SURVEYING TRENDS IN ANALOGY-INSPIRED PRODUCT INNOVATION

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SURVEYING TRENDS IN ANALOGY-INSPIRED PRODUCT INNOVATION

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SUMMARY

Analogies play a well-noted role in innovative design. Analogical reasoning is central to the practice of design-by-analogy, and it is also the driving force behind the emerging discipline of bio-inspired design. In both practices, analogies are used to derive abstracted principles from prior examples to generate new design solutions. Design-by-analogy, or analogy-inspired design, is the subject of intense research and efforts to develop analogy methods and computational tools. These tools aim to retrieve relevant examples from distant knowledge domains – known to be a difficult task for designers – and help inspire new, creative technological solutions.

Though several analogy tools have been developed, they are not currently built on empirical knowledge of how inventors inherently use analogies in real-world practice. Such a foundation is needed for developing effective analogy-finding tools and methods. While design researchers have conducted numerous laboratory and classroom studies of analogy usage, relatively few studies have systematically examined real-world design-by-analogy to describe its characteristics and impacts. To better teach design-by-analogy and develop support tools for engineers, specific insights are needed regarding, for example, what types of advantages in innovation are gained through design-by-analogy and how different design process characteristics might influence its outcomes.

This research comprises two empirical product studies which investigate analogical inspiration in real-world design to inform the development of new analogy methods and tools. The first, an exploratory pilot study, introduces the product study method and applies several categorical variables to classify product examples. These

variables measure aspects such as the composition of the design team, the driving approach to analogical reasoning, and the achieved benefits of using the analogy-inspired concept. Additionally, the pilot study places special focus on comparing the critical functions (akin to "black box" functions) of products with those of their inspiring source analogs. With knowledge gained from the pilot study, the product study method is developed to a greater level of rigor in a second, full-scale descriptive study. The full-scale product study uses formal collection and screening methods and a refined set of classification variables to analyze examples. It adopts a cross-sectional approach, using statistical tests of association to detect relationships among variables. Combined, these surveys of real-world analogy-inspired innovation inform the development of analogy tools and provide a general account of distant analogy usage across engineering disciplines.

CHAPTER 1

INTRODUCTION

Analogies play a well-noted role in innovative design. Analogical reasoning is central to the practice of *design-by-analogy*, and it is also the driving force behind the emerging discipline of *bio-inspired design*. In both practices, analogies are used to derive abstracted principles from prior examples to generate new design solutions. Design-by-analogy, or *analogy-inspired design*, is the subject of intense research and efforts to develop analogy methods and computational tools. These tools aim to retrieve relevant examples from distant knowledge domains – known to be a difficult task for designers – and help inspire new, creative technological solutions.

Design researchers have conducted numerous laboratory and classroom studies of analogy usage; however, relatively few studies have systematically examined real-world design-by-analogy to describe its roles and impacts. Naturalistic observations of design professionals show that analogies are commonplace, being spontaneously and naturally generated to communicate and solve problems. Teaching design-by-analogy and developing support tools for engineers, however, require more specific insights, such as what types of advantages in innovation are gained through design-by-analogy and how different design process characteristics might influence its outcomes.

This thesis examines analogy-inspired product examples and their design processes through two empirical product studies. The first, an exploratory pilot study, introduces the product study method and applies several categorical variables to classify product examples. These variables measure aspects such as the composition of the design team, the driving approach to analogical reasoning, and the achieved benefits of using the analogy-inspired concept. Additionally, the pilot study places special focus on comparing the critical functions (akin to “black box” functions) of products with those of their inspiring source analogs. With knowledge gained from the pilot study, the product study method is developed to a greater level of rigor in a second, full-scale descriptive study. The full-scale product study uses formal collection and screening methods and a refined set of classification variables to analyze examples. It adopts a cross-sectional approach, using statistical tests of association to detect relationships among variables. Combined, these surveys of real-world analogy-inspired innovation inform the development of analogy tools and provide a general account of distant analogy usage across engineering disciplines.

1.1 Context and Motivation

Awareness of intensifying global competition and expanding markets for technology, combined with the advent of large-scale, complex social and ecological challenges, has increased national attention and interest in technological innovation [1-3]. Advancing technology is seen as one of several avenues for addressing major challenges, such as resource scarcity and population growth, and for gaining economic advantage and security at both corporate and national scales. As a response, engineering conceptual design research has aimed to codify and disseminate methods and approaches to make creative, compelling design concepts systematically attainable during technology development [4, 5]. The practice of design-by-analogy, or analogy-inspired design, is recognized as one approach to innovation, and it remains an area of active research in design methodology [4].

Analogy-inspired design is motivated as a discipline by numerous examples which are considered innovative. In literature, frequently-named historical examples include:

- **Wing warping in Wright brothers' airplane (1903):** In developing the breakthrough of controlled, powered flight, Wilbur Wright noticed and adapted the torsional roll control mechanism of birds, which involved creating differential lift across the two wings by increasing the pitch on one wing and decreasing it on the other. The result was the wing warping mechanism used in the 1903 *Flyer* [6].
- **Velcro® fasteners (1941):** The now ubiquitous hook-and-loop tape fastener was invented by George de Mestral after he noticed and examined the burdock seeds which clung to his clothing and his dog's fur. De Mestral adapted the structures of the hook-covered seeds and fibrous fur and clothing to develop his invention [7].

Among modern examples, well-noted cases include:

- **Lotus effect surfaces (1977):** The leaves of lotus plants stay remarkably clean due to a patterned, hydrophobic surface which allows rainwater to wash away contaminants. First characterized through electron microscopy by Wilhelm Barthlott and Nesta Ehler [8], the "lotus effect" surface has inspired several self-cleaning products and spurred interest in other specialized plant surfaces [9-14]
- **500-series Shinkansen train (1997):** The redesign of the Japanese high-speed trainset to address noise pollution was informed by observations of birds. Engineers adapted the structure of owl feathers and the shape of kingfisher beaks to redesign two sources of unwanted noise: the current-collecting pantograph and the nose of the train when entering tunnels [15, 16].

- **WhalePower wind turbine blades (2000):** Investigations of humpback whale flippers by Frank Fish revealed the stall-delaying effects of leading edge protuberances, known as tubercles. These bumpy features are being incorporated in fan and turbine blades to improve their efficiency [17-19].
- **Gecko-inspired adhesive surface (2007):** Gecko feet display a remarkable ability to attach to and detach from surfaces during climbing activity. Researchers at UC Berkeley studied and mimicked the microscopic hairs on gecko feet to produce a new reversible adhesive tape which is activated by sliding friction [20].

Considering these and other motivating examples gives rise to two overarching questions for research on analogy-inspired design:

Motivating Question #1: *What principles and characteristics describe analogical inspiration processes?*
Motivating Question #2: *How should methods and tools be developed to support analogical inspiration?*

The first question motivates descriptive research, concerned with understanding current design practice and developing theories of analogy usage in design. The second question is the theme of normative research, aimed at developing and validating new formalisms and aids for improving design practice through the use of analogies.

Descriptive research in engineering design has deepened the discussion of analogy usage, extending earlier work in psychology, cognitive science, and artificial intelligence concerning analogical reasoning in problem solving. Significantly, a particular class of analogy usage appears difficult to stimulate, namely, analogies which connect widely-separated knowledge domains. Commonly termed "distant" analogies, these are contrasted against “near” analogies which connect similar knowledge domains and are more easily stimulated. As pertains to analogy- and bio-inspired design, distant analogies have been shown to hold potential for inspiring novel solutions. A challenge thus exists to promote the use of distant analogies in the face of its apparent difficulty – a challenge which normative research addresses.

Normative research has produced several tools for retrieving relevant examples to stimulate analogical design reasoning. Many of these aids focus on biological analogies. Since much biological knowledge, as commonly recorded, is seen as intrinsically distant from engineering, many analogy tools represent biological phenomena using systematic modeling frameworks or specialized vocabularies to facilitate knowledge transfer. Other, more general analogical retrieval tools frequently operate on semantic relatedness between problem and example descriptions to determine the relevance of examples to present. While many approaches are grounded in general theories of analogical reasoning, only a few take into account real-world analogy usage practices to achieve a more holistic viewpoint for aiding analogy-inspired innovation. Real-world accounts are lacking and have been substituted, for example, by analog accounts from laboratory and classroom settings. There thus exists a need for studying and describing existing practices which have produced successful realizations of analogy-inspired design.

1.2 Research Scope

To address the motivating questions and provide an account of real-world analogy-inspired design, the following question is used to define the research scope for a pair of successive empirical product studies:

Scope-defining question:

*What **trends and relationships** exist among **design context characteristics** (such as designers' occupations and driving approaches to analogy mapping), **analogy characteristics** (such as distance, number, and source domain), and **outcome characteristics** (such as functional or performance benefits achieved) in real-world cases of analogy-inspired design?*

Aspects of analogy-inspired design processes, such as design context, analogy characteristics, and product outcomes, may have underlying relationships which can inform the development of tools and methods. For example, the benefits gained from using analogies may vary depending upon the diversity of design teams. Evaluating this relationship can motivate, or preclude, recommendations about design team composition in relation to analogy-inspired design. This question thus directs the research toward detecting trends and relationships of interest which merit further exploration.

For the pilot study, an additional research focus is defined by a second question:

Auxiliary research focus for pilot study:

*How are **critical functions** considered and used in real-world cases of analogy-inspired design?*

This question takes the assumption that certain functions in product and analog systems can be identified as critical to mapping and compares these functions between products and their analogs. In analogy tool development, functional similarity between an analog system and an intended product is taken to be a driving requirement for forming analogies. For this reason, many tools have been developed around abstracting and modeling functions in order to retrieve relevant examples based on matches. This question asks whether other modes of function use exist which are not accounted for by simple function matching.

1.3 Thesis Organization

The remaining chapters of this thesis are structured as follows: Chapter 2 reviews relevant research concerning analogy- and bio-inspired design. It also reviews prior instances of the empirical product study method and briefly discusses the cross-sectional design used in the second study in this work. Chapter 3 presents the exploratory pilot study which initially demonstrates an empirical product study of analogy-inspired products and which gives special attention to critical functionality of products and analogs. Chapter 4 presents the fully-developed cross-sectional empirical product study which expands the methods of the pilot study to survey trends in analogy usage. Chapter 5 concludes with insights gained from this research, evaluation of the work completed and its contributions, and opportunities for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Analogical Reasoning

Analogies play a significant role in human reasoning and, thus, have been intensely studied in psychology, cognitive science, and artificial intelligence [21-26]. Analogical reasoning is commonly understood to involve comparing and transferring (or, collectively, “mapping”) knowledge between a source domain and a target domain. Descriptions of analogical thought also variably include the sub-processes shown in Figure 1.

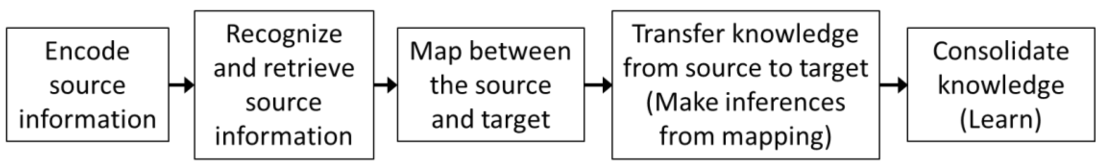

Figure 1. Steps in analogical reasoning. Adapted from [26, 27]

While competing theories have been advanced for modeling analogical reasoning in humans and computers [26, 28, 29] (notably [30-33] and [34, 35]), engineering design research has predominantly embraced the structure-mapping theory proposed by Gentner [23-25], which centers around a distinction between attributes and relationships among concepts in domains. Structure mapping theory holds that analogical comparisons have a significant number of concept relationships that can be mapped between a source and target while having few concept attributes that can be mapped. Equivalently, analogies are said to depend upon structural similarity of relationships and less upon superficial similarity of attributes. These conditions distinguish analogies (and their close relatives, abstractions) from other types of comparisons, as seen in Figure 2 and give them their explanatory power for uncovering insights about a target domain using concept relationships mapped from a source domain.

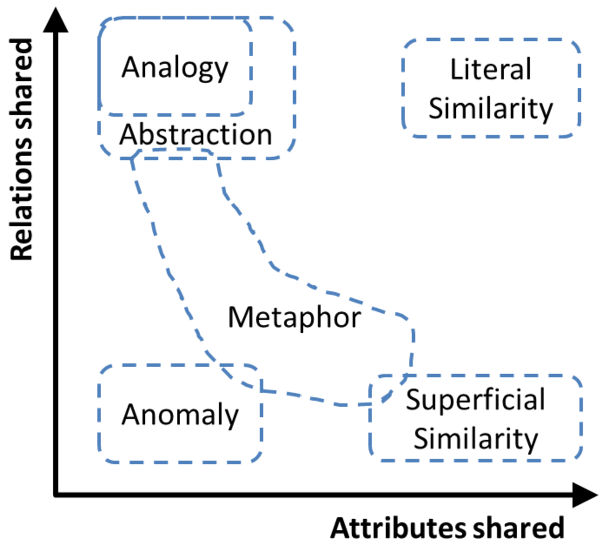

Figure 2. Classes of similarity from structure mapping theory. Adapted from[24]

2.2 Analogy-Inspired Design

In science and engineering, analogies are used extensively in gaining and refining knowledge, in formulating and solving problems, and in communicating ideas [36, 37]. Naturalistic studies of scientists, engineers, and designers have described the ubiquity of analogy usage [38-40], as well as its spontaneity [41-43] in problem-solving contexts. Despite these favorable observations, contrasting laboratory study results largely suggests that retrieving analogies from widely-disparate knowledge domains is difficult, or at least difficult to induce in experiments, in which subjects appear overly attentive to superficial rather than structural similarity [44, 45]. A challenge remains, then, to understand how structural similarities can be better communicated to induce and reinforce distant analogy retrieval.

Early work established the loosely-dichotomous characteristic of analogy distance, in which “near” analogies derive from identical or highly similar source domains relative to the target domains, while “distant” analogies derive from highly disparate source domains [36, 37]. Ward additionally distinguished two purpose types in analogy usage: explanatory, where analogies aid in understanding a target domain, and inventive, where analogies aid in creating new concepts and artifacts [36].

Particularly in engineering conceptual design, designers can benefit from inventive analogies which inspire new ideas and result in innovative products [46, 47]. Notable product examples include Velcro® fasteners, inspired by its inventor’s examination of burdock seeds [7], and the Dyson vacuum cleaner, which was inspired by its inventor’s chance observation of a sawmill dust collector [48]. Lesser-known, but still successful, examples abound and include the hunting-accident-inspired avalanche airbag [49]. These examples, and many more, motivate the investigation of analogy usage in design – a practice broadly termed *design-by-analogy* [27, 50, 51] or *analogy-inspired design*. The potential fruits of analogy-inspired design have thus sparked ongoing analogy research efforts in engineering design [52-56], architectural design [57], computational system design [58, 59], and other disciplines such as management [60].

Design research has probed for descriptions of how analogies arise during design, how they are understood and used by designers, and what their impacts on design outcomes are. Many themes in design analogy research are inherited from prior work in psychology and cognitive science. For instance, work by Moss, *et al.*, extended the work of Christensen and Schunn on the effects of timing and incubation during analogy-based problem solving [43]. Moss, *et al.* find that distant-domain information successfully inspires novel solutions when introduced after the start of problem solving, during a break, but that it is less successful when introduced before the start [55, 61, 62]. The intervening break presents an “open goal” scenario in which distant information becomes more readily accessible by designers for forming useful analogies. Another area of design analogy research concerns a particularly intriguing property of distant analogies, namely, their ability to mitigate design fixation. Design fixation entails undesirable adherence to prior sets of ideas which limits the output of conceptual design [63]. In this area, analogy research is intertwined with studies on design example usage, given that examples serve as source analogs for analogical reasoning. Experiments have revealed the dual nature of analogies with regard to fixation [64-66]. While examples which produce near analogies are likely to induce fixation, highly dissimilar examples which yield distant analogies can introduce ideas from outside the fixation set and break fixation. The latter discovery raises the question of how to best present examples to designers and thereby improve the likelihood of benefitting from them. Linsey, *et al.*, began to answer this through experiments, finding that general representations of unfamiliar examples are more accessible than domain-specific representations when solving cross-domain design problems [54].

A major theme in descriptive research has been the investigation of analogical distance and its relation to problem-solving in design. Most researchers continue the convention of casting distance as a dichotomous variable while exploring the effects of near and distant analogies on ideation. For example, ideation studies have researched in what ways presenting distant examples is more beneficial than presenting near examples [56, 67, 68]. Breaking with tradition, notable design research efforts have begun engaging in systematic quantification of distance. An early case was McAdams and Wood's distance metric based on functional similarity, which computed distances as inner products of vectors, with each vector comprising the normalized importance ratings of various functions relative to an individual design [51]. Their metric was devised to aid selection among concepts generated during design-by-analogy activity. More recent work has drawn from computational natural language processing (NLP) techniques for estimating semantic distance between words and text documents. A number of cases leverage the WordNet::Similarity tool [69] which works with WordNet [70, 71], an English language database that connects words by their parts of speech, definitions, and relationships. WordNet::Similarity offers several measures of word-to-word distance within the WordNet structure [69, 72], thus providing approximations of semantic distance. In design research, using WordNet::Similarity involves selecting concept keywords for input in the query. The resulting measures can be used to justify definitions for "distant" vis-à-vis "near" [73, 74]. Finally, Fu, *et al.*, apply a unique and powerful approach using latent semantic analysis (LSA) to determine relatedness between examples in patent documents. The LSA results are fed into Bayesian inference algorithms to generate network structures for a large set of examples, from which node-to-node distances can be calculated. [75].

Springing from descriptive research, the complementary approach of normative research has aimed to introduce and demonstrate refined techniques for analogy retrieval, mapping, and transfer in design with the goal of enhancing designer creativity and efficacy [5]. These efforts have resulted in ideation methods and computational tools for enhancing analogy-inspired design and creativity. These methods and tools are reviewed further in Section 2.2.2.

This thesis continues in the vein of descriptive research and aims to identify trends in real-world analogy usage. It does so with an eye toward advancing normative efforts to enhance analogy usage by searching for trends which may impact decisions regarding design team composition, approaches to analogy usage, and other aspects of the design process.

2.2.1 Bio-Inspired Design

A special case of analogy-inspired design has gained attention for its potential to spur innovation toward addressing significant societal challenges. Known primarily as *bio-inspired design*, it involves the use of natural systems, such as cells, organisms, and ecosystems, as source analogs for inspiring new design solutions. Related terms such as bionics, biomimicry, and biomimetic design also reflect the treatment of nature as a subject for imitation and a source of solutions to engineering problems [76-78]. Bio-inspired engineering products are diverse, ranging from structures, materials, and mechanisms, to manufacturing processes, to robotics and intelligent systems. The contrasts between natural systems and engineering systems are striking, compelling, and have been recognized and pondered throughout human civilization [6]. Personified, nature itself appears to conduct design, producing systems which operate, interact, and evolve in changing conditions and diverse environments. This character of nature, acknowledged even in historical works of innovation (such as Da Vinci's ornithopters and the Wright Brothers' *Flyer*) [6, 67], has become a renewed focus for engineers advancing the state of human design. At its core, the effort to systematically appropriate nature's "design knowledge" depends on skillful use of analogies.

As with research on general analogy usage in design, research on biological analogies also aims to describe their origins, uses, and impacts and to develop theories of bio-inspired design [46, 79]. Process models have emerged which distinguish bio-inspired design from other approaches. Student project observations by Helms, Vattam, and Goel reported two distinct approaches to biological analogy usage: problem-driven, which begins with engineering problems that are then solved by biology-inspired concepts, and the solution-driven approach, which begins with knowledge about biological phenomena and applies it to solve engineering problems [80-82]. Additionally, their work has proposed a framework, called compound analogical design, to describe how design problems and biological knowledge coevolve in the course of design work, while also accounting for the use of multiple distinct biological analogies during the process [83, 84]. Given the inherent analogical distance between biology and engineering, bio-inspired design requires either expertise in both domains or aids for translating knowledge between domains. In response, a number of tools and frameworks have emerged to make biological knowledge more accessible to engineering designers. These are reviewed further in Section 2.2.2.

Bio-inspired design publications almost invariably involve claims regarding nature's fundamental disposition toward efficient designs, citing the selection pressures experienced by biological systems over the course of evolution [76, 78, 85]. Only recently has academic research examined the variety and extent of these claims and begun to scrutinize the efficiency of bio-inspired products [86]. While it is possible for bio-inspired designs to be efficient and promote sustainability, a more pragmatic stance would argue that nature, rather than being inherently optimal or optimizing, is better seen as a rich source of ideas that have not yet been incorporated into the long progression of human innovation [87]. This benefit to creativity, for all its merits, is no guarantee of feasibility or economic viability. The challenge thus remains to consider bio-inspired design carefully and holistically [88], particularly with respect to the manufacturability and cost-effectiveness of designs [89], and to avoid naively assuming or promoting its benefits.

