care (TCCC) has improved survival of casualties in modern warfare. The TCCC consists of three stages: (1) Care Under Fire, (2) Tactical Field Care and (3) Tactical Evacuation Care. Classic TCCC includes such interventions as placement of a tourniquet and needle decompression of a pneumothorax during first or second stages of TCCC[1].The casualty transportation during first or second stage of TCCC may be critical. Use of conventional stretchers or litters is not always possible. Systems used currently are SKED® or Talon II® stretcher. These have certain limitations which are well known.

Transportation between Care Under Fire and Tactical Field Care is critical and may include hostile fire, as well as limited resources. For example Special Operations missions can include only 8 to 10 persons[2]. The TCCC Care Under Fire guideline dictates the principle of suppression of hostile fire for prevention of new casualties and additional injuries. Hence only one person may be available to initiate first aid and/or evacuation. In comparision the care by single a person to allow movement of a casualty within the Tactical Field Care will require long distance travel in a relatively safe environment. At this stage carrying of the casualty in the transportation may be plausible by few rescuers. The third stage of TCCC – Tactical Evacuation – includes a helicopter or ground transport. This has specific requirements, for example lift-to-evacuate to the helicopter.

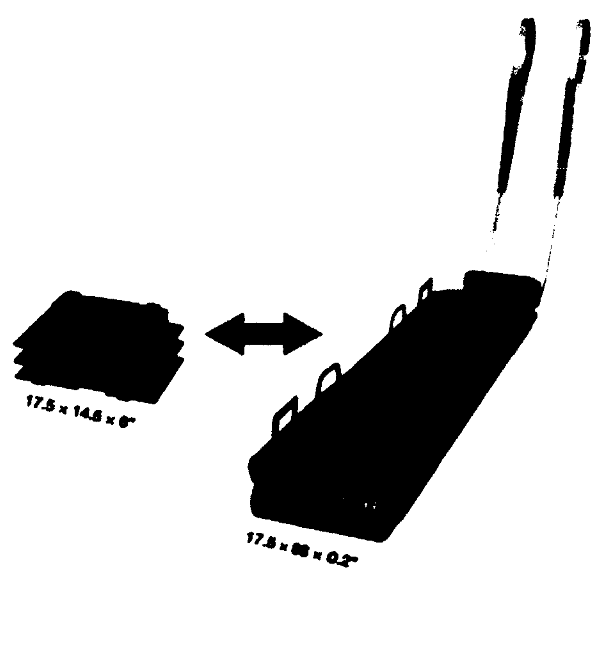
In our opinion the medical evacuation device must be deployed by one person, and serve as a universal evacuation unit through-out all three stages. Our concept has the facility to provide spinal support as well as head and neck support. This can be achieved by the integrated design features or if available additional devices (i.e. neck collar, pelvic splint). To address rough conditions our concept has certain characteristics to protect the injured, provide shock absorption and thermostasis as well as to decrease effort required from the rescuer. Bearing in mind space limitations in the military transport, the concept is collapsable and compact as well as light weight (below 8 pounds).

1. Pannell D, Brisebois R, Talbot M, Trottier V, Clement J, Garraway N, et al. Causes of Death in Canadian Forces Members Deployed to Afghanistan and Implications on Tactical Combat Casualty Care Provision. J Trauma. 2011 Nov.;71:S401–S407.
2. Butler FK, Hagmann J, Butler EG. Tactical combat casualty care in special operations. Mil Med. 1996 Aug.;161 Suppl:3–16.

HEXAPEREON

REQUIREMENTS

COLLAPSIBLE
The HexaPereon system includes a portable and collapsible stretcher bed assembly, composed of six segments that fold laterally and longitudinally into a box with dimensions: 17.5 x 14.5 x 6 inches. To deploy the device, the rescuer must pull on pulley straps until all segments lock into place and become a rigid structure with dimensions: 17.5 x 88 x 0.2 inches. The assembly collapses by releasing the locking mechanism at the base of the head segment. HexaPereon can then be attached to the soldier's backpack with straps or stored in a locker.