2.2.2 Methods and Computational Tools for Analogy Retrieval and Transfer

Several creative methods and computational tools have been developed to support analogy-inspired and bio-inspired design. Shown in Table 1, a selection of methods is discussed in a broad overview below, loosely organized by chronology and by approach to representing, retrieving, and/or evaluating information for forming analogies.

Table 1. Classification of analogy retrieval methods and tools

Analogy retrieval approaches and selected methods and tools	
Guided intuition / problem reformulation	Synectics • TRIZ-BioTRIZ • WordTree-WordTree Express
Modeling frameworks	ARGO • Idea-Inspire • DANE • Strategy Repository
Functional keyword abstraction	AskNature • Engineering-to-Biology Thesaurus
Semantic processing and similarity	BioMAPS • Visual Lexicon • Patent Structuring • Effects Knowledge Base • Unsilo (formerly BioQL)
Performance metrics	DAPPS

Early analogical reasoning methods for creativity revolved around guided intuition and problem re-formulation. Synectics is an early method developed to help diverse teams collaboratively use distant analogies to inform and solve problems [90, 91]. Introduced in 1961, the method has since fallen largely out of design research discussion.

In contrast, another long-established method, TRIZ (or, TIPS - Theory of Inventive Problem Solving), continues to be taught, promoted, and considered in design [92, 93]. TRIZ is based on a set of generalized problem-solving principles first publicized in 1956 after a decade of intermittent development in the Soviet Union [92]. It instructs problem solvers to identify important contradictions (or tradeoffs) in the problem which can then be solved using the TRIZ principles. The TRIZ approach was extended in 2002 by Vincent, *et al.*, to incorporate biological design principles in a tool known as BioTRIZ [94, 95] – the accompanying online database, however, has been unavailable since 2008 [67]. A recent method, WordTree, combines both collaborative intuition and the WordNet database to diversify the linguistic representations (particularly the functional terms) used in design problems [27]. Developed by Linsey in 2007, WordTree was later implemented in a software tool, known as WordTree Express, which automatically generates WordTree diagrams from designers' input [96, 97]. This example is indicative of the trend in analogy tool development away from traditional group-based methods and toward computer-mediated techniques, as the remaining examples below make clear.

Among computational analogy tools, a major theme has been the use of specialized modeling and representation frameworks for describing systems and phenomena. Such software tools find their heritage in knowledge-based or expert systems, such as ARGO [50], aimed at replicating human expertise and reasoning. Modern tools include the IDEA-INSPIRE tool, built around the SAPPhIRE causal modeling framework [98], the Design by Analogy to Nature Engine (DANE), built around Structure-Behavior-Function (SBF) modeling [99-102], and the Strategy Repository, built around description logics and Petri net representations [67]. While modeling frameworks provide some rigor for representing and, particularly, comparing systems, they come with significant overhead as the database builders must learn the framework and manually populate entries in the system, a tedious task which currently limits the tools' scalability. Relatedly, designers also must learn the modeling framework to use these systems, which impedes usability – this can be addressed by early familiarization of students through coursework.

WordTree and its software implementation are closely related to a class of tools centered on functional keyword abstraction. These tools prompt the designer to input keyword queries, typically verbs for functions and nouns for their objects, which express the problem or sub-problem they wish to solve, e.g., "reduce noise". These keywords are then used to search a database and return relevant examples. Notable examples include the Biomimicry 3.8 organization's AskNature database [103], and the approaches by Nagel, *et al.*, using the Engineering-to-Biology Thesaurus together with the Design Repository [104-106]. As with the modeling-based tools, these tools require manual population and curation of databases, though the task is made less demanding due to reduced formality. The AskNature database is used in the current work as a source of bio-inspired product examples for study.

An emerging class of analogy retrieval tools leverages the power of computational semantic processing to analyze existing content and infer similarity. These include Bio Search [107, 108], which can use standard biology texts as search corpuses, the visual lexicon system by Restrepo [109], which combines image recognition and WordNet-powered similarity searches to find prior design examples, and the patent-structuring algorithm by Fu, *et al.*, mentioned early in Section 2.2. The proposed Effects

Knowledge Base by Wu, *et al.* [110], would employ a functional semantic retrieval algorithm to retrieve effects (solution principles), but utilizes functional abstraction and modeling to represent effects, making it a hybrid of the tool classes discussed so far. AskNature, in partnership with company BioQL, had announced an AskNature ProSearch tool to be launched in April 2013, promising semantic retrieval from biology publications [111, 112]. However, the tool has yet to materialize, and BioQL has rebranded itself and launched its own multi-domain semantic search tool: Unsilo [113].

Finally, an analogy tool has been proposed to retrieve potentially-relevant examples based on quantitative metrics in addition to functionality. Known as the Design Analogy Performance Parameter System (DAPPS) tool, it, like the modeling- and function-based tools presented above, would require a manually populated database. However, it would encode and be able to retrieve examples based on quantitative performance metrics reported in experimental studies, particularly from integrative and comparative biology and biophysics. It is the development of the DAPPS tool that motivates the current thesis work, particularly the examination of how performance impacts are expressed for existing analogy-inspired products.

2.3 Empirical Product Studies in Design Research

Engineering design research has benefited from the inductive method of empirical product study in many instances. The method involves collecting and studying existing engineering products and, sometimes, natural systems in order to derive general principles and characteristics from specific examples. Researchers have implemented the method for examining specific classes of products such as electromechanical products [114], innovative award-winning products [115, 116], products which transform [117], flexible products [118, 119], small consumer products [120, 121], and bio-inspired products [86, 122]. Additionally, the method has been used for motivating new design guidelines [118-120, 123, 124], identifying trends in design [86], developing and validating design formalisms [114-119, 121, 125-127], and discovering promising avenues for further research and applications [120, 122]. Often, the motivation for empirical studies follows from a belief that "intrinsic principles are being used implicitly [in engineering product design] but have not been formalized for systematic and repeated use" [117]. In many cases, the research outcome is a set of comprehensive, mutually independent, and generalized design characteristics or principles for a class of products [115, 116], and in some instances, the product study method itself is developed as a tool to be used by others for obtaining design heuristics [123, 124].

Depending on the research goal, study collections range in size from less than ten products [86] to hundreds of products [121]. Researchers' interactions with the products vary from direct, physical examination and disassembly [114] to indirect study through available patents, literature, or conceptual models [117, 122, 125]. Physical examination is often required for research examining the form, arrangement, and/or structure of products and their components [114, 119], while indirect study through product literature and models has been sufficient for research on abstract design principles and properties such as the expressiveness of the Functional Basis vocabulary [125].

Compared to other methods for studying design processes, empirical product studies have the advantage of using diverse collections of completed, real-world design examples as subjects for study, rather than the small numbers of often-fictitious examples used in controlled design experiments [4]. Additionally, an empirical product study can simultaneously characterize many facets of a product class and generate multiple heuristics, compared with a handful of hypotheses tested in a controlled study. Empirical product studies do not supplant other methods but often synergize with them, for instance, when joined with controlled experiments to test product study findings [115, 116, 128], or when joined with deductive methods to expand sets of heuristics [117].

The current work comprises 2 empirical product studies, a pilot study and a second, full-scale study. Each study is concerned with a separate collection of analogy-inspired product examples, which include nature-inspired products and also products inspired by man-made systems. They focus on the design processes which produced the analogy-inspired products, leveraging an empirical product study method to survey a diverse population of real-world products. The studies, particularly the full study, are departures from prior empirical product studies which focused on product characteristics such as components, flexibility, and innovation. Instead, the current work examines *process* characteristics of analogy-inspired products, such as design context, approaches to analogy, and outcomes and aims to identify correlational patterns in those characteristics. The second study expands upon the methods in the pilot study, adopting the design of a cross-sectional study.

2.4 Cross-sectional Studies

Cross-sectional studies are descriptive, pre-experimental studies which survey numerous aspects of a wide population [129]. They are well-established across research in sociology, epidemiology, and public health [130, 131], with major examples including the decennial U.S. Census and the National Health Interview Survey [132, 133]. Cross-sectional study designs describe populations by measuring variables for a population sample at a single point in time. They can study many variables at once, revealing the prevalence of individual variables and also statistical associations between variables. However, because the measurement of explanatory (independent) and outcome (dependent) variables is simultaneous rather than sequential, causality is difficult to establish from cross-sectional studies alone. As such, they are useful primarily for identifying associations for further testing in follow-up studies.

2.5 Summary

Analogical reasoning has long attracted research interest due to its role in problem solving and creativity. Beginning in psychology, cognitive science, and artificial intelligence, the study of analogy has spread to engineering design researchers who have sought after systematic descriptions and guidelines for their use. While experimental and observational research has revealed much about the nature and effects of analogy usage in design, additional validation and new hypotheses can be gained from examining successfully-realized analogy-inspired products. Such work holds the possibility of revealing new heuristics for analogy methods and tools. Towards addressing these opportunities, two empirical product studies, a pilot study and a full-scale study, are conducted on separate collections of analogy-inspired products. These studies and their results are detailed in the remaining chapters of this thesis.

CHAPTER 3

PILOT PRODUCT STUDY – CRITICAL FUNCTIONS

3.1 Overview

A pilot study was conducted to demonstrate the empirical product study method for investigating analogy usage patterns in design. Figure **3** depicts the study process. A key assumption of the pilot study was that inventors commonly focus on critical functions when forming analogies. Analysis aimed to compare critical functions between products and their analogs and to identify how designers use these functions. The study also developed and applied 5 classification variables to study the design processes which produced the analogy-inspired products. This chapter discusses the pilot example collection, classification variables, and results of analysis.

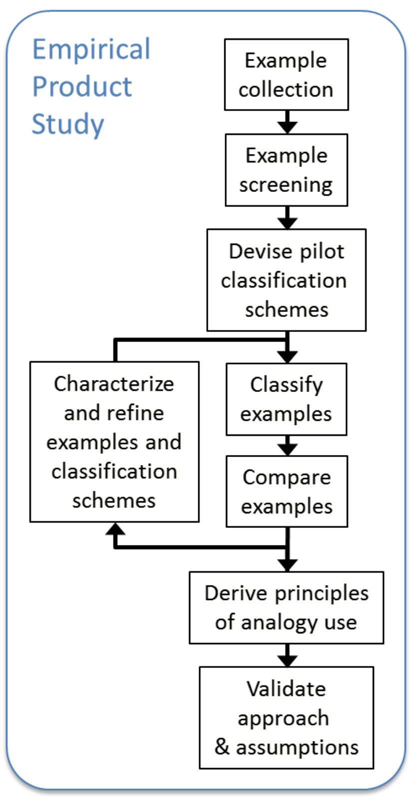

Figure 3. **Empirical product study method for analogy-inspired product examples**

3.2 Pilot Study Product Example Collection

Products studied included commercially-sold products like the Dyson vacuum cleaner [48], academic research prototypes like Caltech's nonlinear acoustic lens [134], and nascent concepts such as paint based on beetle exoskeletons [135]. The pilot product collection was non-systematically compiled prior to the study from various sources including technical reports, general reference websites such as HowStuffWorks, and news and technology magazines such as BBC News and Popular Science. This provided a broad initial collection for the pilot study which was screened to obtain a final set for analysis.

3.3 Definitions of Terms

Analogy benefit – see **Main benefit**

Analogy difference – a classification variable; a categorical scale based on the number of areas in which the product differs from the inspiring analog. The areas considered were:

- **Critical function** – see **Critical function** below
- **Construction** – the material composition and geometric form taken by the product or analog
- **Operating environment** – the environment and conditions in which the product or analog is used

Classification variable – a variable used in this study which labels examples based on characteristics of the product, the inspiring analog, or the design process which produced the product

Critical function – a classification variable; for engineered systems: a function that is essential to fulfilling the purpose or needs for which the system is designed; for natural systems/phenomena: the normal, proper physiological activity or consequence of the system [136]. In both cases, the function identification follows a method similar to that proposed in design texts regarding play-acting [137]. Future work will aim to make this definition more rigorously defined using the Functional Basis taxonomy [126].

Driving approach to analogy mapping – a classification variable for identifying what drove the use of analogies for inspiring the example product. It described the design process using following labels:

Solution-driven: proceeding from knowledge about a system/phenomenon to identify a design problem that can be solved by the knowledge

Problem-driven: proceeding from a design problem to identify a system/phenomenon which can be used to solve the problem

Main benefit (of analogy usage) – a classification variable identifying the primary contribution of the inspiring analog toward solving the design problem of the product, applying the following labels:

Function-benefit: the analog primarily displays a new mode of accomplishing a task

Performance-benefit: the analog primarily fulfills an existing task mode (function) in a better way

User-Interaction-benefit: the analog primarily presents a new mode of user interaction, e.g. to improve intuitive usage

3.4 Product Example Screening

Examples of analogy-inspired design were scrutinized using product descriptions in their source documents. Explicit mention of a design-inspiring analogy was sought within descriptions to confirm analogical inspiration. Otherwise, analogical inspiration was tentatively inferred from names or appearance. Product subsystems (e.g., the mobility system of a robot) were treated as separate examples so long as they were each inspired by a distinct analogy. In this manner, 77 tentative product examples were initially identified. Figure 4 shows a typical example from the collection.

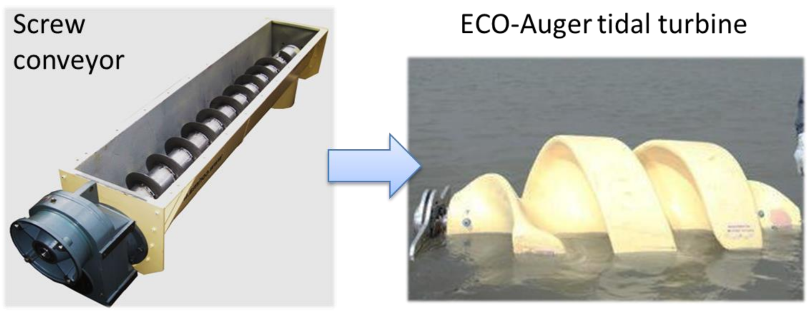

Figure 4. An example of analogy-inspired design. Screw conveyors (left) inspired a tidal turbine electrical generator (right). [138, 139]

Subsequent screening showed that 12 products did not represent analogy-inspired design – instead, for example, they merely bore a suggestive name or appearance – which led to their invalidation. Figure 5 illustrates one instance of misidentification: avalanche airbags appeared similar to car airbags, but investigation revealed that the product was inspired by a forester who survived avalanches when carrying slain hunting game that increased his volume [49]. The example was thus replaced to indicate the correct analog (forester carrying slain game).

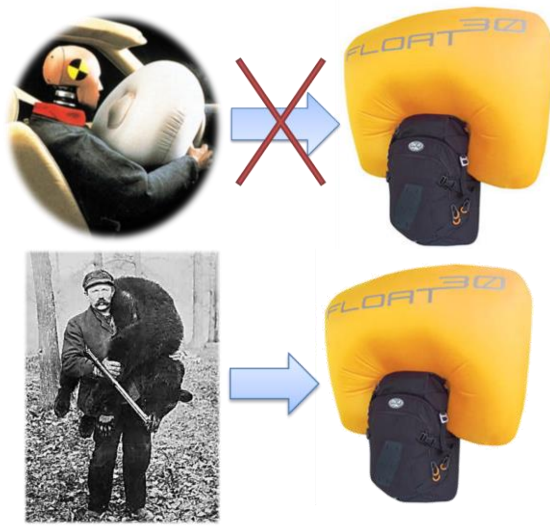

Figure 5. Avalanche airbags were thought to be inspired by car airbags (above) due to superficial similarity. Later investigation correctly identified the inspiring analog as a forester carrying slain hunting game (below) [140-142]

Screening identified another 8 examples whose sources used other analogous systems to explain a product idea but did not indicate an actual inspiring analogy. These were termed "explanatory" examples after Ward's description [36, 40], and were excluded from the final analysis and results. Example screening results are summarized in Table 2.

Table 2. Analogy example screening summary

	# of examples
Initial collection	77
Invalidated - Mistaken inference	7
Invalidated - Lack of descriptive information	5
Explanatory [36, 40]	8
Final screened collection	**57**

3.5 Pilot Classification Variables

The study centered on a matrix in which product-analog examples appeared as row entries, as shown in Figure 6. For each entry, the product and analog were recorded along with locations of source information. Classification variables, detailed below, were then devised and applied to label the examples, with labels appearing in successive columns. Some variables were used to classify only a subset of the examples before moving on to the next variable. This allowed insights to be developed across many classification variables in a relatively short time.

3.5.1 Classification variables: Critical functionality and performance

The investigation of critical functionality and performance was the basis for 6 paired variables: Product/Analog Critical Functions, Product/Analog Critical Solutions, and Product/Analog Performance Effects. Figure 6 shows a selection of typical entries. The critical functions were first identified using descriptions of the behavior of the product or analog system, yielding a black-box-like description (active verb-object noun) of the system [137]. In some instances, results were then corroborated or corrected by revisiting the product source information.

Example descriptions also identified the solution principles which fulfilled the critical functions, and solutions' performance effects. For example, the ECO-Auger tidal turbine generator in Figure 4 performed the critical function of "Convert fluid flow into rotation" which was accomplished by a plastic water screw [143]. The source description gave the performance effects as greater environmental friendliness, greater operating range of water depths, and lower manufacturing cost over similar products. Likewise, the analog system of screw conveyors performed the critical function "Convert rotation into material flow" which was accomplished by a motorized screw. Source descriptions stated that the design afforded ease of motion and mechanical advantage for moving material. These details were entered into the product matrix, as depicted in Figure 6.

Product	Analog	Product critical functions	Product critical solutions	Product performance "effect"	Analog critical functions	Analog critical solutions	Analog performance "effect"
Penguin robot mobility	**Penguin mobility**	Change hydrodynamic flow	Flexible, responsive, shape-changing head and tail	Maneuverability +X%	Change hydrodynamic flow	Flexible, muscular, shape-changing head and tail	Maneuverability +X%
Anaconda wave turbine	***Sea snake / Eel***	Convert motion into hydraulic energy	Passive, flexible, tubular body	Durability +X%, Simplicity +X%	*Impart force on liquid*	*Muscular, flexible, tubular body*	*Simplicity +X%*
Tidal current turbine screw	**Augers, screw conveyors**	Convert fluid flow into rotation	Composite water screw	Environmental friendliness +X%, Cost -X%, Operating	Convert rotation into substance flow	Screw driven by hand or by motor	Ease of motion +X%, Mechanical advantage +X%
Sharklet antibacterial film	**Shark skin**	Prevent biological material adhesion	Nanoscale-patterned film	Adhesion -X%	Prevent biological material adhesion	Nanoscale-patterned skin	Adhesion -X%

Figure 6. Product study matrix, showing examples (rows) and classification variables (columns). Italics denote explanatory examples which were excluded from analysis.

3.5.2 Classification variable: Main Benefit of Analogy Usage

A variable was devised to investigate the primary benefit analogs contributed toward inspired products. It applied the following labels to the examples:

- **Function:** the analog primarily presents a new mode of accomplishing a task
- **Performance:** the analog primarily presents a better way to accomplish an existing function

This variable aimed to uncover whether there are preferences for seeking either functional or performance benefits. Decisions between these two labels were often aided by the question "Does the analogy primarily contribute something new or something better toward product behavior?", with "new" indicating functional benefit and "better" denoting performance. A third label, User Interaction, was introduced when a set of examples failed to fit either definition of the initial two:

- **User Interaction:** the analog primarily presents a new mode of user interaction, e.g. to improve intuitive usage

Figure 7 shows a selection of labeled examples. Figure 8 shows Sharklet antibacterial film, inspired by the self-cleaning texture of shark skin and was “the first ‘surface topography' proven to [inhibit bacterial aggregation]" [144]. The shark skin contributed a new mode of repelling bacteria using surface patterning; thus, the analogy was labeled as a Function-benefit example. In contrast, the ECO-Auger tidal turbine in Figure 4 did not gain a new function mode from its inspiration. Tidal turbine technology already existed which used tidal currents to rotate a shaft [143]. The screw conveyor's helical form contributed not a new function mode but better performance by operating without harming fish [143]; thus, the analogy was labeled as a Performance-benefit example.

The Black&Decker Dustbuster in Figure 8 provides an example of a User-Interaction-benefit analogy. The Dustbuster's design was partly inspired by the Trimline phone. The form mimicked the "nesting" property of the phone handset in its charger base so that Dustbuster users would intuitively know to replace the handheld unit in its base after use [145].

Product	Analog	Main benefit of analogy	Analogy "difference"	Inventors' main field of work
Sharklet antibacterial film	**Shark skin**	Function	1 - Low	Academic
Velcro	**Hooked cocklebur seed burrs**	Function	1 - Low	Commercial
Ekco Clip'n'stay clothespin	***Animal jaw***	Performance*	1 - Low*	Commercial
Tidal current turbine screw	**Augers, screw conveyors**	Performance	2 - Middle	Commercial
Nonlinear acoustic lens	**Newton's cradle toy**	Function	2 - Middle	Academic
Cs-137 trapping material	**Venus flytrap**	Function	3 - High	Academic

Figure 7. Selected examples with classification labels. Asterisks denote explanatory examples which were excluded from analysis.

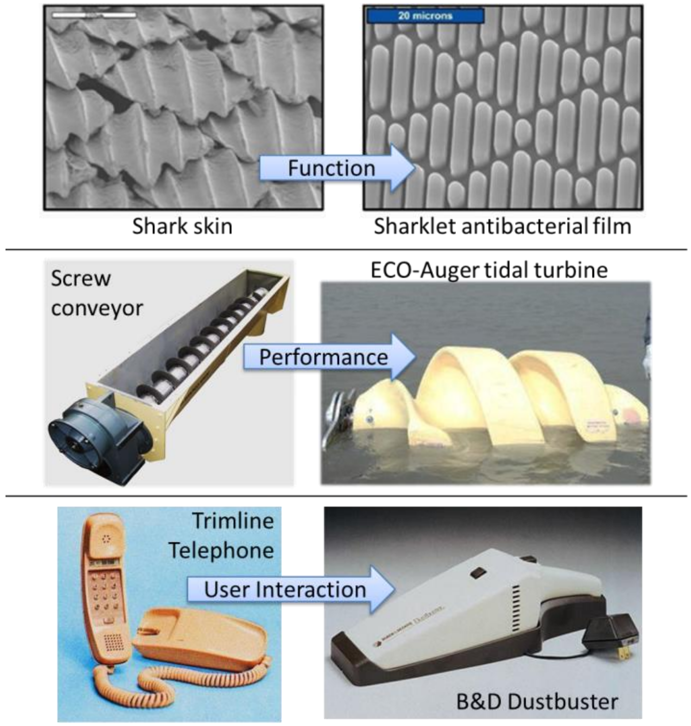

Figure 8. Examples of Function-benefit (top), Performance-benefit (middle), and Interaction-benefit (bottom) analogies [138, 139, 146-148]

3.5.3 Classification variable: Analogy Difference Level

The analogy difference variable attempted to provide a measure of distance between the product and the analog which inspired it. The variable utilized a three-level scale to compare products with their analogs in the areas of (1) critical function, (2) construction, and (3) operating environment. The variable counts the number of differing areas and assigns a level as follows:

- **Low-difference:** difference in 1 area
- **Medium-difference:** significant difference in 1 area, or difference in 2 areas
- **High-difference:** significant difference in 2 areas, or difference in 3 areas

Example frequencies were expected to decrease with increasing difference level, since the levels are estimators of how difficult it is to recognize and apply a particular analogy. Data from this variable could reveal the relationship of such difficulty with other characteristics of analogy usage, such as the inventors' field of work. Also, this variable was a step toward relating analogy usage with product innovation, since more innovative products may require accessing more difficult analogies. Example entries appear in Figure 7, while Figure 9 highlights two of these examples. Velcro® was designated Low-difference because it only differed in construction from its analog, the cocklebur seed [149]. In contrast, the molecular cesium trap was assigned High-difference because it differed significantly from its analog the Venus flytrap in construction (atoms vs. plant matter) and operating environment (chemical solution vs. open air) [150].

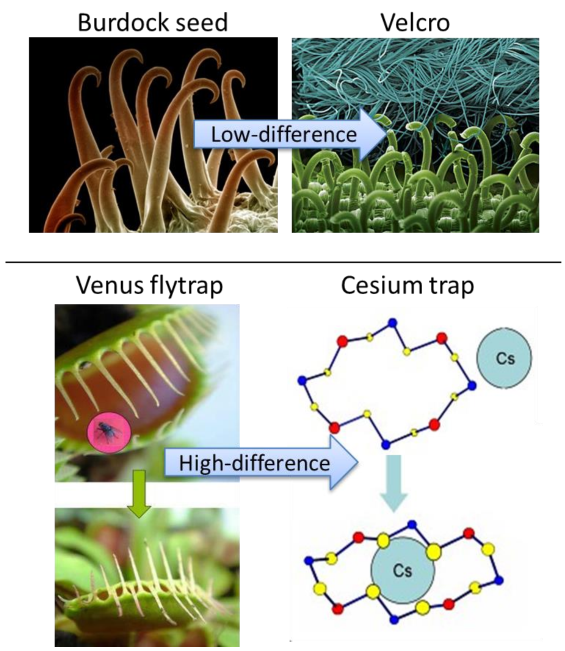

Figure 9. Examples of Low-Difference analogy (top) and High-Difference Analogy (bottom) [151-154]

3.5.4 Classification variable: Inventors' Primary Field of Work

The inventors of each product example were identified as either Academic (professors and students), Commercial (companies and entrepreneurs), or Military (laboratory researchers). They were categorized according to their primary institutions as recorded in the source. This variable aimed to help determine whether inventors engaged in different types of work differ in the way they use analogies.

3.5.5 Classification variable: Analogy Origin and Driving Approach

Another variable examined the process of how each analogy entered into the product's design process and what drove the use of analogy. It applied the following labels for driving approaches to analogy mapping:

- **Solution-driven:** Knowledge of analog system motivated discovery of problem solved by that knowledge
- **Problem-driven:** Consideration of problem motivated discovery of analog system

This variable is further explained in Figure 10 and follows the findings of Helms, *et al.* concerning two approaches in biologically inspired design which they termed problem-driven and solution-driven [81]. Figure 11 shows some examples which were explored using this variable.

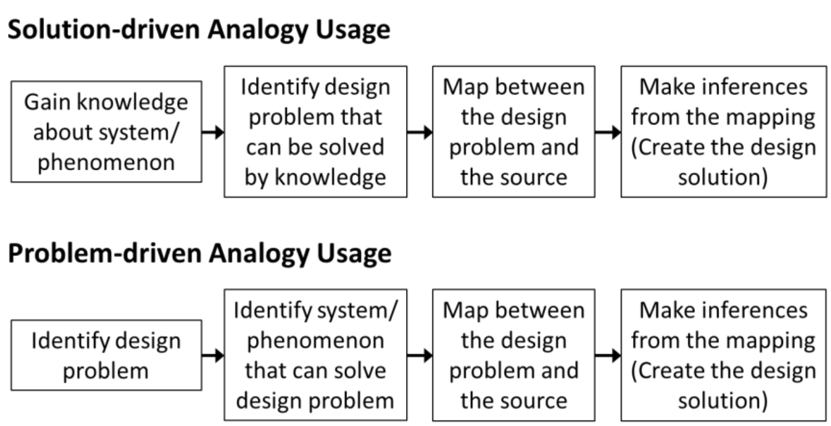

Figure 10. Driving approaches to analogy mapping

Product	Analog	Circumstances of analogy introduction	Driver of analogy
Sharklet antibacterial film	Shark skin	Observation of sharks while investigating antifouling surfaces	Problem-driven
Velcro	Hooked cocklebur seed burrs	Observed natural system following curiosity	Solution-driven
Tidal current turbine screw	Augers, screw conveyors	Applied past experience and knowledge in augers and water screws	Solution-driven
Dyson vacuum cleaner	Sawmill dust collector	Problem first identified, Serendipitous analog discovery	Problem-driven
Avalanche airbags	Carrying slain game	Serendipitous discovery of burial prevention when carrying large game	Solution-driven

Figure 11. Examples with analogy origins and driving approaches

The example of the Dyson cyclonic vacuum cleaner illustrates a problem-driven analogy application. While James Dyson considered the problem of suction loss in traditional filter bag vacuum cleaners, he made a chance observation of a sawmill dust collection cyclone. Dyson's recognition that it separated particles from air with no diminishing effectiveness was the key to an analogous solution for his vacuum cleaner design [48]. The analogy solved a problem in consideration, and thus the example was labeled as Problem-driven.

3.6 Results and Discussion

Contingency tables were used to count examples under each categorical label, summarize results, and analyze analogy characteristics. Analysis yielded four patterns of analogy usage, demonstrating the basic effectiveness of the product study method:

1) Inventors commonly directly transfer critical functions from analog systems to use in their products. Direct transfer occurs between one or two critical functions.

2) Inventors can invert critical functions found in analog systems when adapting solutions for their products.
3) Academic inventors and commercial inventors differ in analogy type usage.
4) Driving approach to analogy mapping affects analogy usage behavior.

Each of these patterns is described further in the following sections.

Table 3. Pilot study classification summary

Classification variables and labels	# of examples
Critical Function Matching	
Identical - One critical function	17
Identical - Two critical functions	4
Different - Inverted	1
Different - Other	2
Total	**24**
Analogy Benefit	
Function	30
Performance	24
Interaction	3
Total	**57**
Analogy Difference Level	
Level 1 – Low-difference	47
Level 2 – Medium-difference	9
Level 3 – High-difference	1
Total	**57**
Inventors' Field of Work	
Academic	32
Commercial	24
Military Research	1
Total	**57**
Driving Approach to Analogy Mapping	
Solution-driven	9
Problem-driven	4
Total	**13**

3.6.1 Pattern #1: Critical function direct transfer

In total, 28 pairs of product and analog critical functions were identified for 24 different analogy examples. Table 3 summarizes the results. 17 analogy examples showed matching in one critical function pair and 4 examples displayed matching in two pairs. Together, these comprise 25 pairs out of 28. The remaining 3 pairs showed different critical functions between the product and analog, with one of these showing an interesting inversion between the functions.

Figure 12 depicts these pair types. The Sharklet antibacterial film described earlier shows a typical case of having the same critical function as its shark skin inspiration: "Prevent material adhesion". In contrast, the Caltech nonlinear acoustic lens prototype has a different critical function from the Newton's cradle toy which inspired it [155]. The lens "conditions acoustic energy" to produce a focused solitary wave in the target medium, whereas the cradle toy "transmits kinetic energy" between its spheres while operating [155]. This suggests that structural features other than function are being used for analogical transfer.

The results suggest that it is common for designers to directly transfer the critical function of the inspiring analog to their product solution. Thus, a key step in design-by-analogy could be recognizing an analog system’s critical function(s) as relevant for solving a design problem. This is not surprising given the importance of function in design as described by many engineering design texts [90, 137], and the fact that several current analogy retrieval systems are based on functional specification [98, 99, 103].

3.6.2 Pattern #2: Critical function inversion

As mentioned above, the study also revealed the interesting mode of inverted function transfer, whereby inventors reverse the sense of the critical function in the analog before applying it to their design. In the tidal turbine example discussed earlier and shown again in Figure 12, the inventor reversed the critical function “Convert rotation to material flow” in screw conveyors to introduce the function “Convert fluid flow to rotation” in his tidal turbine [143]. Upon examination of remaining examples, another inverted conversion between energy and motion was found. Shown in Figure 13, wind turbine blades inspired by whale flippers show a reversal from fins which "convert mechanical motion to fluid flow" for propulsion and maneuvering to blades which "convert fluid flow to mechanical motion" to turn a generator [17].

Invertible conversions like these may provide a potent source of analogies for design. Further investigation would likely reveal additional real-world instances of inverted function transfer.

Identifying this mode of analogy usage offers an additional degree of freedom for configuring computational analogy retrieval. If a designer specifies an invertible critical function to a computational analogy tool, the tool could invert the specified function and retrieve additional examples for potential inspiration.

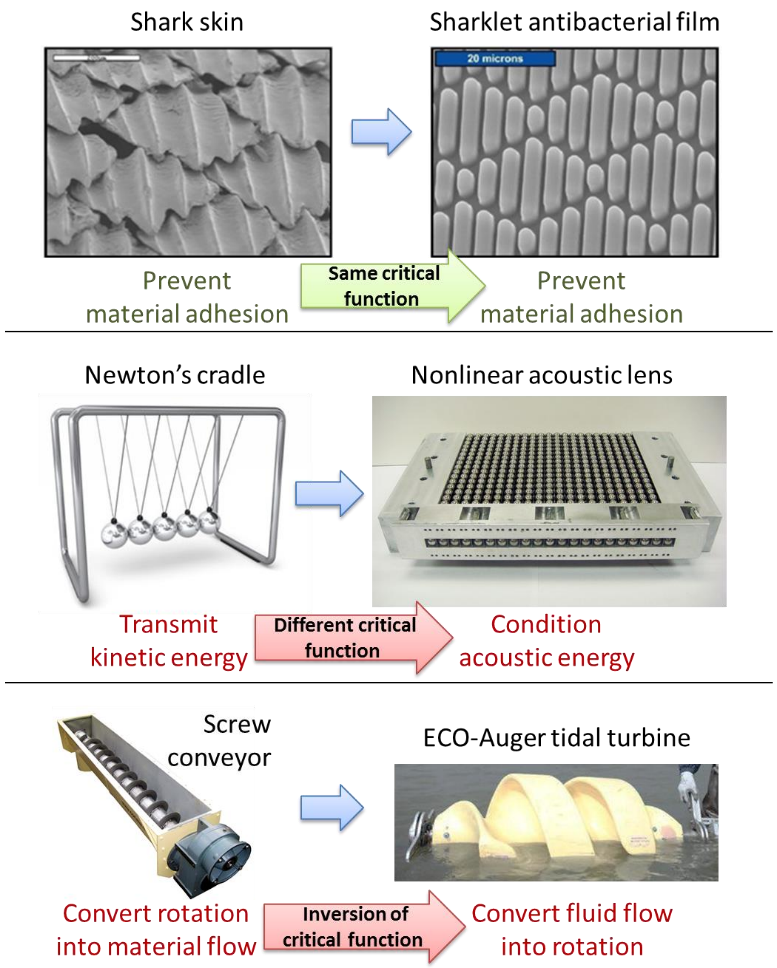

Figure 12. Examples of critical function direct transfer (top), difference (middle), and inverted transfer (bottom) [134, 138, 139, 148, 156]

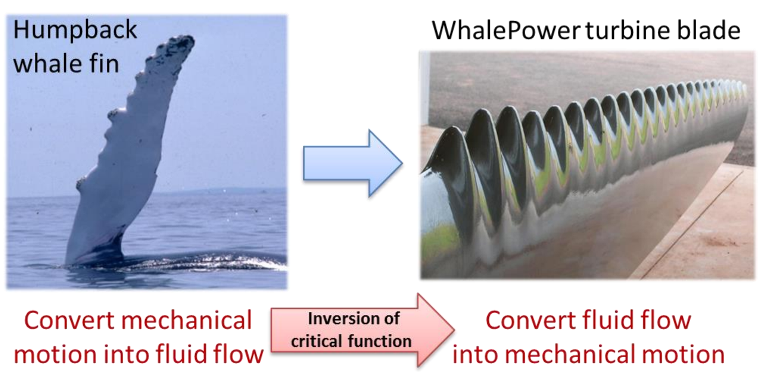

Figure 13. Critical function inversion in whale-inspired wind turbine blade example [17, 157, 158]

3.6.3 Pattern #3: Field-dependent analogy usage

Contingency tables revealed distinct patterns in analogy characteristics when sorted by the inventors' field of work, which supports the idea that analogy usage behavior is domain-dependent. This agrees with Christensen and Schunn's finding that analogy usage patterns are field-dependent, distinguishing engineers from scientists [40]. They found that engineering designers use more cross-domain analogies whereas prior studies found that scientists used mostly within-domain.

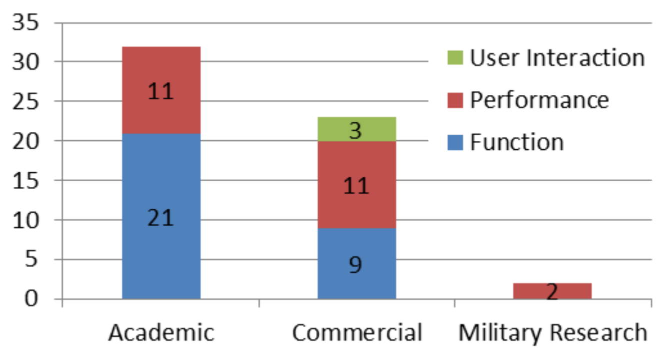

Figure 14. Comparison of analogy benefit types across different fields

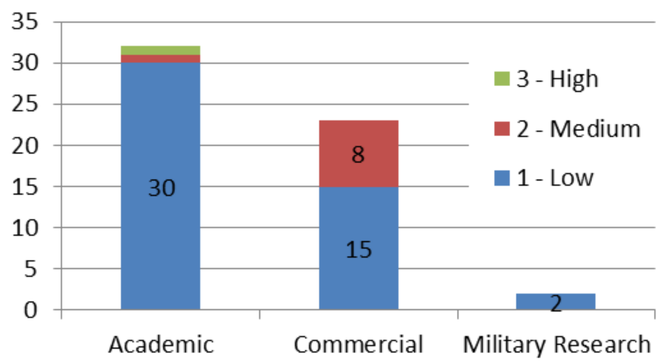

Figure 15. Comparison of analogy difference levels across different fields

Figure 14 shows a clear dominance of Function-benefit analogies over Performance-benefit analogies for academic inventors (21 examples vs. 11), together with a weak dominance of Performance-benefit over Function-benefit for commercial inventors (11 vs. 9). This pattern suggests that academic inventors more commonly recognize potential analogies by their useful or novel functional principles. In contrast, commercial inventors have more balanced tendencies, being only slightly more likely to recognize the performance improvements that analogies provide in achieving existing functions.

A second pattern appears in Figure 15. Academic inventors heavily use analogies of Low-difference (30 of 32 examples). In contrast, commercial inventors use a higher proportion of Medium-difference analogies (8 of 23).

This finding supports the incorporation of analogy benefit and difference level in an analogy retrieval tool. First, by having designers clarify the desired analogy benefit, the tool can rank examples differently according to their analogy benefit characteristics (functions, performance effects, user interactions) in order to best convey their potential relevance to the design problem. Second, using analogy difference level as a metric provides more information for filtering the examples presented to the designer.

3.6.4 Pattern #4: Potential effects of driving approach

For a small number of examples, the study investigated the approach taken for analogy mapping. Examining the design processes of 13 products found that all could be characterized as either solution-driven or problem-driven, with solution-driven processes outnumbering problem-driven processes (9 vs. 4).

Table 4. Driving approaches vs. other characteristics

	Field of Work		
Driving Approach	Academic	Commercial	Military
Solution-driven	5	4	
Problem-driven	1	3	
	Analogy Benefit		
Driving Approach	Function	Performance	User Interaction
Solution-driven	5	4	
Problem-driven	3	1	
	Analogy Difference Level		
Driving Approach	1- Low	2- Medium	3- High
Solution-driven	6	3	
Problem-driven	3	1	

Table 4 gives the data comparing driving approach with other characteristics. Some suggestive patterns emerge in the data, from which three preliminary insights are formed:

- Academic inventors may take solution-driven approaches more often when using analogies (5 of 6), while commercial inventors may be more balanced between solution-driven and problem-driven approaches (4 vs. 3).
- Problem-driven approaches may produce more Function-benefit analogies than Performance-benefit analogies (3 vs. 1). Solution-driven approaches may be more balanced in producing both Function- and Performance-benefit analogies (5 vs. 4).
- Analogy difference level may be independent of driving approaches. Both solution-driven and problem-driven approaches show a high proportion of Low-difference examples over Medium-difference examples.

Developing these insights will help in implementing analogy retrieval for different driving approaches. Aiding a problem-driven search for potential solutions is distinct from aiding a solution-driven search for potential problems to solve, so it is important to understand each case in order to support both types of analogy-inspired design.

3.6.5 Pilot Study Limitations

The pilot study results are conditional upon validation through inter-rater analyses using refined, systematic classification variables which will appear in the full-scale study to follow. Additionally, because Patterns #1 and 2 (Critical Function Borrowing and Inversion) and Pattern #4 (Effects of Driving Approach) were derived from smaller sets of data, stronger conclusions could be made about these findings if analysis was expanded to a larger data sample.

3.7 Summary

The pilot empirical product study revealed four patterns of analogy retrieval and usage in a collection of analogy-inspired products. The findings described how inventors directly transfer and invert critical functions from analogs when designing products. They also described how academic and commercial inventors appear to differ in how they use analogies, and provided preliminary insights on how solution-driven and problem-driven approaches compare.

The results support that critical functionality is an effective basis for analogy retrieval. In addition, a large number of analogies were recognized to improve performance, suggesting that there is a need to retrieve analogies based on both function and performance specifications. The study also unexpectedly discovered analogy examples which improve user interaction rather than functionality or performance, which suggests a third basis for analogy retrieval to implement in a computational tool.

The pattern of inverting critical functions was a very interesting finding and merits further exploration. The finding came through the ECO-Auger tidal turbine example, last shown in Figure 12, which has an inverted critical function ("Convert fluid flow to rotation") compared to its inspiring analog, the screw conveyor ("Convert rotation to material flow"). This finding gives additional latitude for a computational analogy retrieval tool, since it suggests the possibility of retrieving examples beyond those with directly similar critical functions. If a designer specifies a critical function which is invertible, the tool could invert the specified function and retrieve additional, inverted-function examples for potential inspiration.