REQUIREMENTS

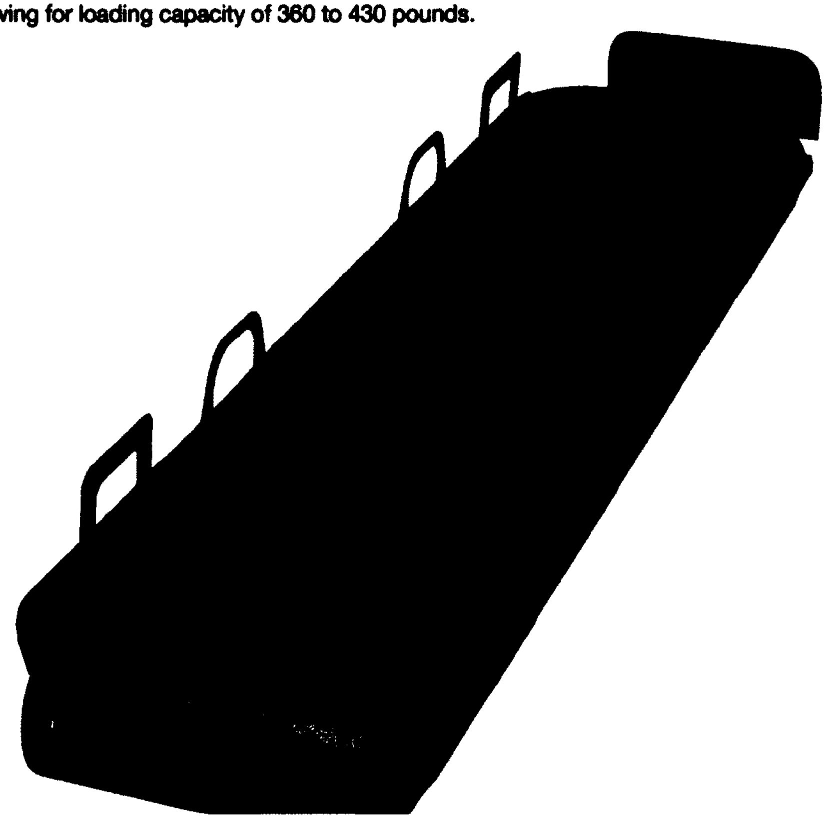
LIGHTWEIGHT

The HexaPerson system is robust, lightweight and resilient as it utilises carefully matched materials and structures.

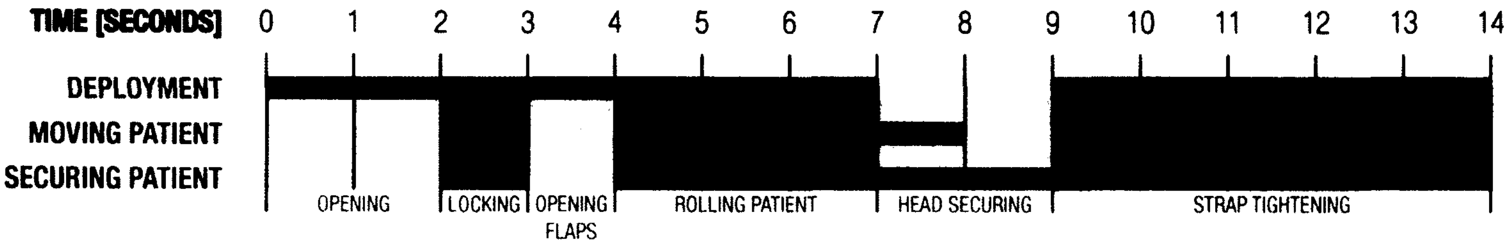
Part	Density (g/cc)	Total weight (lbs)
HDPE central segments	0.93	5.96
HDPE head-and-neck support	0.93	0.08
LDPE auxiliary flaps	0.91	1.78
Aerogel middle layer	0.0001	0.01
Pluma Vires (Cordura + aramid)	1.18	0.15
		[illegible]