CHAPTER 4

FULL-SCALE CROSS-SECTIONAL PRODUCT STUDY

4.1 Overview

In follow-up to the pilot study, an empirical product study of 70 analogy-inspired products is conducted to investigate factors involved in the analogy-inspired design process. Systematic collection of products for study uses random sampling from three technology magazines and a bioinspired design database. These are screened to remove inaccurate and unreliable reports of analogical inspiration. Seven variables are developed and used to systematically classify each example according to design team composition, analogy mapping approach, analogies used, and design outcomes. The study incorporates a cross-sectional study approach, using statistical tests of association, in order to investigate relationships between variables.

4.1.1 Comparison with pilot study design

An at-a-glance comparison of this study with the pilot study follows in Table 5. In addition to the differences below, critical functions were not investigated further in this study, which instead conducts a deeper, formal examination of the analogy usage patterns first suggested by the pilot study.

Table 5. Comparison of pilot and and full-scale study designs

	Pilot Study	Full-scale Study
Number of products studied	57 (fewer for critical function and driving approach)	70
Types of examples studied	Concepts, prototypes, and products	Prototypes and products
Product collection method	Informal, from various sources	Partitioned random sampling from AskNature database and from technology magazines (3)
Product screening method	Removal of explanatory and mis-identified analogy examples. Tentative inference of analogical inspiration allowed.	Standard protocol for acceptance and rejection (7 criteria). Conservative; rejects questionable examples.
Number of classification variables	4 (+ 6 critical function and performance variables)	7
Classification variable definition	Ad hoc	Systematic, formalized
Repeatability assessment	None	Interrater agreement with Cohen's kappa statistic
Statistical analysis	None	Barnard's exact test for association

4.2 Example Collection Sources and Screening

The study required a collection of examples along with primary and secondary sources describing the analogy-inspired products, their inspiring analogs, and their development. A strategy of partitioned random sampling and subsequent screening was chosen to gather examples. In all, 70 analogy-inspired product examples were collected, 35 from each of 2 sampling partitions: (1) the AskNature.org biomimicry product database containing 195 bio-inspired products and concepts [103], and (2) the online articles of three technology magazines: *Popular Science* [159], *MIT Technology Review* [160], and *New Scientist* [161], as returned from Google keyword searches. These searches used the keywords “inspired”, “bioinspired”, “biomimetic”, and “biomimicry”, and were formatted as site-specific queries with single keywords [162]. For example, “site:www.technologyreview.com bioinspired” returned results for the keyword “bioinspired” from the *MIT Technology Review* website. Approximately 3000 results from 12 searches (4 keywords per magazine) were then filtered to remove duplicate links, yielding about 2200 uniquely titled results for screening.

Examples from each partition were screened in random sequence using a common protocol. To accept an example into the study collection, the screening protocol required that:

1. The example product (henceforth, “product”) must be specifically inspired by an analogous system (henceforth, “analog”). For example, researchers at the University of Toronto developed self-assembling molecular nanowires which appear in the AskNature database of biomimicry products [163]. Despite AskNature’s description of the similarity between the self-assembling nanowires and self-assembly in nature, independent sources did not suggest that the researchers were actually inspired by nature in their work [164]. Thus, the nanowires example was not accepted into the collection.
2. The product’s intended applications must have been determined before its development. This criterion rejected many products which were developed to replicate and study a scientific phenomenon, such as a type of coil spring developed by Harvard researchers to mimic cucumber plant tendrils [165, 166]. Experiments with the springs validated the researchers’ hypotheses about the tendrils’ mechanical behavior [167, 168]. Because the study focuses on analogies used to solve design problems, it is not concerned with analogies and products used primarily for scientific inquiry, and the screening protocol attempted to excluded these from the collection.

3. The product must have a functional prototype or commercially-marketed product which demonstrates its operation. This criterion rejected examples which were only in the conceptual stage and had not yet been developed.
4. The product must not replace or compete with the analog which inspired it. In some cases of design, the objective is to replace systems with analogous products, which is distinct from the use of analogies from separate systems to solve design problems. In this vein, products such as prosthetics designed to replace damaged organs were not included in the study, nor were products such as artificial tissue proxies designed to replace biological samples in laboratory research [169], since these all derive their functional principles directly from the systems they aim to replace.
5. The product must not incorporate the analog as a part of its operation. This criterion follows a distinction made by Janine Benyus concerning technology inspired by nature [170, 171], which separates “bio-utilization” and “bio-assisted” technologies from “biomimicry” products. The first two categories incorporate natural systems directly in the technology and do not display the analogical abstraction that is the hallmark of analogy-inspired design. Thus, examples like the genetic modification of a bacterium to express a variant of a natural protein or the use of soil-dwelling organisms to treat sewage are not accepted into the collection [172, 173].
6. The product must not simply transpose the analog technology for use in another domain. This criterion rejected examples in which existing technology was simply adapted and re-applied, as with a case of a 3D-imaging device where surgeons

"borrowed a 3-D stereoscopic imaging technology from the video-game industry to help them guide their tools during intricate beating-heart surgeries" [174]. Because the study focuses on design using abstracted principles from analogies, it excluded examples where there was little or no abstraction done in developing the product from the inspiring analog.

7. Additionally, the product must correctly implement the analog's functional principles. This criterion rejected only one screened example: the Eastgate Building in Zimbabwe, which implements an energy-efficient cooling concept inspired by termite mounds [175, 176]. It was, however, based on a commonly-held but "erroneous conception of how termite mounds actually work" which was refuted by later research [177].

Figure 16 shows the progression of screening to obtain the final 70 examples.

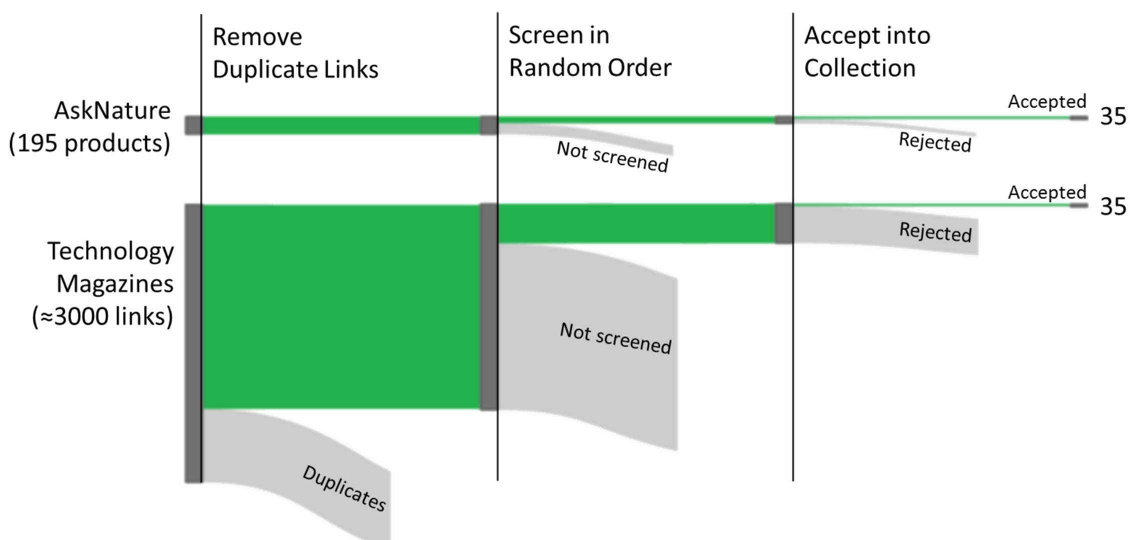

Figure 16. Screening examples to obtain the final example collection. Visualized using RAW [178]

The screening protocol was verified for repeatability through a test of interrater agreement between the current author and a mechanical engineering postdoctoral scholar using 10 screened examples. An initial 60% agreement (Cohen's kappa = 0.09) was obtained, reflecting poor agreement. After discussions to address disagreements and refine the protocol into the version presented above, a final 90% agreement (Cohen's kappa = 0.80), indicating substantial agreement, was achieved for a separate set of 10 screened examples.

While careful efforts were made to minimize bias in the example collection to facilitate statistical inference, there exist some weaknesses in the study's sampling strategy. An ideal strategy would give all reported analogy-inspired design examples an equal chance of inclusion in the study. In comparison, the actual strategy favors inclusion of some examples over others. Because the two partitions (AskNature.org and Technology Magazines) are not disjoint, examples that have appeared in both partitions were more likely to be screened and accepted into the collection. Additionally, within the Magazines partition, examples that have appeared in multiple magazines had a higher likelihood of being screened and accepted than examples mentioned in only one magazine. While unavoidable in the strategy, this bias may provide a potential benefit: multiply-reported examples can be expected to have more accessible primary and secondary source information over singly-reported examples.

4.3 Example Categorization using Classification Variables

As in the procedures of the pilot study, the product collection examples were categorized using several classification variables for analysis. These variables were developed with the goal of understanding analogy usage in practice. Many describe underlying aspects of the analogy-inspired design process which otherwise cannot be directly measured. In this sense, the variables serve as *measures* for underlying phenomena (latent variables) in analogy-inspired design [179], whose associations (dependencies) are to be investigated. For instance, the benefits gained from using analogies may vary depending upon the diversity of design teams, but benefit and diversity cannot be directly measured. Instead, the classification variables *Additional Function* and *Improved Performance* serve as measures for describing benefit, and *Biological Cross-disciplinarity* serves as a measure for describing diversity. Finding associations between these variables would suggest how the benefits of analogy usage are dependent on design team diversity.

The seven classification variables are listed in Table 6, grouped by what they describe. Context variables describe the personnel and circumstances related to the design example. Analogy variables describe the analogical mapping(s) made in the design example. Outcome variables describe product characteristics and achievements relating to innovation. The variables are developed further in subsequent sections using selected examples from the collection.

Table 6. Classification variables for studying analogy-inspired design examples

Variables:	Categories:	Used to describe:
Context variables: Describing the personnel and circumstances related to the design example		
1. Inventors' Occupation	Academic only, Non-academic only, Mixed	The **professional backgrounds** of the personnel involved
2. Biological Cross-disciplinarity	BCD, Non-BCD	The **diversity** of the personnel involved
3. Driving Approach to Analogy	Solution-driven, Problem-driven	The **design scenario** surrounding the analogy-inspired example
Analogy variables: Describing the analogical mapping(s) made in the design example		
4. Analogy Source Domain	Natural analogs, Man-made analogs	The **source(s)** of the inspiring analog
5. Analogy Multiplicity [83, 84]	Single, Compound	
Outcome variables: Describing the outcomes achieved in the design example		
6. Additional Function [115, 116]	Additional function, No additional function	The **benefits** achieved by the analogy-inspired concept
7. Improved Performance	Improved performance, No improved performance	

4.3.1 Classification variable: Inventors' Occupations

Inventor's occupation ("Occupation") is a context variable describing the professional backgrounds of the inventors at the time of analogy inception, as reported in available sources, such as publication author information, online faculty and corporate team member profiles. It uses 3 categorical labels: (1) Academic only, (2) Non-academic only, and (3) Mixed. Product examples labeled "Academic only" involved only personnel with appointments at academic institutions (such as universities or federal research institutions), as in the case of VelociRoACH, a cockroach-inspired legged robot developed by UC Berkeley researchers [180-183]. "Non-academic only" examples involved only personnel without academic appointments (such as private entrepreneurs and employees of commercial firms), as in the case of ORNILUX, a spiderweb-inspired bird-friendly glass developed by German glass manufacturer Arnold Glas [184-186]. Examples labeled "Mixed" involved personnel both with and without academic appointments, as in the case of a beetle-inspired fog collecting surface developed by the UK defense research firm Qinetiq and the University of Oxford [187-190].

4.3.2 Classification variable: Biological Cross-disciplinarity

Biological cross-disciplinarity (BCD) is a context variable describing the diversity of the product development team, specifically with respect to biological disciplines. It includes two categorical labels: (1) BCD (biologically cross-disciplinary), describing teams combining at least 1 biology professional and at least 1 non-biology professional, and (2) Non-BCD, describing individuals and teams of only biology or only non-biology professionals. An example of a Non-BCD team is the previously-mentioned UC Berkeley group that developed VelociRoACH [180-183]. As reported in their paper [183], the research team members are all affiliated with the Mechanical Engineering or Electrical Engineering and Computer Sciences departments at UC Berkeley, and none were considered biology professionals for classification. In contrast, the beetle-inspired fog collecting surface was developed by a BCD team which included a zoologist from the University of Oxford and an engineering team from Qinetiq [190]. Thus, the research team included both biology and non-biology professionals and was labeled as BCD.

4.3.3 Classification variable: Driving Approach to Analogy Mapping

Driving Approach is a context variable describing the approach to analogy mapping in the design examples. It uses two categories to describe the process of mapping between knowledge domains: (1) Solution-driven, describing a mapping process that begins with knowledge about an analog and ends with the discovery of a problem that the analog can solve (analog domain → problem domain), and (2) Problem-driven, describing a mapping process that begins with a problem and ends with a discovery of an analog that could solve the problem (problem domain → analog domain). These terms were coined by Helms, *et al.*, in their cognitive studies of student design teams [80, 81], in which they codified the solution- and problem-driven approaches. The beetle-inspired fog catching surface was considered a solution-driven example in this study. The researchers began with a scientific inquiry into the Namib desert beetle's fog-condensing mechanisms, and proceeded from their discovery of the cuticle's bumpy structure to design the novel fog catching system [190]. Their recognition of the analog system (Namib beetles) preceded their recognition of the problem it could solve. In contrast, the toy-inspired Buckliball collapsible membrane was considered a problem-driven example. Buckliballs were conceived when MIT and Harvard researchers, while seeking to design the simplest, reversibly-collapsible 3D structures, found a solution in the construction of the Hoberman Twist-O children's toy [191-195]. Their recognition of the analog system (the Twist-O toy) came after their conception of the problem it could solve.

Table 7 summarizes the context variable examples from Sections 4.3.1 - 4.3.3.

Table 7. Classifications of selected examples under the 3 context variables

Product	Analog	Sources	Inventors' Occupation	Biological Cross-Disciplinarity (BCD)	Driving Approach
UC Berkeley VelociRoACH	American cockroach	[180-183]	Academic only	Non-BCD	Problem-driven
Arnold Glas ORNILUX	Spider webs	[184-186]	Non-academic only	Non-BCD	Solution-driven
Qinetiq/Oxford fog collecting surface	Namib desert beetle	[188-190]	Mixed	BCD	Solution-driven
MIT/Harvard Buckliballs	Hoberman Twist-O toy	[191-195]	Academic only	Non-BCD	Problem-driven

4.3.3.1 An aside on driving approach to analogy categories

In reality, analogy mapping involves subtle deviations from the solution- and problem-driven categories. The idealized categories only identify the originating domain in analogy mapping; however, as shown in Figure 17, the path taken in accessing and connecting ideas across domains may proceed through various ideas and levels of abstraction. This can be true even when they originate in the same domain and end in the same concept. Vattam, *et al.*, alluded to this in their framing of interactions between problem decomposition and analogical transfer [84]. Their work details how analogy retrieval can proceed iteratively, co-evolving with understanding of the original problem.

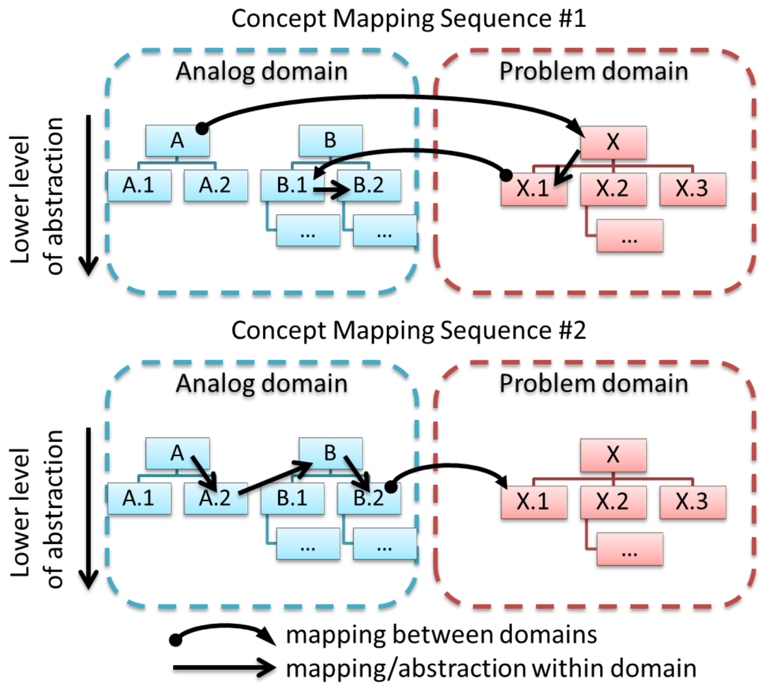

Figure 17 Two hypothetical sequences of analogical concept mapping. Both originate in the analog domain and, thus, both would be labeled solution-driven, despite being clearly different.

One real-world example supporting this view comes from Dr. Carolyn Dry's work on self-healing construction materials. Her self-healing concrete [196-198] is one of the examples in the study and is labeled as a solution-driven example. In a personal email correspondence with the author, Dr. Dry related her ideation process [199]:

> "I am an **architect** and my dad was **pharmacist** so I thought of putting **time release pills** in a **building material**. Then I found out that making **cement** causes 8-10% of the world's CO_2 so it could benefit from a self-repairing function" … "Well concrete is a commodity and therefore the field is very, very cost sensitive and reluctant to make any changes. The **composites** field is the opposite, so for a new technology to flourish I began to focus on composites." (Emphasis added)

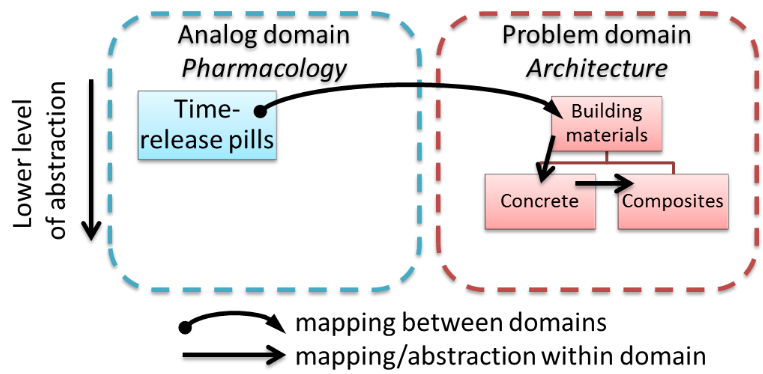

Figure 18 Dr. Carolyn Dry's analogical concept mapping sequence

Dr. Dry linked several concepts at different levels of abstraction, as diagrammed in Figure 18. It proceeded from two general knowledge domains, pharmacology and architecture, and initially defined two specific concepts in each: time-release pills (pharmacology) and building materials (architecture). The concept of building materials was then refined further into more-specific concepts of concrete and, later, composites. The "path" traced through these concepts is only approximated by the Solution-driven model which concerns the starting and ending concept domains and does not account for intermediate concepts which are accessed in ideation.

While there exist nuances of ideation in design practice, this study continues the convention established by Helms, *et al*. It treats the archetypal models as representative processes of analogy mapping in product design and attempts to apply them to the examples in the study.

4.3.4 Classification variable: Analogy Source Domain

Analogy Source Domain is an analogy variable that describes the domain of the inspiring analog in the design example analogy. It includes 2 categories: (1) Natural analogs, which are not created by humans, and (2) Man-made analogs, which are. Of the previously discussed examples, the cockroach-inspired VelociRoACH robot was a case of inspiration from a natural analog, and the toy-inspired Buckliballs were a case of inspiration from a man-made analog.

4.3.5 Classification variable: Analogy Multiplicity

Analogy Multiplicity is an analogy variable that describes how many distinct analogies contributed to the design example, and follows the definition of compound analogies by Vattam, *et al.*: analogies where “the overall solution is obtained by combining [multiple, distinct] solutions [which each contribute to solving] different parts of the problem” [83, 84]. The variable has two categories: (1) Single analogies and (2) Compound analogies. In the study, all compound-analogy examples involved exactly 2 distinct analogies. All the product examples discussed in previous sections have been single-analogy examples. For a compound-analogy example, there is the 500 series Shinkansen high-speed train developed by West Japan Railway Company [15, 16, 200]. When tackling the problem of "tunnel boom" noise pollution caused by the train's high speed entrance into tunnels, the engineers took inspiration from kingfisher birds to redesign the nose shapes of the leading and trailing train cars. Additionally, when tackling the problem of noise pollution from the current collector pantographs, the engineers were inspired by owls' leading edge feather serrations to redesign the pantograph as a T-shaped collector with serration features. Combined, these two distinct analogies contributed to solving two separate noise generation problems, making the 500 series Shinkansen a compound-analogy design example.

Table 8 summarizes the analogy variable examples from Sections 4.3.4 - 4.3.5.

Table 8. Classifications of selected examples under the 2 analogy variables

Product	Analog	Sources	Analogy Source Domain	Analogy Multiplicity
UC Berkeley VelociRoACH	American cockroach	[180-183]	Natural systems	Single
MIT/Harvard Buckliballs	Hoberman Twist-O toy	[191-195]	Man-made systems	Single
JR West 500 series Shinkansen	Kingfisher AND Owl	[15, 16, 200]	Natural systems	Compound

4.3.6 Classification variable: Additional Function

Additional Function is an outcome variable that describes what the designers achieved by using the analogy in their solution – that is, it describes the benefits of using the analogy. In particular, it identifies whether the analogy-inspired solution yielded added functional capabilities over contemporary competing products, and it has 2 categories: (1) Additional function and (2) No additional function. The definition of "additional function" comes from Saunders, *et al.*, in their empirical study of innovative mechanical products, in which they compared award-winning products against their competitors and identified whether a given product "allows the user to solve a new problem or perform a new function while still performing the function of the comparison product[s]" [115, 116]. Also following the method of Saunders, *et al.*, competing products were identified by selecting classes of products which are functionally equivalent to the analogy-inspired product and provide the most likely alternatives for accomplishing its functions. For example, the 500 series Shinkansen did not perform any additional functions compared to its predecessors (such as the 300 series Shinkansen), which all transported passengers, thus giving it the label of "No additional function". In contrast, ORNILUX glass performed the additional function of preventing bird collisions in comparison with conventional architectural glass, while still performing the original functions of transmitting light and separating indoor environments, thus earning it the "Additional function" label.

4.3.7 Classification variable: Improved Performance

Like Additional Function, Improved Performance is another outcome variable that describes the benefits of analogy usage. It identifies whether the analogy-inspired solution provided greater performance in the functions of contemporary competing products, according to source descriptions' claims, and it has 2 categories: (1) Improved performance and (2) No improved performance. Returning to the previous examples, the 500 series Shinkansen trainsets accomplished the transportation function of predecessor trains with less noise and greater energy efficiency, earning it the "Improved performance" label. In contrast, ORNILUX glass did not accomplish the light transmission and environmental separation functions with any greater efficacy than conventional glass, giving it the "No improved performance" label.

Table 9 summarizes the outcome variable examples from Sections 4.3.6 - 4.3.7.

Table 9. Classifications of selected examples under the 2 outcome variables

Product	Analog	Sources	Comparison Products	Additional Function	Improved Performance
JR West 500 series Shinkansen	Kingfisher AND Owl	[15, 16, 200]	JR West 300 series Shinkansen	No additional function	Improved performance (noise, energy efficiency)
Arnold Glas ORNILUX	Spider webs	[184-186]	Conventional glass	Additional function (bird collision deterrence)	No improved performance

4.3.8 Typical screening and classification process

To better illustrate the method of studying examples, this section details the collection, screening, and classification of a typical example in the study collection: the fog collecting material developed by Qinetiq and Oxford University researchers introduced in Section 4.3.1. This example originated in the AskNature.org product database partition which was screened in random order [187]. During screening, sources in addition to the original AskNature entry were identified for studying the fog collecting material example. These were a BBC.com news article [188], a Nature news article [189], and a Nature journal publication by the researchers [190].

First, based on the source information, the screening protocol was used to scrutinize the example for acceptance. The first screening criterion requires evidence of specific inspiration by an analog: in this case, evidence showed that researchers were specifically inspired to make a fog collecting material which mimicked the phenomenon they observed in Namibian beetles, so the example passes this criterion. The second screening criterion requires that the purpose of the product be determined before its production: evidence showed that the researchers were studying the beetles and intended from the beginning to develop the material for fog collection. The third criterion requires that a physical embodiment must have been produced and used to demonstrate the concept function: the researchers embedded glass spheres into wax-coated slides and successfully demonstrated and evaluated the concept. The fourth and fifth criteria require that there be no evidence that the product competes with or incorporates the inspiring analog: the fog catching material is not constructed from beetles, nor does it replace them. The sixth criterion requires that the example not simply transpose technology to a new application: the fog catching material is a new technology based on example from nature and thus does not simply reapply an existing technology. Finally, the seventh screening criterion prohibits examples which are based on incorrect understanding of the inspiring analog: the fog collecting material correctly adapts the hybrid hydrophobic-hydrophilic pattern of the beetle to the new product. Having passed all the screening criteria, the fog collecting material was accepted into the study.

To classify the example using Inventors' Occupation, the Nature journal publication was consulted to discover the authors' affiliations. This showed that one author was affiliated with the Department of Zoology at Oxford, while the other was affiliated with the Mechanical Sciences Sector at Qinetiq. Based on the definitions in Section 4.3.1, the example is labeled as "Mixed" occupation since the research team includes both academic and non-academic personnel.

The same evidence is used in classifying by Biological Cross-Disciplinarity. Based on the definitions in 4.3.1, the example is labeled "BCD" because the research team includes both a biology professional (the Oxford zoologist) and a non-biology professional (the Qinetiq scientist).

To determine the Driving Approach for the example, two excerpts from the AskNature source and the Nature journal publication were cited: "Oxford biologist Dr. Andrew Parker and Dr. Chris Lawrence of QinetiQ were studying tenebrionid (Stenocara) beetles in the barren Namibian Desert when they discovered the shell of these insects has a bumpy surface texture." [187]; "The mechanism by which water is extracted from the air and formed into large droplets has so far not been explained, despite its biomimetic potential." [190]. The sources thus reveal that the problem of fog collection was not known before the analog was identified (in this case, the beetle being studied), making the example a case of the “Solution-driven” approach to analogical inspiration.

For classification by the analogy variables Source Domain and Multiplicity, the fog collecting material was inspired by the Namib desert beetle, thus it was labeled as a “Natural” analog example with respect to Source Domain and a “Single” analogy example with respect to Multiplicity.

Finally, for classification by the outcome variables Additional Function and Improved Performance, the method required identification of comparison products that are cited or inferred from the source information. To accomplish this, two relevant excerpts were taken from the BBC news article and the Nature news article: “’This would make fog harvesting several times more efficient than current water collecting methods,’ Dr Parker told BBC News Online.” [188]; “Their current efforts are already "several times more efficient" than other fog collectors, says Parker.” [189]. These sources identify the comparison products as current fog collection products, and make the comparative claim that the beetle-inspired fog collectors are more efficient, collecting water at a higher rate for a given area of collector. The sources give no evidence that the fog collecting material accomplishes anything in addition to collecting water from fog – thus the example is labeled “No additional function”. Meanwhile, the excerpts do present the claim that the beetle-inspired collectors accomplish fog collection with greater efficiency, giving the example the “Improved performance” label.

4.4 Repeatability of Example Categorization

Repeatability assessments were performed for the variables deemed to be most subjective: Driving Approach, Additional Function, and Improved Performance.

Independent classifications of Driving Approach for 10 randomly chosen examples were compared between the current author and a graduate researcher, with an initial low agreement of 50%. Following a general clarification of the classification protocol, the graduate researcher revised their classifications, resulting in a substantial agreement of 80% (kappa = 0.64). For Additional Function, independent classifications were compared between the current author and a mechanical engineering professor for 10 examples, with a low agreement of 60% (kappa = 0.05). Further work is needed to improve agreement. For Improved Performance, independent classifications were compared between the current author and a mechanical engineering doctoral candidate for 10 examples, with an initial agreement of 90% (kappa = 0 due to low-occurrence category). Subsequent discussion to ameliorate disagreements resulted in perfect agreement for the same set of examples.

4.5 Categorical Data Analysis: Frequencies and Contingency Tables

Following categorization of all product examples, the (univariate) frequencies of individual classification variables were analyzed along with the joint (bivariate) frequencies between pairs of variables. Individual variable frequencies are summarized in Table 11, showing the numbers and percentages of examples classified under each variable category.

In addition to measuring the category distributions of each variable, analysis aimed to detect associations, or dependencies, between variables. Associations for discrete, categorical data are analogous to correlations for continuous, quantitative data. They may be found by testing the null hypotheses of mutual independence between variables. For these tests, data is organized into contingency tables, such as Table 10, whose cells list joint frequencies – the number of examples under each combination of categories for a pair of variables. With the 7 classification variables in this study, there are 21 contingency tables comparing all the pairs of variables.

Table 10. Contingency table for Biological Cross-Disciplinarity and Multiplicity. Expected cell frequencies appear in parentheses, with those lesser than 5 appearing in italics.

		Analogy Multiplicity		
		Single	Compound	Total
Biological Cross-Disciplinarity	Non-BCD	49 (48.81)	2 *(2.19)*	51
	BCD	18 (18.19)	1 *(0.81)*	19
	Total	67	3	70

Common tests of independence for contingency tables, such as the Pearson chi-square test and the likelihood ratio test (G-test), require table cells to have sufficiently large expected frequencies to meet the normality assumptions of the approximated chi-square distribution [201, 202]. For 2x2 contingency tables like the ones in this study, the common rule of thumb requires all expected cell frequencies to exceed 5. Since most tables in the study, such as Table 10, failed this requirement, a different test of independence was needed which does not depend on normality assumptions. Barnard's exact test is an alternative which does not use an approximated distribution to estimate p-values. Though it is computationally demanding, it is advantageous for hypothesis testing over other alternatives, such as Fisher's exact test, because of its greater power for 2x2 tables [202, 203]. Barnard's test calculates exact p-values by enumerating all possible tables for a given sample size, drawn from a multinomial distribution with 2 nuisance parameters, and summing the probabilities for all tables which are "as or more extreme" than the table being tested [203, 204]. It uses a multinomial model which assumes that only the total sample size is known in advance (and not the row or column totals, as

Fisher's exact test assumes) [203]. To increase the power of the test, an interval approach is used to constrain the nuisance parameter values used to calculate the "extremeness" of the tables [203, 205]. Using the multinomial Barnard's exact test with the interval approach, significance tests were carried out for all 21 tables in the study.

Upon detecting association between a pair of variables, two types of relationships can be inferred: symmetric and asymmetric. Interpretation depends upon researchers' reasoning of potential causal mechanisms, just as all correlation data must be interpreted with regard to causal relationships. In symmetric relationships, neither variable is inferred to have an influence on the other – rather, they are both interpreted as dependent variables [206]. In this study, symmetric relationships may exist among context variables, among analogy variables, and among outcome variables. In asymmetric relationships, one variable is inferred to be dependent on the other [206]. Asymmetric relationships in this study concern whether the analogy variables depend upon context variables, and whether the outcome variables depend upon the context variables and the analogy variables.

4.6 Results and Discussion

Table 11 shows the frequencies of examples under the categories of each variable. Among context variables, academic-only teams (74%) are found to contribute a majority of examples, compared to non-academic-only teams (21%). Mixed-occupation teams involving both academic and non-academic personnel were rare (3%). The prevalence of academic-only examples may suggest a preferential bias in academic teams for reporting analogical inspiration, as consistent with the prevalence of researchers' appeals to apparent benefits of biological inspiration in their publications [86].

Table 11. Frequencies of classification variable categories.
Categories with an asterisk (*) were ignored in contingency table analysis.

Variables:	Categories:	No. (%) of examples:
Context variables:		
1. Inventors' Occupation	Academic only	52 (74%)
	Non-academic only	15 (21%)
	Mixed*	3* (4%)
2. Biological Cross-disciplinarity	Non-BCD	51 (73%)
	BCD	19 (27%)
3. Driving Approach	Solution-driven	28 (40%)
	Problem-driven	30 (43%)
	Undetermined*	12* (17%)
Analogy variables:		
4. Analogy Source Domain	Natural analogs	64 (91%)
	Man-made analogs	6 (9%)
5. Analogy Multiplicity	Single	67 (96%)
	Compound	3 (4%)
Outcome variables:		
6. Additional Function	Additional function	15 (21%)
	No additional function	55 (79%)
7. Improved Performance	Improved performance	63 (90%)
	No improved performance	7 (10%)

Non-BCD teams in the study outnumbered BCD teams (73% vs. 27%). Since cross-disciplinary teams are believed to be more innovative, and given the need for deep understanding of both problem and analog domains when forming analogies, more examples from BCD teams were expected.

In examples where driving approaches could be identified, solution-driven and problem-driven cases contributed nearly the same number of examples (28 vs. 30). A possible explanation for this is that both forms of analogy usage are equally viable and thus equally prevalent in product design. 12 examples, however, could not be identified as having either solution- or problem-driven approaches.

For the analogy variables, the collection examples were predominantly inspired by natural analogs and rarely inspired by man-made analogs, even among the 35 examples from technology magazines. One explanation may be that inspiration from man-made analogs is underreported and inspiration from natural analogs is over-reported, which would be consistent with the attention currently being given to bio-inspired design concepts. Concurrently, this observation could also support the idea that natural analogs provide a richer source of novel solution concepts than man-made analogs, and thus appear more often in current innovative work. Additionally, the collection was mainly comprised of single analogy examples, while compound analogy examples were rare. This contrasts with the results of the cognitive study by Vattam, *et al.* [84], in which 6 out of 9 student bio-inspired design projects utilized compound analogies. The scarcity of man-made analogs and of compound analogies in the study collection presented a challenge for detecting statistical associations involving analogy variables.

Lastly, among outcome variables, only a minority (21%) of example products displayed additional function relative to comparison products, while the vast majority (90%) displayed improved performance over comparison products. The low occurrence of additional function agrees with Saunders, *et al.* [115, 116], who find that even among design-award-winning products, only 38.1% display additional function, and who propose that the relatively low occurrence stems from the difficulty of integrating more functions into products. The findings suggest that analogies are more often successfully used to improve a product in its existing functions than to add more functions to a product, which supports the continuing interest in using analogies for improving products' performance.

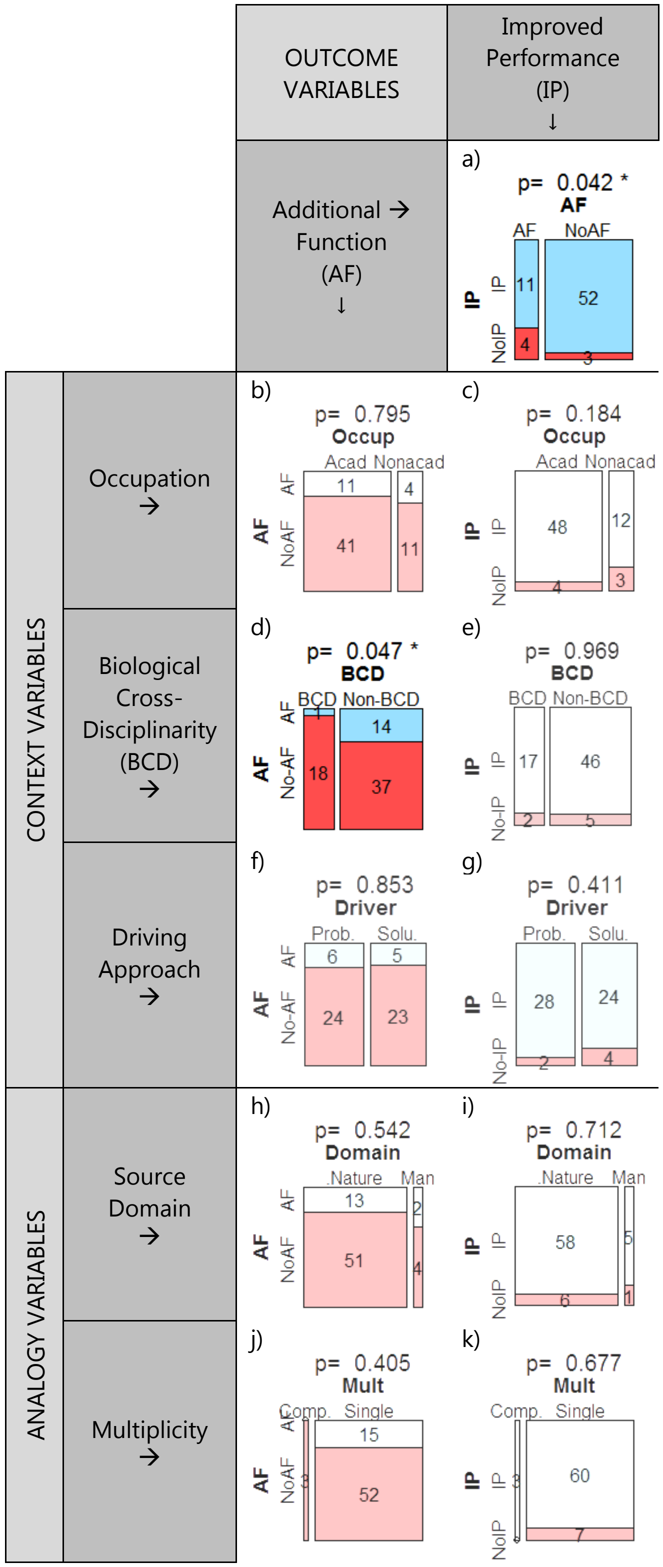

Figure 19. Results plots of the 11 contingency tables involving outcome variables, with Barnard's exact p-values for the null hypotheses of no association. Visualized using the 'vcd' package [207, 208] in R [209].

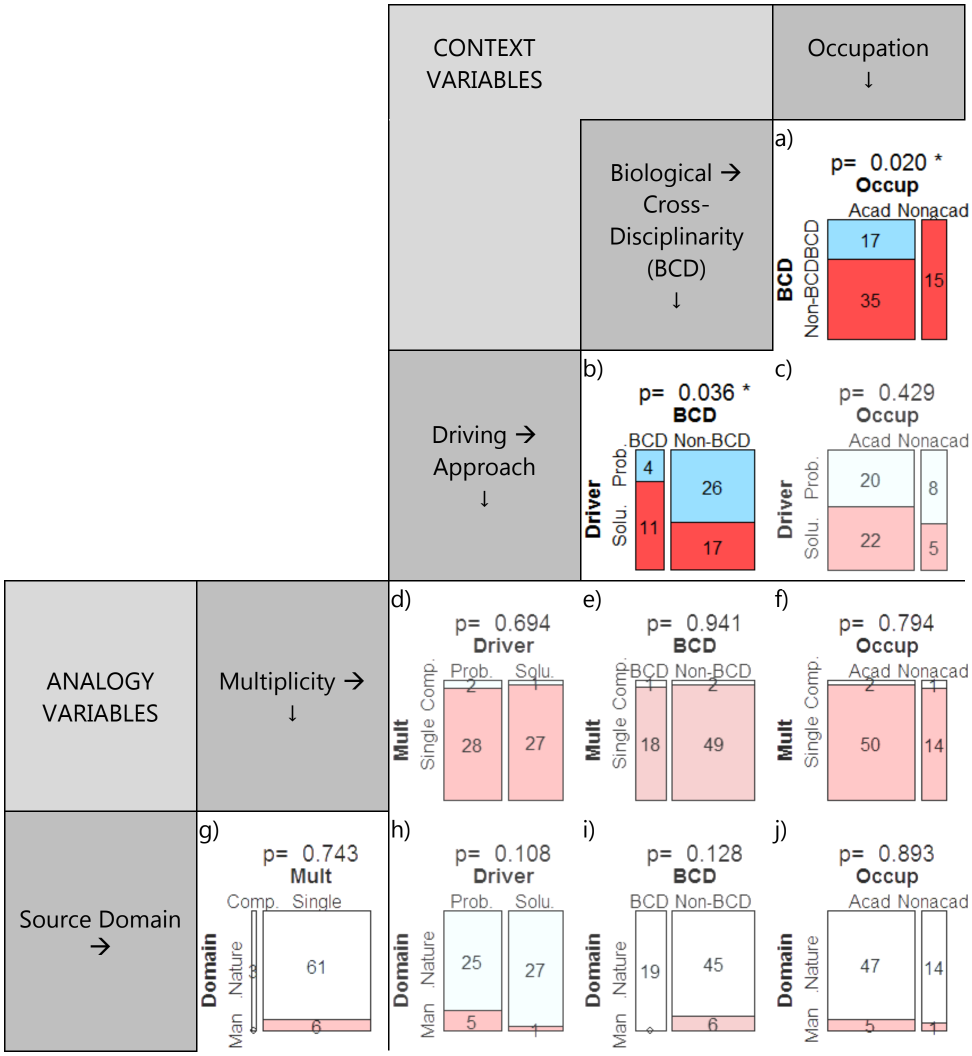

Figure 20. Results plots of the remaining 10 contingency tables not involving outcome variables, with Barnard's exact p-values for the null hypotheses of no association. Visualized using the 'vcd' package [207, 208] in R [209].