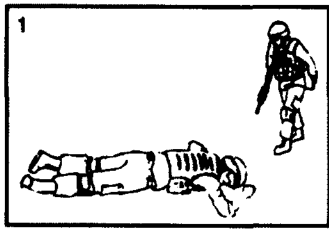
STRONG

The combination of HDPE with Pluma Vires hybrid material yields an extremely high tensile strength of the device, allowing for loading capacity of 360 to 430 pounds.

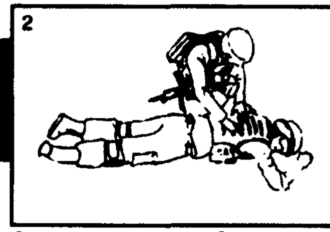


QUICK LOADING

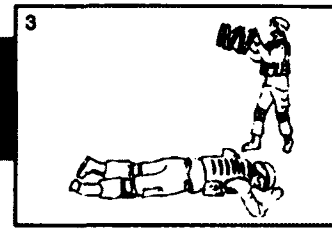




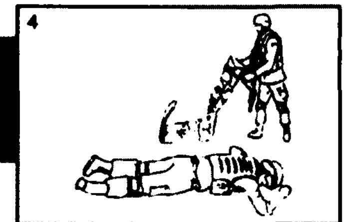
Self Aid-Buddy Aid: First aid (i.e. Application of a tourniquet)



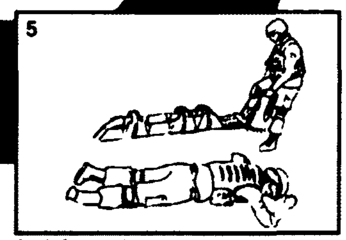
Preparation to evacuation. Collect only equipment critical for mission and patients weapon.



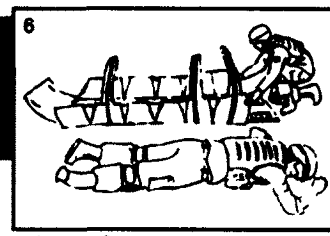
Remove HexaPerson from the cover. Deploy by holding from the sides.



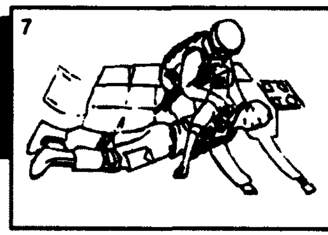
Pull the pulley st... ...ted by arrows) to ex...



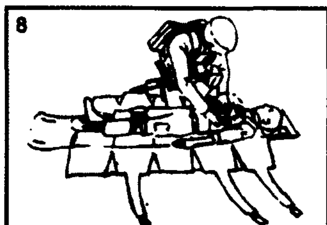
Apply force to lock in the working position. Lock the pulley straps to secure. Red line and symbol "Stop" will become v...ble.



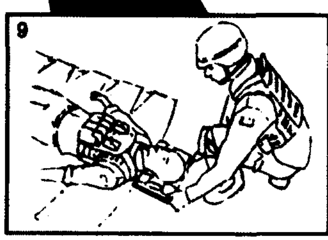
Unfold side flaps.



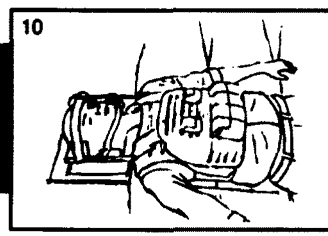
Transfer patient to HexaPerson. If other rescuers available, ask for help.