Figure 19 and Figure 20 together show the results of the 21 contingency table analyses regarding associations between variables. The plot for each table shows 4 rectangles whose areas reflect the number of examples in the 4 table cells, with category labels on the upper and left edges. For the null hypotheses of no association, testing at the 0.05 level, non-significant results are shown in faded shading, while significant results are shown in full shading to indicate potential association. Only a few tables, 4 of 21, showed statistically significant association, although with 21 tests at the 0.05 level, about

1 table is expected to display significance when there ought to be none (the familywise Type I error rate).

As seen in Figure 19(b)-(k), only one out of ten pairs of outcome variables with context variables and analogy variables showed statistically significant association: the pair of Additional Function and Biological Cross-disciplinarity in Figure 19(d). BCD teams were found to contribute examples with Additional function statistically less often than non-BCD teams (5% vs. 27%). It is surprising to find cross-disciplinary team composition negatively associated with an outcome variable, when the benefits of diverse, multi-disciplinary teams are well-documented and professionally promoted. This result, if true, would suggest that cross-disciplinary teams are not as well-suited to the problem of adding function to products – a counter-intuitive result which merits closer examination.

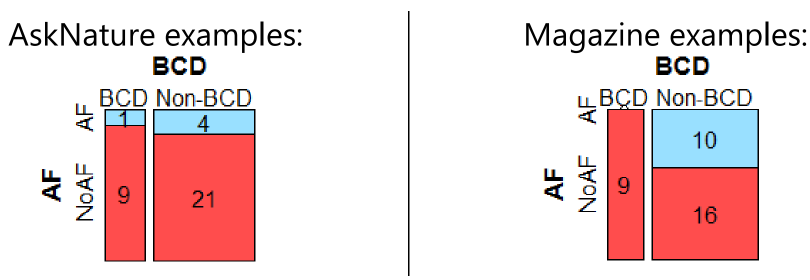

Figure 21. Results plots of Biological Cross-Disciplinarity X Additional Function contingency tables for examples from AskNature (left) and technology magazines (right)

When the data from AskNature and technology magazine partitions are separately examined, as shown in Figure 21, the difference between non-BCD and BCD teams vanishes for the AskNature data, but remains large in the technology magazine data, where all examples with additional function come only from non-BCD teams. The inconsistency between partitions suggest that the result is a false positive, a consequence of uncorrected multiple testing and possibly a consequence of overly-conservative classification which underestimated the number of BCD teams. An investigation with a larger sample of products may serve to resolve this discrepancy.

The plot in Figure 19(a) shows the symmetric association between Additional Function and Improved Performance, indicating that examples having additional function are less likely to have improved performance than examples having no additional function – essentially, a negative association is observed between the two outcome variables.

The otherwise nonexistent associations involving outcome variables in Figure 19 is striking. For example, the results indicate that academic-only teams and nonacademic-only teams produce examples with additional function and improved performance at statistically indistinguishable rates. Similar comparisons are found between Solution-driven and Problem-driven approaches, between Single and Compound analogy cases, and between Natural and Man-made analogy cases. This would surprisingly suggest that, for the specific goals of achieving Additional Function and Improved Performance, no statistically-founded recommendations can be made from this study regarding how to compose teams, which analogy mapping approach to take, and what type or number of analogies to use.

Among the remaining tables in the study, only two symmetric associations were detected. The first of these, as shown in Figure 20(a), indicates that academic design teams were identified as BCD significantly more often than non-academic teams. The second association, shown in Figure 20(b), indicates that BCD teams contributed solution-driven examples significantly more often than non-BCD teams. The latter result is intriguing and suggests a relationship between the mixing of biology and nonbiology professionals and the type of approach used to generate an analogy-inspired product. The explanatory mechanisms for such a relationship cannot be determined from the current study data alone, but at least 3 mechanisms can be suggested to be at play: (1) Selection mechanisms, e.g., BCD teams as a group are more likely to attempt and complete projects which are solution-driven in nature than non-BCD teams; (2) Aptitude mechanisms, e.g., given the use of solution-driven approaches, BCD teams as a group are more likely to successfully produce a product using that approach than non-BCD teams; and (3) Team diversification mechanisms, e.g., given the use of solution-driven approaches, teams which begin as non-BCD may have incentives to invite biologists or nonbiologists in order to leverage a wider knowledge pool to successfully produce the product, which leads to a greater number of BCD teams associated with solution-driven approaches. Follow-up experimetns

No significant association was found between the inventors' occupations and their use of different driving approaches to analogy, contradicting the preliminary results of the pilot study which suggested that there may be a preference for solution-driven approaches by academic teams [122]. No associations were found between context variables and analogy variables, owing in part to the low occurrence of compound analogies and man-made analogs. Repeating the investigation with a larger sample would improve the likelihood of detecting existing associations, especially for variables with low-occurrence categories.

4.6.1 Comparison with pilot study results

The full-scale study was motivated in part by the findings of the pilot study. It is notable, then, that apparent relationships in the pilot study results were not corroborated by the full-scale study. Specifically:

- **Pattern #3 in pilot study results (differences between academic and non-academic inventors) was not supported in full-scale study results:** The pilot study suggested that designers' occupation, a context characteristic, was related to the type of benefit achieved, an outcome characteristic. Academic designers were thought to achieve novel functionality more frequently, and improved performance less frequently, than non-academic designers. The full-scale study, however, did not find a statistically significant difference between academic and non-academic designers with respect to their use of analogies to achieve different types of benefits or advantages.
- **Pattern #4 in pilot study results (differences between driving approaches to analogy mapping) was not supported in full-scale study results:** The pilot study suggested that driving approaches, a context characteristic, may be related to designers' occupation (context) and benefits achieved (outcome). Solution-driven approaches appeared to be more associated with academic designers and with products which achieve novel functionality. The full-scale study, however, did not detect any statistically significant associations of solution- or problem-driven approaches with specific occupations or with particular achieved advantages.

These discrepancies can be attributed to the larger sample size in the full scale study and the more systematic classification methods used to categorize examples.

4.7 Summary

This study demonstrates a cross-sectional empirical product study method for investigating variables and trends in analogy-inspired product innovation. The study surveyed a collection of 70 analogy-inspired products sampled from the AskNature product database and three technology magazines, analyzing them using a set of classification variables. The results reveal an intriguing snapshot of analogy usage. Of the product examples in the collection, 74% were created by academic teams, 21% by nonacademic teams, and 4% by mixed-occupation teams. 73% of examples came from non-BCD teams compared to 27% from BCD teams. Considering the necessity for deep understanding of both product and analog domains, along with the belief that cross-disciplinary teams are more innovative, more examples from BCD teams were expected. Approximately equal numbers of examples were classified as solution-driven and as problem-driven cases of analogy mapping, suggesting that both approaches are equally viable for successfully designing products. Concerning the usage of different types of analogies, natural analogs were heavily used (91%), while analogs based on man-made products were rarely used (9%). Additionally, the use of single analogies (96%), which implement solutions derived from a single analog, greatly exceeds the use of compound analogies (4%), which implement solutions derived from multiple distinct analogs. In the measurement of design outcomes, only 21% of examples had additional functional capabilities relative to comparison products, while 90% of examples displayed improved performance over comparison products. This result shows that analogies are widely successful in improving product performance, and it strongly supports ongoing interest in using analogies to enhance product innovation.

The search for trends in analogy usage uncovered few significant associations between the study variables. Interestingly, for achieving the goals of improved performance and additional function in products, the results fail to support any recommendations as to how to compose design teams, which analogy mapping approach to take, and what type or number of analogies to use. For instance, results show that problem-driven and solution-driven approaches yield improved product performance at statistically indistinguishable rates, such that neither approach is shown to be advantageous over the other for increasing performance.

CHAPTER 5

CONCLUSION

In developing new tools and methods for design-by-analogy, researchers can benefit from insight into real-world practices of analogy-inspired design. To contribute such insight, an empirical product study method was developed, refined, and applied in a pair of studies as summarized in preceding chapters of this thesis. This chapter evaluates the presented work against the research scope and motivating questions set forth in Chapter 1. It concludes with a discussion of limitations in this work along with opportunities for continued research.

5.1 Evaluation of Research

The scope-defining question for this thesis is repeated below:

> *Scope-defining question:*
>
> *What **trends and relationships** exist among **design context characteristics** (such as designers' occupations and driving approaches to analogy mapping), **analogy characteristics** (such as distance, number, and source domain), and **outcome characteristics** (such as functional or performance benefits achieved) in real-world cases of analogy-inspired design?*

In response to this question, the following trends have been determined for the characteristics examined in the full-scale study:

- More analogy-inspired product examples are realized by academic design teams than by non-academic, or commercial, design teams.
- More analogy-inspired products are realized by non-BCD design teams than by BCD design teams.

- Approximately equal numbers of analogy-inspired products are produced by solution-driven and problem-driven approaches.
- Analogy-inspired designs are predominantly inspired by natural systems and rarely inspired by man-made systems.
- Analogy-inspired design predominantly involves single analogy examples, while compound analogy examples are rare.
- Compared to competing solutions, analogy-inspired designs commonly achieve improved performance and rarely achieve additional functionality.

Against expectations, few statistically significant relationships were detected between the characteristics examined in the full-scale study, namely:

- Analogy-inspired designs which achieve improved performance are less likely to also achieve additional functionality, and vice versa.
- Academic design teams are more likely to be BCD than non-academic teams.
- BCD teams are more strongly associated with solution-driven approaches than non-BCD teams, who are more strongly associated with problem-driven approaches. This is result merits further research in order to investigate the causative mechanisms which may be active.
- BCD teams are less likely than non-BCD teams to produce designs that achieve additional functionality. This is an interesting result which contradicts our expectations and merits further research.

Notably, apparent relationships in the pilot study results were not corroborated by the full-scale study. Specifically:

- The pilot study suggested that designers' occupation, a context characteristic, was related to the type of benefit achieved, an outcome characteristic. Academic designers were thought to achieve novel functionality more frequently, and improved performance less frequently, than non-academic designers. The full-scale study, however, did not find a statistically significant difference between academic and non-academic designers with respect to their use of analogies to achieve different types of benefits or advantages.
- The pilot study suggested that driving approaches, a context characteristic, may be related to designers' occupation (context) and benefits achieved (outcome). Solution-driven approaches appeared to be more associated with academic designers and with products which achieve novel functionality. The full-scale study, however, did not detect any statistically significant associations of solution- or problem-driven approaches with specific occupations or with particular achieved advantages.

Given these results, the presented work has been partially successful in addressing the defined research scope. Individual frequency distributions for multiple characteristics were measured and reported as trends, but analysis of joint frequencies in contingency tables yielded fewer relationships between characteristics than expected.

For the pilot study, a second research question was defined in Chapter 1:

Auxiliary research focus for pilot study:

*How are **critical functions** considered and used*
in real-world cases of analogy-inspired design?

In response to this question, two modes of critical function usage have been uncovered which support the concept of functionality as a basis for analogy retrieval tools.

- Designers commonly borrow critical functions from analog systems when adapting solutions for their products.
- Designers can invert critical functions from analog systems when adapting solutions for their products. The inversion examples detected in the study all involved reversible conversions of motion or energy.

The description of these modes embodies a successful response to the auxiliary research focus of the pilot study, which was the investigation of critical functionality.

5.2 Contributions of Research

In light of the presented results, the contributions of this thesis to the larger body of knowledge can be considered, guided by the two motivating questions from Chapter 1.

Motivating Question #1:

What principles and characteristics describe analogical inspiration processes?

The trends and relationships reported in this thesis provide one response to the first question. Relative to the characteristics investigated, the following conclusions from the investigation are salient:

1. **Analogical inspiration has been used to achieve improved performance and additional functionality in products.** Other advantages achieved include *novel functionality* and *enhanced user interaction*, as observed in the pilot study.
2. **Problem- and solution-driven (solution-driven) approaches are both used** in diverse instances of real-world analogy-inspired design, validating the approaches first codified by Helms, *et al.*, in a classroom study of bio-inspired design [80]. Both approaches appear to occur with nearly equal frequency, based on the full-scale study.
3. **Biological cross-disciplinarity in teams is associated with solution-driven approaches** in analogy-inspired design. This follows from the result showing that BCD team examples are more often associated with solution-driven approaches than problem-driven approaches, when compared with non-BCD teams. 3 mechanisms were proposed to explain this result, which merits further investigation.
4. **Critical functionality is a basis for analogical inspiration with two modes**: *direct functional transfer*, implying a straightforward matching of functions between analog and solution, and *inverted functional transfer*, where the senses of functions become reversed between the analog and solution. Inverted transfer examples in this work all involved the inversion of “Convert” functions.

As another response to the first motivating question, **a cross-sectional empirical product study method has been developed and demonstrated** in this thesis. The method combines the hypothesis-generating and pattern-finding power of traditional empirical product studies with the statistical rigor of cross-sectional study designs. It additionally incorporates formal sampling and screening techniques to minimize sampling bias and ensure generalizability of results. The method provides an improved capability for studying analogy-inspired design by serving as a versatile tool for systematic surveys of real-world examples. It thus empowers the research community to add ecological validity to the body of knowledge concerning analogies in design, addressing the concern raised by Cagan, *et al*, in a review of empirical design research: "[It] is critically important that research [which] examines the role of a certain type of cognition [in] creative design should strive for alignment across all levels of complexity and ecological relevance" (emphasis added) [4, 210].

Motivating Question #2:

How should methods and tools be developed to support analogical inspiration?

The 4 major research conclusions given in response to the first motivating question also form the basis for addressing the second question:

1. **Analogy tools should support consideration of expected performance impacts from analogy-inspired concepts.** Given that the majority of analogy-inspired products exhibit some advantage in performance over competitors (but rarely additional functionality or other advantages), analogy tools should aim to facilitate early thinking about how analogy-inspired concepts will impact design performance.
2. **Analogy tools should be developed to serve both problem- and solution-driven approaches**, since both are equally prevalent in practice. Tools need not

serve both approaches simultaneously, but there is currently a lack of tools for supporting solution-driven approaches.

3. **Analogy tools should incorporate critical functionality transfer and its two modes:** *direct functional transfer*, as already commonly applied in analogy tools, and *inverted functional transfer*, which is not explicitly accounted for in any analogy tool. In one instance, an introduction to the Biomimicry Taxonomy for the AskNature database tool briefly encourages users to search for functions which are opposite to what they intend to accomplish [211], but the tool itself does not support inversions of particular inputs. A separate, earlier case in the context of intelligent software agents is worth mention, however. Work by Murdock and Goel implemented an case-based reasoning framework in a reasoning program, known as REM (Reflective Evolutionary Mind), which could operate on an existing software agent (ADDAM) made to plan the disassembly of physical devices [212]. REM used internal definitions of inverse relations in order to adapt ADDAM to accomplish the inverse task of assembly planning. This example suggests that computational tools for analogy retrieval may use similar internal definitions of inverse functional relations in order to facilitate inverted functional transfer, and that these inverse relations can be defined on a higher-level meta-tool which operates on an original analogy retrieval tool (in the same manner as the REM program operated on the ADDAM tool to accomplish inversion).

5.3 Criticism and Continuation of Work

This section discusses limitations of the thesis work along with avenues for correction, followed by opportunities for continuing research.

The studies presented in this work suffer from the following methodological limitations which merit discussion:

- **Limitations from sampling bias in study collection.** Some limitations relate to bias in the collection of examples gathered for the studies. Bias in the reporting of examples presented an issue. Given that biomimicry and bio-inspired design have been effective buzzwords in academia in recent years [88], it is expected that examples from academia would be reported at a higher rate than examples outside academia. This has the dual effect of introducing inaccurately reported examples of bio-inspired design and overpopulating the collection with examples from academia. The screening protocol of the full-scale study addressed inaccurate reporting by excluding inaccurate and spurious accounts of analogical inspiration. To address the imbalance of academic and non-academic examples in this study collection, separate studies of each occupational domain are merited to distinguish the characteristics of both areas to discover if they in fact differ. Likewise, combining examples from separate partitions (AskNature and technology magazines) may have diluted the resulting frequency data. Misleading results may appear if the frequency distributions strongly differ between partitions. Thus, a separate study of each partition is merited, which would allow cross-validation of results from AskNature examples against results from examples reported in technology magazines and elsewhere.

- **Limitations of sample size.** Effect size estimation was not carried out prior to the study to determine necessary sample sizes. The major result of this was that insufficiently sample size strongly affected analysis concerning analogy characteristics, namely, Analogy Source Domain and Analogy Multiplicity. Each of these had a low-occurrence category (Man-made analogs and Compound analogies, respectively) which diminished the power of statistical tests to detect associations – thus limiting the ability to draw conclusions about these aspects of analogy-inspired design.
- **Limitations in repeatability of examples classification variables.** The full-scale studies relied on classification variables which were tested for repeatability using interrater agreement analyses. For all but one variable, namely, Additional Function, sufficient agreement was achieved to support repeatability (see Section 4.4). The Additional Function variable was adapted from the procedure of Saunders, *et al.*, who applied the variable to well-reported commercially-available products [115, 116]. In extending this variable for this work, difficulty was encountered for examples which have few direct or well-defined competitors' products for comparing functionality.

Apart from possibilities for addressing limitations, this work presents additional opportunities for continued research. In particular, this work can readily be extended by expanding the set of classification variables to measure additional aspects of analogy-inspired design:

- **Measures of analogy distance.** It would be greatly interesting to incorporate a measure of analogical distance and to investigate its relation to other variables.

The pilot study attempted to measure distance using Analogy Difference Levels, but systematizing this variable proved excessively difficult for the full-scale study and it was abandoned. However, promising avenues have been identified. Work by Fu, *et al.*, in structuring patent databases using document text-based algorithms suggests a highly-promising objective measure of distance based on node distance within algorithmically-derived concept structures [75]. Unfortunately, the technique is difficult to apply to examples with non-standardized source documents, as encountered in the present study. Furthermore, it is not known whether distance metrics can be calculated for multiple product-analog pairs and directly compared. Other work, such as that by McAdams and Wood [51], suggest a possible vector-based distance calculation using a general basis of system-level characteristics. The need for a viable analogy distance metric thus remains a challenge and an opportunity for the continued study of analogy-inspired product innovation.

- **Measures of product innovation and success.** Expanding the set of outcome variables to measure innovation, manufacturability, efficiency, and other product success indicators would be extremely valuable for understanding the impact of current design-by-analogy practices and products. Product flexibility may be measured using the procedure outlined by Rajan, *et al.* [118, 119]. The innovation characteristics developed by Saunders, *et al.*, concerning architecture, external interaction, user interaction, and cost characteristics [115, 116], are potentially suitable for expanding the current work – one of their characteristics, Additional Function, was already implemented as an outcome variable in this study.

Measurements of environmental impact can be adapted from the work of O'Rourke and Seepersad [86], and sustainability characteristics can be captured using the green design guidelines developed by Telenko and Seepersad [123, 124].

5.4 Closing Remarks

The cross-sectional product study method demonstrated in this work introduces a valuable method for investigating many factors and impacts of real-world analogy usage in design. Findings presented in this thesis contribute to characterizing analogical inspiration in real-world design and to informing the development of support tools for analogy usage. Combined with controlled experimentation, the method promises to reinforce and refute the conclusions of analogy usage studies in laboratory and classroom settings, as well as generate new hypotheses for investigation. As such, cross-sectional product studies represent a versatile new tool, descended from traditional empirical product studies, to augment empirical research in design and innovation.

APPENDIX A

PILOT STUDY EXAMPLE COLLECTION

The 57 product examples examined in the pilot study originate from a collection of articles gathered informally prior to the study. 77 initial examples are listed below, with #1-57 accepted in the final collection and #58-77 being removed from study.

Table 12. Analogy-inspired product examples in the pilot study analysis. Examples with asterisks were later thought to be explanatory rather than inventive analogies [36].

	Product / Solution Concept	Inspiring Analog	Sources
1	Sharklet antibacterial film	Shark skin	[144, 148, 213]
2	Avalanche airbags	Carrying slain game	[49, 140, 214]
3*	Avalanche airbag ripcord*	Parachute ripcord*	[140]
4	Smart sensing and control materials	Fish neuro-musculo-skeletal structure	[215]
5*	Intelligent Micro Optical Imaging Sys.*	Eyes ("6 types")*	[215]
6	Fiber-based fluid transport device	Butterfly proboscis	[215]
7	Nanoparticle-nanofiber interaction	DNA-protein interaction	[215]
8	Penguin robot mobility	Penguin mobility	[216, 217]
9	Penguin robot sonar	Penguin sensing	[216, 217]
10	Penguin robot network	Penguin communication	[216, 217]
11	Morphing aircraft wings	Bird wings	[218]
12	Robotic jellyfish	Jellyfish	[219, 220]
13	Robotic ray	Ray	[221, 222]
14	Marine antifouling surface polymers	Marine organism antifouling mechanisms	[223]
15	Marine hull grooming tool	Marine organism antifouling mechanisms	[223]
16	Hydrocyclone separators	Cyclonic separator	[224]
17	DNA origami lockbox	Lockbox	[225]
18	Marine antifouling surface topology	Dolphin skin	[226]
19	Dyson vacuum cleaner	Sawmill dust collector	[48, 227]
20	Dyson AirBlade hand dryer	Industrial air knives	[228]
21*	Dyson CR01 washing machine*	Hand-washing clothes*	[229]
22	Dyson Air Multiplier fan intake blades	Wings on birds of prey	[230]
23	B&D Dustbuster	Trimline phone and charger receptacle	[145, 146]
24*	B&D Dustbuster*	Vacuum cleaner crevice tool*	[145, 146]
25	B&D Dustbuster	Dustpan	[145, 146]
26	Insect-like flying robots	Flying insects	[231]
27	Reflective paint	Jewel beetle exoskeleton	[135]
28	Ultracane	Bat echolocation	[213]
29	High-speed train	Kingfisher birds	[213]
30	Wings, Fan blades, Turbine blades	Whale flippers with tubercules	[213]
31	Water-walking robot	Basilisk lizard	[213]
32	Electronics fabrication	Puffball sponge enzymatic growth	[213]
33	Self-reinforcing low-force drills	Horntail wasp drill appendages	[213]
34	X-ray detector microtubes	Lobster eyes	[213, 232]
35	Vaccine preservative	Resurrection plants, Water bears	[213]
36	Car panels	Toucan bill	[213]

37	UMaryland monocopter	Maple tree seeds	[233]
38	Synthetic insulation	Penguin down feathers	[234]
39	WeebleCopter	Weeble toy	[235]
40	Plasmobot	Slime molds	[236, 237]
41	Grasshopper robot	Grasshopper	[238]
42	Bat robot	Bat	[239]
43	Hummingbird robot	Hummingbird	[240]
44	Robotic flight yaw maneuver	Animal flight yaw maneuver	[241]
45	Robotic flight turn maneuvers	Animal flight turn maneuvers	[241]
46	Storm Stoppers protective paneling	Collegiate Hubcaps	[242]
47	Nonlinear acoustic lens	Newton's cradle toy	[134, 155, 243]
48	Steel Velcro	Velcro	[244]
49	Velcro	Hooked cocklebur seed burrs	[7, 245]
50	Tidal current turbine screw	Augers, screw conveyors	[143]
51*	Cs-137 trapping material*	Venus flytrap*	[150, 246]
52*	Spiderbot exploratory robot network*	Internet (robust data routing)*	[247]
53	Surface tension suction device	Beetle limb adhesion	[248]
54*	Antibacterial wound dressings*	Land mines*	[249]
55*	Prosthetic ski knee*	Bicycle shock absorbers*	[250]
56	Atmospheric water collection	Namibian beetle	[188]
57	Lotus effect surfaces	Lotus leaf	[251]

Table 13. Examples removed due to mistaken analogy identification

	Product / Solution Concept	Inspiring Analog
58	Avalanche airbag backpack	Car airbag
59	DNA origami	Paper origami
60	DNA origami	Cellular DNA structure self-assembly
61	Vacuum cleaning	Suction through a drinking straw
62	Formation flight algorithm	Bird formation flight behavior
63	Nontoxic silicone anti-fouling paint	Nonstick coating
64	3M Dual Lock fasteners	Mushrooms

Table 14. Examples removed due to lack of descriptive information

	Product / Solution Concept	Inspiring Analog
65	(Indeterminate)	Spider vision
66	(Indeterminate)	Venus flytrap hunting
67	(Indeterminate)	DNA behavior
68	Material production	Biological material production
69	(Indeterminate)	Neuron behavior

Table 15. Examples removed which contain explanatory analogies [36]

	Product / Solution Concept	Inspiring Analog
70	Anaconda wave turbine	Sea snake / Eel
71	Cyclonic separator	Natural vortices
72	Dyson vacuum cleaner telescopic wand	Collapsible hand telescope
73	Dyson DC15 vacuum cleaner "The Ball"	Ballbarrow
74	Dyson Ballbarrow	Rubber ball
75	Ekco Clip'n'stay clothespin	Animal jaw
76	Silent Velcro / Slidingly-engaging fasteners	Zippers
77	3M Dual Lock fasteners	Velcro

APPENDIX B

PILOT STUDY CLASSIFICATION DATA

The 3 tables below display the product example classification for the pilot study classification variables discussed in Chapter 3.

Table 16. Product and analog critical function identification

	Product / Solution Concept	Inspiring Analog	Product critical functions	Analog critical functions
1	Sharklet antibacterial film	Shark skin	Prevent biological material adhesion	Prevent biological material adhesion
2	Avalanche airbags	Carrying slain game	Increase volume	Increase volume
3*	Avalanche airbag ripcord*	Parachute ripcord*	Transmit signal	Transmit signal
4	Smart sensing and control materials	Fish neuro-musculo-skeletal structure	(not identified)	(not identified)
5*	Intelligent Micro Optical Imaging Systems*	Eyes ("6 types")*	(not identified)	(not identified)
6	Fiber-based fluid transport device	Butterfly proboscis	Transport fluid	Transport fluid
7	Nanoparticle-nanofiber interaction	DNA-protein interaction	Allow DOF Attach solid	Allow DOF Attach solid
8	Penguin robot mobility	Penguin mobility	Change hydrodynamic flow Impart force on liquid	Change hydrodynamic flow Impart force on liquid
9	Penguin robot sonar	Penguin sensing	Detect obstacles	Detect obstacles
10	Penguin robot network	Penguin communication	Communicate status	Communicate status
11	Morphing aircraft wings	Bird wings	Change aerodynamic flow	Change aerodynamic flow
12	Robotic jellyfish	Jellyfish	Impart force on liquid	Impart force on liquid
13	Robotic ray	Ray	Impart force on liquid Change hydrodynamic flow	Impart force on liquid Change hydrodynamic flow
14	Marine antifouling surface polymers	Marine organism antifouling mechanisms	Prevent biological material adhesion	Prevent biological material adhesion
15	Marine hull grooming tool	Marine organism antifouling mechanisms	Remove biological material	Remove biological material
16	Hydrocyclone separators	Cyclonic separator	Separate material	Separate material
17	DNA origami lockbox	Lockbox	Allow DOF Recognize key	Allow DOF Recognize key
18	Marine antifouling surface topology	Dolphin skin	Prevent biological material adhesion	Prevent biological material adhesion
19	Dyson vacuum cleaner	Sawmill dust collector	Separate material	Separate material
20	Dyson AirBlade hand dryer	Industrial air knives	Remove liquid	Separate material

21*	Dyson CR01 washing machine*	Hand-washing clothes*	Remove material	Remove material
22	Dyson Air Multiplier fan intake blades	Wings on birds of prey	(not identified)	(not identified)
23	B&D Dustbuster	Trimline phone and charger receptacle	(not identified)	(not identified)
24*	B&D Dustbuster*	Vacuum cleaner crevice tool*	(not identified)	(not identified)
25	B&D Dustbuster	Dustpan	(not identified)	(not identified)
26	Insect-like flying robots	Flying insects	(not identified)	(not identified)
27	Reflective paint	Jewel beetle exoskeleton	(not identified)	(not identified)
28	Ultracane	Bat echolocation	(not identified)	(not identified)
29	High-speed train	Kingfisher birds	Divert air flow	Divert air flow
30	Wings, Fan blades, Turbine blades	Whale flippers with tubercules	(not identified)	(not identified)
31	Water-walking robot	Basilisk lizard	(not identified)	(not identified)
32	Electronics fabrication	Puffball sponge enzymatic growth	(not identified)	(not identified)
33	Self-reinforcing low-force drills	Horntail wasp drill appendages	(not identified)	(not identified)
34	X-ray detector microtubes	Lobster eyes	(not identified)	(not identified)
35	Vaccine preservative	Resurrection plants, Water bears	(not identified)	(not identified)
36	Car panels	Toucan bill	(not identified)	(not identified)
37	UMaryland monocopter	Maple tree seeds	(not identified)	(not identified)
38	Synthetic insulation	Penguin down feathers	(not identified)	(not identified)
39	WeebleCopter	Weeble toy	(not identified)	(not identified)
40	Plasmobot	Slime molds	(not identified)	(not identified)
41	Grasshopper robot	Grasshopper	(not identified)	(not identified)
42	Bat robot	Bat	(not identified)	(not identified)
43	Hummingbird robot	Hummingbird	(not identified)	(not identified)
44	Robotic flight yaw maneuver	Animal flight yaw maneuver	Change orientation	Change orientation
45	Robotic flight turn maneuvers	Animal flight turn maneuvers	(not identified)	(not identified)
46	Storm Stoppers protective paneling	Collegiate Hubcaps	Attach solid	Attach solid
47	Nonlinear acoustic lens	Newton's cradle toy	Direct acoustic energy	Channel kinetic energy
48	Steel Velcro	Velcro	(not identified)	(not identified)
49	Velcro	Hooked cocklebur seed burrs	(not identified)	(not identified)
50	Tidal current turbine screw	Augers, screw conveyors	Convert fluid flow into rotation	Convert rotation into substance flow
51*	Cs-137 trapping material*	Venus flytrap*	(not identified)	(not identified)
52*	Spiderbot exploratory robot network*	Internet (robust data routing)*	(not identified)	(not identified)
53	Electronic surface tension suction device	Beetle limb adhesion	(not identified)	(not identified)

54*	Antibacterial wound dressings*	Land mines*	(not identified)	(not identified)
55*	Prosthetic ski knee*	Bicycle shock absorbers*	(not identified)	(not identified)
56	Atmospheric water collection	Namibian beetle	(not identified)	(not identified)
57	Lotus effect surfaces	Lotus leaf	(not identified)	(not identified)

Table 17. Product example classification for Main Benefit of Analogy Usage, Analogy Difference Level, and Inventors' Primary Field of Work

	Product / Solution Concept	Inspiring Analog	Main Benefit of Analogy Usage	Analogy Difference Level	Inventors' Primary Field of Work
1	Sharklet antibacterial film	Shark skin	Function	1	Academic
2	Avalanche airbags	Carrying slain game	Function	2	Commercial
3*	Avalanche airbag* ripcord	Parachute ripcord*	Performance	1	Commercial
4	Smart sensing and control materials	Fish neuro-musculo-skeletal structure	Function	1	Academic
5*	Intelligent Micro Optical Imaging Systems*	Eyes ("6 types")*	Performance	1	Academic
6	Fiber-based fluid transport device	Butterfly proboscis	Function	1	Academic
7	Nanoparticle-nanofiber interaction	DNA-protein interaction	Function	1	Academic
8	Penguin robot mobility	Penguin mobility	Performance	1	Commercial
9	Penguin robot sonar	Penguin sensing	Performance	1	Commercial
10	Penguin robot network	Penguin communication	Function	1	Commercial
11	Morphing aircraft wings	Bird wings	Performance	1	Academic
12	Robotic jellyfish	Jellyfish	Function	1	Commercial
13	Robotic ray	Ray	Performance	1	Commercial
14	Marine antifouling surface polymers	Marine organism antifouling mechanisms	Performance	1	Military Research
15	Marine hull grooming tool	Marine organism antifouling mechanisms	Performance	1	Military Research
16	Hydrocyclone separators	Cyclonic separator	Function	1	Commercial
17	DNA origami lockbox	Lockbox	Function	1	Academic
18	Marine antifouling surface topology	Dolphin skin	Performance	1	Academic
19	Dyson vacuum cleaner	Sawmill dust collector	Performance	1	Commercial
20	Dyson AirBlade hand dryer	Industrial air knives	Performance	2	Commercial

21*	Dyson CR01 washing machine*	Hand-washing clothes*	Performance	1	Commercial
22	Dyson Air Multiplier fan intake blades	Wings on birds of prey	Performance	2	Commercial
23	B&D Dustbuster	Trimline phone and charger receptacle	User Interaction	2	Commercial
24*	B&D Dustbuster*	Vacuum cleaner crevice tool*	User Interaction	1	Commercial
25	B&D Dustbuster	Dustpan	User Interaction	2	Commercial
26	Insect-like flying robots	Flying insects	Function	1	Academic
27	Reflective paint	Jewel beetle exoskeleton	Function	1	Academic
28	Ultracane	Bat echolocation	Function	1	Academic
29	High-speed train	Kingfisher birds	Performance	1	Commercial
30	Wings, Fan blades, Turbine blades	Whale flippers with tubercules	Performance	1	Academic
31	Water-walking robot	Basilisk lizard	Function	1	Academic
32	Electronics fabrication	Puffball sponge enzymatic growth	Function	1	Academic
33	Self-reinforcing low-force drills	Horntail wasp drill appendages	Performance	1	Academic
34	X-ray detector microtubes	Lobster eyes	Performance	1	Commercial
35	Vaccine preservative	Resurrection plants, Water bears	Function	2	Commercial
36	Car panels	Toucan bill	Performance	1	Academic
37	UMaryland monocopter	Maple tree seeds	Function	1	Academic
38	Synthetic insulation	Penguin down feathers	Performance	1	Academic
39	WeebleCopter	Weeble toy	Performance	1	Academic
40	Plasmobot	Slime molds	Function	1	Academic
41	Grasshopper robot	Grasshopper	Function	1	Academic
42	Bat robot	Bat	Function	1	Academic
43	Hummingbird robot	Hummingbird	Function	1	Commercial
44	Robotic flight yaw maneuver	Animal flight yaw maneuver	Performance	1	Academic
45	Robotic flight turn maneuvers	Animal flight turn maneuvers	Performance	1	Academic
46	Storm Stoppers protective paneling	Collegiate Hubcaps	Function	2	Commercial
47	Nonlinear acoustic lens	Newton's cradle toy	Function	2	Academic
48	Steel Velcro	Velcro	Performance	1	Academic
49	Velcro	Hooked cocklebur seed burrs	Function	1	Commercial
50	Tidal current turbine screw	Augers, screw conveyors	Performance	2	Commercial
51*	Cs-137 trapping material*	Venus flytrap*	Function	3	Academic

52	Spiderbot exploratory robot network	Internet (robust data routing)*	Function	1	Academic
53	Electronic surface tension suction device	Beetle limb adhesion	Function	1	Academic
54*	Antibacterial wound dressings*	Land mines*	Function	1	Academic
55*	Prosthetic ski knee*	Bicycle shock absorbers*	Function	1	Commercial
56	Atmospheric water collection	Namibian beetle	Function	1	Academic
57	Lotus effect surfaces	Lotus leaf	Function	1	Academic

Table 18. Product example classification for Driving Approach to Analogy Usage

	Product / Solution Concept	Inspiring Analog	Circumstances of analogy introduction	Driving Approach
1	Sharklet antibacterial film	Shark skin	Observation of sharks while investigating antifouling surfaces	Problem-driven
2	Avalanche airbags	Carrying slain game	Serendipitous discovery of burial prevention when carrying large game	Solution-driven
4	Smart sensing and control materials	Fish neuro-musculo-skeletal structure	General NSF award news. No well-defined product mentioned.	Solution-driven
19	Dyson vacuum cleaner	Sawmill dust collector	Problem first identified, Serendipitous analog discovery	Problem-driven
20	Dyson AirBlade hand dryer	Industrial air knives	Air knife technology was under development in same company and serendipitously linked to hand dryer problem.	Solution-driven
31	Water-walking robot	Basilisk lizard	Inspiration followed studying lizard biomechanics	Solution-driven
44	Robotic flight yaw maneuver	Animal flight yaw maneuver		Solution-driven
45	Robotic flight turn maneuvers	Animal flight turn maneuvers		Solution-driven
46	Storm Stoppers protective paneling	Collegiate Hubcaps	Inspired to adapt own past invention to new problem	Problem-driven
49	Velcro	Hooked cocklebur seed burrs	Observed natural system following curiosity	Solution-driven
50	Tidal current turbine screw	Augers, screw conveyors	Applied past experience and knowledge in augers and water screws	Solution-driven
55*	Prosthetic ski knee*	Bicycle shock absorbers*	Need for high-performance prosthetic led to invention.	Problem-driven
57	Lotus effect surfaces	Lotus leaf	Derived from study of lotus leaf self-cleaning	Solution-driven

APPENDIX C

FULL-SCALE STUDY EXAMPLE COLLECTION

The 70 product examples of the full scale study originate from a systematic search and screening process on two partitions: AskNature.org's bio-inspired product database and the articles of 3 technology magazines: *Popular Science*, *MIT Technology Review*, and *New Scientist*. By design, each partition contributed half of the 70 examples which were accepted for study.

Table 19. Analogy-inspired product examples accepted for the full-scale study. Examples #1-35 originate from the AskNature.org database while #36-70 originate from technology magazines. Examples with asterisks were later thought to be explanatory rather than inventive analogies [36].

	Product / Solution Concept	Inspiring Analog(s) (Feature)	Sources
1	Lunocet	Dolphin (tail)	[252-256]
2	NPD Self-repairing concrete	Time-release pills	[196, 197, 199, 257]
3	NagaokaU antireflective coating film	Moth (eyes)	[258-260]
4	Nike Terra Goatek shoes	Mountain goat (hooves)	[261-263]
5	TAU dipeptide nanospheres	Beta amyloid fibril formation (diphenylalanine recognition motif)	[264-267]
6	µMist® Platform Technology	Bombardier beetle (spray mechanism)	[268, 269]
7	TAU Dye-sensitized solar cell	Asian hornet (xanthopterin pigment)	[270-273]
8	Zeri coffee farming business model	Closed-loop ecosystems (material cycling)	[274-276]
9	LBNL Colorimetric biosensors	Cell membranes (E. coli toxin binding sites)	[277-279]
10	UMichigan Polymer nanocomposite material	Abalone (nacre)	[280-283]
11*	Cornell Vibro-Wind energy harvester*	Leaves*	[284, 285]
12	Logoplaste lightweight PET bottle	Whitebark pine tree [Pinus albicaulis Engelm] (spiral growth pattern)	[286-288]
13	UCSD Enzymatic pharmaceutical synthesis	Bacterium [Streptomyces maritimus] (synthesis)	[289-292]
14	SNU tactile sensor	Beetles (microtrichia)	[293-296]
15	CWRU Adaptive polymer nanocomposites	Sea cucumber (skin)	[297, 298]
16	EMPA Self-healing foams and membranes	Pipevine (self-healing tissue)	[299-302]
17	NWU Medical adhesive	Mussel (adhesive proteins)	[303-305]
18	QinetiQ Oxford Fog catching material	Namibian beetle (fog collection)	[187-190]
19	BASF Mincor TX TT textile coating	Lotus (leaf surface)	[306-308]
20*	Spaldin Tubes mattresses*	Bees (honeycomb)*	[309-312]
21	CAO lightweighting CAD method	Trees (adaptive growth)	[313-316]
22	Biomatrica SampleMatrix	Extremophiles (cryptobiosis, anhydrobiosis, trehalose)	[317-320]

23	Arnold Glas ORNILUX	Spider (UV-reflective silk)	[184-186]
24	Harvard SLIPS slippery surface	Pitcher plant (slippery lining)	[13, 14, 321, 322]
25	Veryan Medical BioMimics 3D stent	Human (vascular system)	[323, 324]
26	TecEco Eco-Cement	Plants and animals (carbon sequestration)	[325-327]
27	Sogang Humidity sensor	Hercules beetle (cuticle)	[328-331]
28*	Novomer CO2-based plastics*	Plants (rubisco and Calvin cycle, CO2 fixation)*	[332-334]
29	MUTE file sharing	Ants (search path behavior)	[335-337]
30	Shinkansen train	Kingfisher (beak) AND Owl (feathers)	[15, 16, 338]
31	Heliotrope sun tracker	Plants (heliotropism)	[339-342]
32	Duke superhydrophobic condenser	Lotus (leaf surface)	[343, 344]
33	Bonn superhydrophobic coating	Salvinia (surface hairs)	[11, 12, 345]
34	NanoChem BioPolymer thermal polyaspartate antiscalant	Oyster (oyster shell protein)	[346-348]
35	UF superhydrophobic hairy surface	Spider (hairs)	[349-351]
36	Fraunhofer IOF Trilobite camera	Wasp parasite [Xenos peckii] (eyes)	[352, 353]
37	EPFL Salamandra robot	Salamander	[354-356]
38	SNU flea robot	Flea (jumping)	[357, 358]
39	Buckliball	Hoberman Twist-O Transforming Sphere	[191-195]
40	Infofuses	DNA	[359-362]
41	UNamur LED Overlayer	Firefly (lantern)	[363-365]
42	UCB VELOCIRoACH	Cockroach (body, gait)	[180-183]
43	HelsinkiUT Nacre coating	Abalone (nacre)	[366-368]
44	UBath Gymnobot	Knifefish (dorsal fin)	[369-371]
45	GE Superhydrophobic metal coating	Lotus (leaf surface)	[10, 372]
46	Brinker Artificial pipeline platelets	Human (blood)	[373-375]
47	WhalePower tubercle wind turbine blades	Humpback whale (fin)	[376, 377]
48	NTU MASTER endoscopic robot	Crab (pincer)	[378-380]
49	UCSB Nanoassembly method	Marine sponge (spicule construction)	[381, 382]
50	TohokuU Amoeboid robot	Slime mold plasmodium (decision making)	[383-386]
51	UF - AFOSR Seagull UAVs	Seagull (wings)	[387-389]
52	UCB Shock absorber	Woodpecker (head)	[390, 391]
53	UUtah Adhesive	Sandcastle worm (reef construction)	[392-395]
54	BU Redowl sniper locator	Human (sound conduction and localization)	[396-399]
55	Harvard Nanofiber rotary jet spinning	Cotton candy machine (fiber spinning)	[400-402]
56	PolyU Holinser forceps system	Dental forceps (manual manipulation)	[403-405]
57	AeroVironment Hummingbird NAV	Hummingbird (hovering flapping flight)	[240, 406-408]
58	UCB Hybrid nacre ceramic	Abalone (nacre)	[409-411]
59	tenKsolar RAIS PV system	RAID (redundancy)	[412, 413]
60	SNU UCR M-Ink	Biological structural coloration	[414-417]
61	UCB UPenn Redesigned RHex	Spiders (leg spines) AND Cockroaches (horizontal leg movement)	[418-421]
62	NUS Robotic touch sensor	Human (fingerprints)	[422-424]
63	UCB Gecko-inspired synthetic adhesive tape	Gecko (foot setae)	[20, 425, 426]
64	Duke Nosehouse	Nasal counterflow exchangers	[427, 428]
65	Caltech VAWT wind farm packing	Fish schooling (vortex interaction)	[429-431]
66	KAIST Robotic human intention reading algorithm	Human (mirror neurons and simulation theory)	[432-434]
67	Stanford PETE solar energy converter	Cogeneration systems (waste heat-to-electricity conversion)	[435, 436]

68	Lockheed Martin SAMARAI monocopter	Maple seeds (autorotation)	[437-440]
69	MIT Brigham Porcupine quill adhesive	Porcupine	[441, 442]
70	Yale Rodolph robot	Bat AND Dolphin	[443-446]

APPENDIX D

FULL-SCALE STUDY CLASSIFICATION DATA

The tables below display the product example classification for the full-scale study classification variables discussed in Chapter 4. Nearly all identifications were based on direct text citations from the example sources – these citations are identified in an Excel spreadsheet data file which is available upon request.