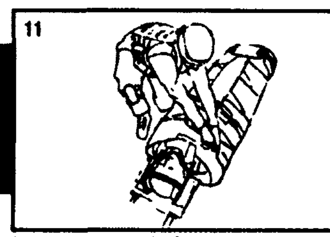
Secu... ...xaPerson (oran... ...nd waist of the patie...



Unfold the head support panels. Lift the flaps.



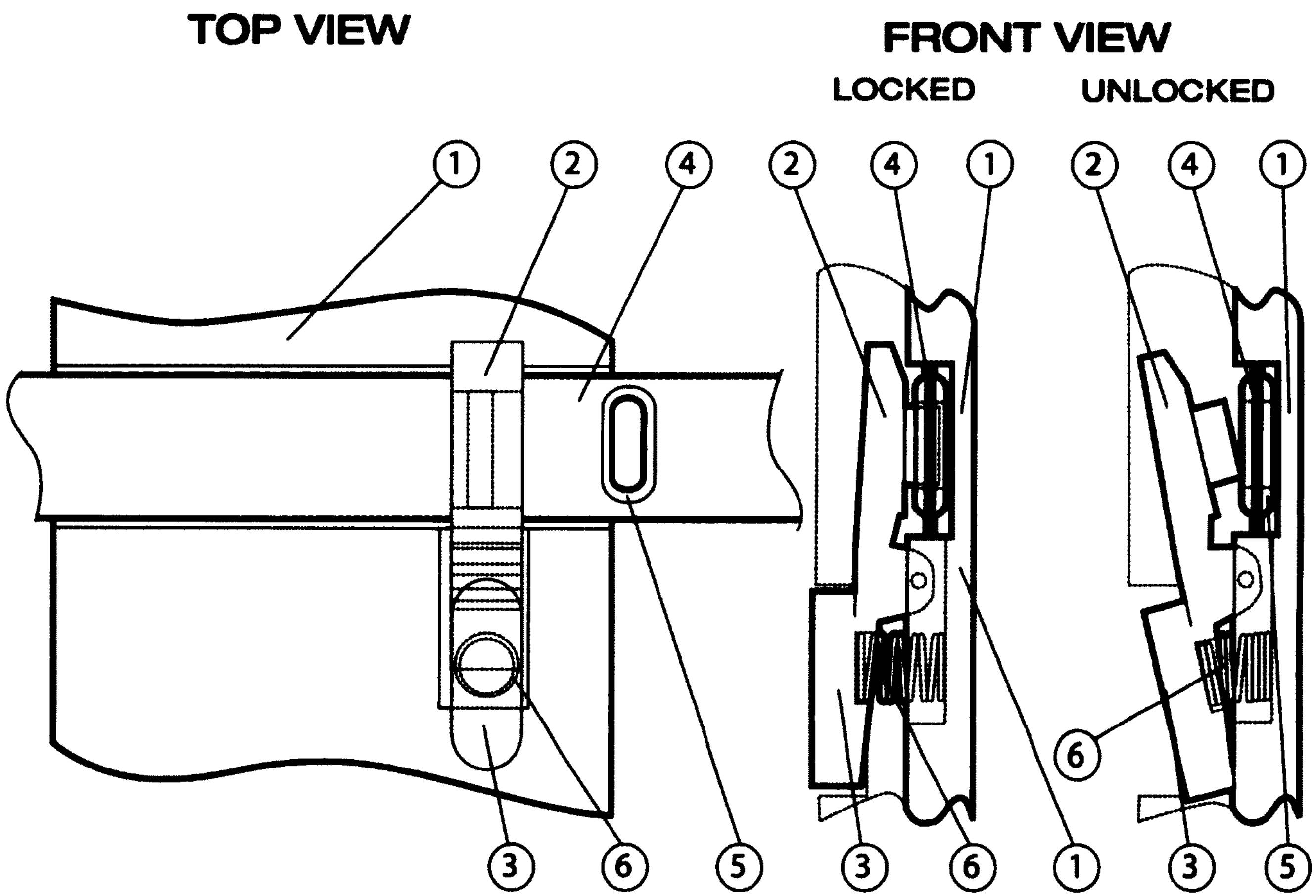
Secure the orange straps over the chin and forehead of patient firmly. Use soft flaps provided to protect the soft tissues.



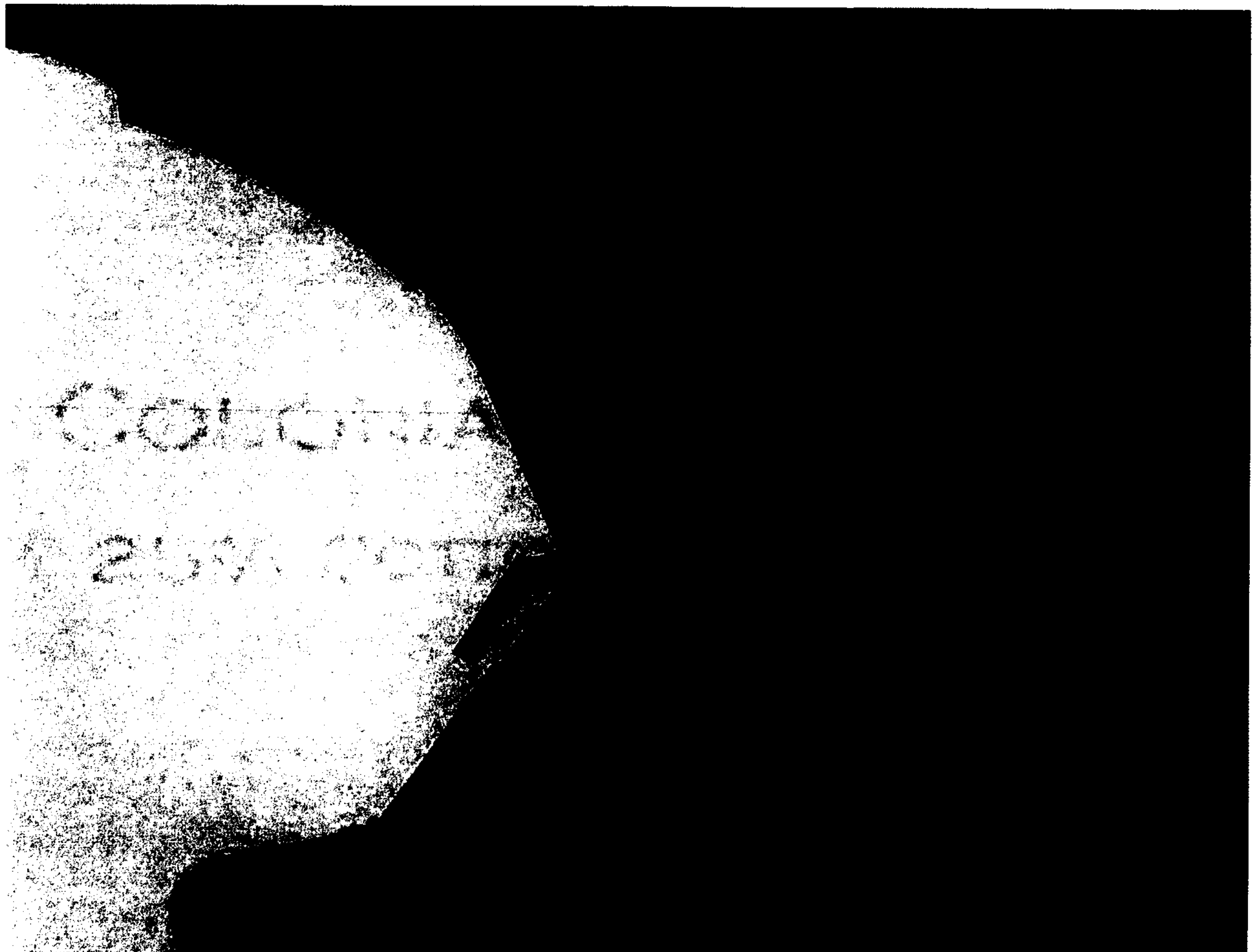
Fold the flap over the feet. Pass the feet strap through the flap and secure on the other side. Secure outer straps over the chest and over the waist.

Casualty ready for evacuation. U... ...he shoulder straps, to pull the casu...ty, or handles to carry, if more than one rescuer is available.

LOCKING MECHANISM



1. BASE
2. LEVER PORTION OF BUTTON
3. BUTTON
4. PULLING STRAP
5. METAL-REINFORCED OPENING
6. RETURN SPRING



APPENDIX D

INTERVIEWS

Question for Jill Mayer Steele

1. What is the definition of bionics according to your father?
2. What is the meaning of bionics symbol?

Questions for Michael Runtz

1. How does nature turn liquid polymer into solid structure?
2. How does nature receive/store/dispense proteins?
3. How does nature shape liquids into solids?
4. How does nature maintain purity?
5. What is the feedback loop in natural process of receiving, containing, and dispensing proteins?
6. How does nature conserve energy?
7. Who are the appropriate champion adapters for these functions?
8. Are there any analogues to "molding" in nature? That is, creating (and duplicating) form using external elements.
9. What are some examples of fast-growing organisms that have a potential to be turned into plastics?

Questions for Biologist at the Table (The Biomimicry Institute)

Design

- How does nature eliminate vestigial elements and make use of failures to improve on the next generation of structures and organisms?
- How does nature adapt its designs for locally sourced building materials?

Raw materials

- What are the most viable biodegradable biopolymer feed stocks that do not infringe on food crops?

- What minerals does the above biodegradable biopolymer feedstock need to maximize growing productivity?

Manufacturing

- How does nature make use of molds (multiple times/once, how does it reintegrate them into materials cycle)?
- Are there any analogues to "molding" in nature? That is, creating (and duplicating) form using external elements.
- In general, how does nature turn liquid into solid structures (ex. egg shell)?

Assembly

- How does nature assemble for disassembly?

Distribution

- Are there other organisms besides mycelia that act as distributors of nutrients and water on forest floor?

Consumer use

- How does nature upgrade on previous structures in the built environment and repair?

Post-consumer use

- How much separation/specialization do compost streams need to retain effective growing environments?

Questions for Hans Koopman

1. What are some latest developments in the field of injection molding, pertaining to ecological sustainability?
2. Which natural bioplastics have the most potential to have a substantial share on the polymers market?
3. Which part of injection molding process is the most energy intensive and are there any solutions on the market that address this problem? (Thermoplastic production, compounder, injection molder, etc.)
4. Are there injection molding processes that completely bypass the "compounding" stage for natural bioplastics?
5. How does pressure and temperature differ between petroleum-based and natural bioplastics during the process of injection molding?
6. Are there alternatives to steel molds on the market? If so, what advantages and drawbacks do they have?
7. What, if any, developments need to be made before desktop injection molding can be widespread?
8. In your opinion, which bioplastics stand a good chance of becoming prevalent? What qualities support this?
9. Is there such a thing as a compostable thermoset, or bioplastics that can replace silicone and other high temperature application polymers? If so, what process cures these bioplastics (e.g. heat, electrical current, exposure to oxygen, 2-part mixing)?
10. What approximate percentage of injection molded parts have large enough production runs to necessitate high-endurance molds? What's an average run volume?

Questions for Infantryman and a doctor

1. What is the process of evacuation of injured soldier from a battlefield?
2. What are the most common injuries a soldier experiences on a battlefield?
3. How does nature connect dissimilar materials or create compliant connections (relevant to collapsibility)?
4. What are the main requirements for safe transport of a patient with spine injury?