Table 20. Product example classification for context variables: Inventors' Occupation, Biological Cross-disciplinarity, and Driving Approach to Analogy Usage

	Product / Solution Concept	Inspiring Analog(s) (Feature)	Inventor's Occupation	Biological Cross-disc.	Driving Approach
1	Lunocet	Dolphin (tail)	Non-academic	Non-BCD	Problem-driven
2	NPD Self-repairing concrete	Time-release pills	Academic	Non-BCD	Solution-driven
3	NagaokaU antireflective coating film	Moth (eyes)	Academic	Non-BCD	Problem-driven
4	Nike Terra Goatek shoes	Mountain goat (hooves)	Non-academic	Non-BCD	Problem-driven
5	TAU dipeptide nanospheres	Beta amyloid fibril formation (diphenylalanine recognition motif)	Academic	Cross	Solution-driven
6	µMist® Platform Technology	Bombardier beetle (spray mechanism)	Academic	Non-BCD	Solution-driven
7	TAU Dye-sensitized solar cell	Asian hornet (xanthopterin pigment)	Academic	Cross	Solution-driven
8	Zeri coffee farming business model	Closed-loop ecosystems (material cycling)	Non-academic	Non-BCD	Problem-driven
9	LBNL Colorimetric biosensors	Cell membranes (E. coli toxin binding sites)	Academic	Non-BCD	(undetermined)
10	UMichigan Polymer nanocomposite material	Abalone (nacre)	Academic	Cross	(undetermined)
11*	Cornell Vibro-Wind energy harvester*	Leaves*	Academic	Non-BCD	(undetermined)
12	Logoplaste lightweight PET bottle	Whitebark pine tree [Pinus albicaulis Engelm] (spiral growth pattern)	Non-academic	Non-BCD	Problem-driven
13	UCSD Enzymatic pharmaceutical synthesis	Bacterium [Streptomyces maritimus] (synthesis)	Academic	Cross	(undetermined)
14	SNU tactile sensor	Beetles (microtrichia)	Academic	Non-BCD	Problem-driven

15	CWRU Adaptive polymer nanocomposites	Sea cucumber (skin)	Academic	Cross	Solution-driven
16	EMPA Self-healing foams and membranes	Pipevine (self-healing tissue)	Academic	Cross	(undetermined)
17	NWU Medical adhesive	Mussel (adhesive proteins)	Academic	Cross	Solution-driven
18	QinetiQ Oxford Fog catching material	Namibian beetle (fog collection)	Mixed	Cross	Solution-driven
19	BASF Mincor TX TT textile coating	Lotus (leaf surface)	Non-academic	Non-BCD	(undetermined)
20*	Spaldin Tubes mattresses*	Bees (honeycomb)*	Non-academic	Non-BCD	Problem-driven
21	CAO lightweighting CAD method	Trees (adaptive growth)	Academic	Non-BCD	Solution-driven
22	Biomatrica SampleMatrix	Extremophiles (cryptobiosis, anhydrobiosis, trehalose)	Non-academic	Non-BCD	Solution-driven
23	Arnold Glas ORNILUX	Spider (UV-reflective silk)	Non-academic	Non-BCD	Solution-driven
24	Harvard SLIPS slippery surface	Pitcher plant (slippery lining)	Academic	Non-BCD	Problem-driven
25	Veryan Medical BioMimics 3D stent	Human (vascular system)	Academic	Non-BCD	Solution-driven
26	TecEco Eco-Cement	Plants and animals (carbon sequestration)	Non-academic	Non-BCD	(undetermined)
27	Sogang Humidity sensor	Hercules beetle (cuticle)	Academic	Cross	Solution-driven
28*	Novomer CO2-based plastics*	Plants (rubisco and Calvin cycle, CO2 fixation)*	Academic	Non-BCD	(undetermined)
29	MUTE file sharing	Ants (search path behavior)	Non-academic	Non-BCD	Solution-driven
30	Shinkansen train	Kingfisher (beak) AND Owl (feathers)	Non-academic	Non-BCD	Problem-driven
31	Heliotrope sun tracker	Plants (heliotropism)	Academic	Non-BCD	Problem-driven
32	Duke superhydrophobic condenser	Lotus (leaf surface)	Academic	Non-BCD	Problem-driven
33	Bonn superhydrophobic coating	Salvinia (surface hairs)	Academic	Cross	Solution-driven
34	NanoChem BioPolymer thermal polyaspartate antiscalant	Oyster (oyster shell protein)	Non-academic	Non-BCD	Solution-driven
35	UF superhydrophobic hairy surface	Spider (hairs)	Academic	Non-BCD	Problem-driven
36	Fraunhofer IOF Trilobite camera	Wasp parasite [Xenos peckii] (eyes)	Academic	Non-BCD	Solution-driven
37	EPFL Salamandra robot	Salamander	Academic	Non-BCD	(undetermined)
38	SNU flea robot	Flea (jumping)	Academic	Non-BCD	Problem-driven
39	Buckliball	Hoberman Twist-O Transforming Sphere	Academic	Non-BCD	Problem-driven
40	Infofuses	DNA	Academic	Cross	Problem-driven

41	UNamur LED Overlayer	Firefly (lantern)	Academic	Non-BCD	Problem-driven
42	UCB VELOCIRoACH	Cockroach (body, gait)	Academic	Non-BCD	Problem-driven
43	HelsinkiUT Nacre coating	Abalone (nacre)	Academic	Cross	(undetermined)
44	UBath Gymnobot	Knifefish (dorsal fin)	Academic	Non-BCD	(undetermined)
45	GE Superhydrophobic metal coating	Lotus (leaf surface)	Non-academic	Non-BCD	Solution-driven
46	Brinker Artificial pipeline platelets	Human (blood)	Academic	Non-BCD	Solution-driven
47	WhalePower tubercle wind turbine blades	Humpback whale (fin)	Academic	Non-BCD	Solution-driven
48	NTU MASTER endoscopic robot	Crab (pincer)	Mixed	Cross	Problem-driven
49	UCSB Nanoassembly method	Marine sponge (spicule construction)	Academic	Non-BCD	Solution-driven
50	TohokuU Amoeboid robot	Slime mold plasmodium (decision making)	Academic	Non-BCD	(undetermined)
51	UF - AFOSR Seagull UAVs	Seagull (wings)	Academic	Non-BCD	Problem-driven
52	UCB Shock absorber	Woodpecker (head)	Academic	Cross	Solution-driven
53	UUtah Adhesive	Sandcastle worm (reef construction)	Academic	Non-BCD	Solution-driven
54	BU Redowl sniper locator	Human (sound conduction and localization)	Academic	Cross	Solution-driven
55	Harvard Nanofiber rotary jet spinning	Cotton candy machine (fiber spinning)	Academic	Non-BCD	Problem-driven
56	PolyU Holinser forceps system	Dental forceps (manual manipulation)	Academic	Non-BCD	Problem-driven
57	AeroVironment Hummingbird NAV	Hummingbird (hovering flapping flight)	Non-academic	Non-BCD	Problem-driven
58	UCB Hybrid nacre ceramic	Abalone (nacre)	Academic	Non-BCD	Solution-driven
59	tenKsolar RAIS PV system	RAID (redundancy)	Non-academic	Non-BCD	Problem-driven
60	SNU UCR M-Ink	Biological structural coloration	Academic	Non-BCD	Solution-driven
61	UCB UPenn Redesigned RHex	Spiders (leg spines) AND Cockroaches (horizontal leg movement)	Academic	Cross	Solution-driven
62	NUS Robotic touch sensor	Human (fingerprints)	Academic	Non-BCD	Problem-driven
63	UCB Gecko-inspired synthetic adhesive tape	Gecko (foot setae)	Academic	Cross	Solution-driven
64	Duke Nosehouse	Nasal counterflow exchangers	Academic	Non-BCD	Solution-driven
65	Caltech VAWT wind farm packing	Fish schooling (vortex interaction)	Academic	Cross	Problem-driven
66	KAIST Robotic human intention reading algorithm	Human (mirror neurons and simulation theory)	Academic	Non-BCD	Problem-driven

67	Stanford PETE solar energy converter	Cogeneration systems (waste heat-to-electricity conversion)	Academic	Non-BCD	Problem-driven
68	Lockheed Martin SAMARAI monocopter	Maple seeds (autorotation)	Mixed	Non-BCD	Problem-driven
69	MIT Brigham Porcupine quill adhesive	Porcupine	Academic	Cross	Problem-driven
70	Yale Rodolph robot	Bat AND Dolphin	Academic	Non-BCD	Problem-driven

Table 21. Product example classification for analogy variables: Analogy Source Domain and Analogy Multiplicity

	Product / Solution Concept	Inspiring Analog(s) (Feature)	Source Domain	Multiplicity
1	Lunocet	Dolphin (tail)	Natural	Single
2	NPD Self-repairing concrete	Time-release pills	Man-made	Single
3	NagaokaU antireflective coating film	Moth (eyes)	Natural	Single
4	Nike Terra Goatek shoes	Mountain goat (hooves)	Natural	Single
5	TAU dipeptide nanospheres	Beta amyloid fibril formation (diphenylalanine recognition motif)	Natural	Single
6	µMist® Platform Technology	Bombardier beetle (spray mechanism)	Natural	Single
7	TAU Dye-sensitized solar cell	Asian hornet (xanthopterin pigment)	Natural	Single
8	Zeri coffee farming business model	Closed-loop ecosystems (material cycling)	Natural	Single
9	LBNL Colorimetric biosensors	Cell membranes (E. coli toxin binding sites)	Natural	Single
10	UMichigan Polymer nanocomposite material	Abalone (nacre)	Natural	Single
11*	Cornell Vibro-Wind energy harvester*	Leaves*	Natural	Single
12	Logoplaste lightweight PET bottle	Whitebark pine tree [Pinus albicaulis Engelm] (spiral growth pattern)	Natural	Single
13	UCSD Enzymatic pharmaceutical synthesis	Bacterium [Streptomyces maritimus] (synthesis)	Natural	Single
14	SNU tactile sensor	Beetles (microtrichia)	Natural	Single
15	CWRU Adaptive polymer nanocomposites	Sea cucumber (skin)	Natural	Single
16	EMPA Self-healing foams and membranes	Pipevine (self-healing tissue)	Natural	Single
17	NWU Medical adhesive	Mussel (adhesive proteins)	Natural	Single
18	QinetiQ Oxford Fog catching material	Namibian beetle (fog collection)	Natural	Single
19	BASF Mincor TX TT textile coating	Lotus (leaf surface)	Natural	Single
20*	Spaldin Tubes mattresses*	Bees (honeycomb)*	Natural	Single
21	CAO lightweighting CAD method	Trees (adaptive growth)	Natural	Single
22	Biomatrica SampleMatrix	Extremophiles (cryptobiosis, anhydrobiosis, trehalose)	Natural	Single
23	Arnold Glas ORNILUX	Spider (UV-reflective silk)	Natural	Single
24	Harvard SLIPS slippery surface	Pitcher plant (slippery lining)	Natural	Single

25	Veryan Medical BioMimics 3D stent	Human (vascular system)	Natural	Single
26	TecEco Eco-Cement	Plants and animals (carbon sequestration)	Natural	Single
27	Sogang Humidity sensor	Hercules beetle (cuticle)	Natural	Single
28*	Novomer CO2-based plastics*	Plants (rubisco and Calvin cycle, CO2 fixation)*	Natural	Single
29	MUTE file sharing	Ants (search path behavior)	Natural	Single
30	Shinkansen train	Kingfisher (beak) AND Owl (feathers)	Natural	Compound
31	Heliotrope sun tracker	Plants (heliotropism)	Natural	Single
32	Duke superhydrophobic condenser	Lotus (leaf surface)	Natural	Single
33	Bonn superhydrophobic coating	Salvinia (surface hairs)	Natural	Single
34	NanoChem BioPolymer thermal polyaspartate antiscalant	Oyster (oyster shell protein)	Natural	Single
35	UF superhydrophobic hairy surface	Spider (hairs)	Natural	Single
36	Fraunhofer IOF Trilobite camera	Wasp parasite [Xenos peckii] (eyes)	Natural	Single
37	EPFL Salamandra robot	Salamander	Natural	Single
38	SNU flea robot	Flea (jumping)	Natural	Single
39	Buckliball	Hoberman Twist-O Transforming Sphere	Man-made	Single
40	Infofuses	DNA	Natural	Single
41	UNamur LED Overlayer	Firefly (lantern)	Natural	Single
42	UCB VELOCIRoACH	Cockroach (body, gait)	Natural	Single
43	HelsinkiUT Nacre coating	Abalone (nacre)	Natural	Single
44	UBath Gymnobot	Knifefish (dorsal fin)	Natural	Single
45	GE Superhydrophobic metal coating	Lotus (leaf surface)	Natural	Single
46	Brinker Artificial pipeline platelets	Human (blood)	Natural	Single
47	WhalePower tubercle wind turbine blades	Humpback whale (fin)	Natural	Single
48	NTU MASTER endoscopic robot	Crab (pincer)	Natural	Single
49	UCSB Nanoassembly method	Marine sponge (spicule construction)	Natural	Single
50	TohokuU Amoeboid robot	Slime mold plasmodium (decision making)	Natural	Single
51	UF - AFOSR Seagull UAVs	Seagull (wings)	Natural	Single
52	UCB Shock absorber	Woodpecker (head)	Natural	Single
53	UUtah Adhesive	Sandcastle worm (reef construction)	Natural	Single
54	BU Redowl sniper locator	Human (sound conduction and localization)	Natural	Single
55	Harvard Nanofiber rotary jet spinning	Cotton candy machine (fiber spinning)	Man-made	Single
56	PolyU Holinser forceps system	Dental forceps (manual manipulation)	Man-made	Single
57	AeroVironment Hummingbird NAV	Hummingbird (hovering flapping flight)	Natural	Single
58	UCB Hybrid nacre ceramic	Abalone (nacre)	Natural	Single
59	tenKsolar RAIS PV system	RAID (redundancy)	Man-made	Single
60	SNU UCR M-Ink	Biological structural coloration	Natural	Single

61	UCB UPenn Redesigned RHex	Spiders (leg spines) AND Cockroaches (horizontal leg movement)	Natural	Compound
62	NUS Robotic touch sensor	Human (fingerprints)	Natural	Single
63	UCB Gecko-inspired synthetic adhesive tape	Gecko (foot setae)	Natural	Single
64	Duke Nosehouse	Nasal counterflow exchangers	Natural	Single
65	Caltech VAWT wind farm packing	Fish schooling (vortex interaction)	Natural	Single
66	KAIST Robotic human intention reading algorithm	Human (mirror neurons and simulation theory)	Natural	Single
67	Stanford PETE solar energy converter	Cogeneration systems (waste heat-to-electricity conversion)	Man-made	Single
68	Lockheed Martin SAMARAI monocopter	Maple seeds (autorotation)	Natural	Single
69	MIT Brigham Porcupine quill adhesive	Porcupine	Natural	Single
70	Yale Rodolph robot	Bat AND Dolphin	Natural	Compound

Table 22. Product example classification for outcome variables: Additional Function (AF) and Improved Performance (IP). Comparison products which were inferred and not explicitly identified in source text are given in parentheses.

	Product / Solution Concept	Inspiring Analog(s) (Feature)	Comparison products	AF	IP
1	Lunocet	Dolphin (tail)	Conventional monofins and bi-fins	-	YES
2	NPD Self-repairing concrete	Time-release pills	(Traditional concrete repair)	-	YES
3	NagaokaU antireflective coating film	Moth (eyes)	Uncovered solar cells	-	YES
4	Nike Terra Goatek shoes	Mountain goat (hooves)	(Trail running shoes)	-	YES
5	TAU dipeptide nanospheres	Beta amyloid fibril formation (diphenylalanine recognition motif)	(Nanostructures), (Materials), Kevlar, Steel, (Super-hard materials)	-	YES
6	µMist® Platform Technology	Bombardier beetle (spray mechanism)	Conventional fuel injector systems	-	YES
7	TAU Dye-sensitized solar cell	Asian hornet (xanthopterin pigment)	Conventional solar cell	-	-
8	Zeri coffee farming business model	Closed-loop ecosystems (material cycling)	Traditional coffee farming, Traditional mushroom farming	YES	YES
9	LBNL Colorimetric biosensors	Cell membranes (E. coli toxin binding sites)	(Conventional pathogen detection), Immunoassays, Cell cultures	-	YES
10	UMichigan Polymer nanocomposite material	Abalone (nacre)	(Ceramics), (Artificial nacres), (Materials), Steel, Kevlar	-	YES

11*	Cornell Vibro-Wind energy harvester*	Leaves*	Rotary wind turbines	-	YES
12	Logoplaste lightweight PET bottle	Whitebark pine tree [Pinus albicaulis Engelm] (spiral growth pattern)	Traditional PET bottles, Unmodified Vitalis PET bottle	-	YES
13	UCSD Enzymatic pharmaceutical synthesis	Bacterium [Streptomyces maritimus] (synthesis)	Conventional antibiotic synthesis	-	YES
14	SNU tactile sensor	Beetles (microtrichia)	Conventional strain gauge sensor	-	YES
15	CWRU Adaptive polymer nanocomposites	Sea cucumber (skin)	Traditional polymers, Traditional composite materials	YES	-
16	EMPA Self-healing foams and membranes	Pipevine (self-healing tissue)	Conventional pneumatic structures	-	YES
17	NWU Medical adhesive	Mussel (adhesive proteins)	Conventional medical adhesives	-	YES
18	QinetiQ Oxford Fog catching material	Namibian beetle (fog collection)	(Other water collecting methods), (Other fog collection systems)	-	YES
19	BASF Mincor TX TT textile coating	Lotus (leaf surface)	Teflon textile coating	-	-
20*	Spaldin Tubes mattresses*	Bees (honeycomb)*	Traditional mattress	-	YES
21	CAO lightweighting CAD method	Trees (adaptive growth)	Traditional structure design?, Linear analysis methods, Non-optimized structures?	-	YES
22	Biomatrica SampleMatrix	Extremophiles (cryptobiosis, anhydrobiosis, trehalose)	Vaccine refrigeration	-	YES
23	Arnold Glas ORNILUX	Spider (UV-reflective silk)	Conventional glass panel	YES	-
24	Harvard SLIPS slippery surface	Pitcher plant (slippery lining)	Nanostructured superhydrophobic surfaces (Lotus effect surfaces), Untreated surfaces	-	YES
25	Veryan Medical BioMimics 3D stent	Human (vascular system)	Straight stents	-	YES
26	TecEco Eco-Cement	Plants and animals (carbon sequestration)	Conventional Portland cement	YES	YES
27	Sogang Humidity sensor	Hercules beetle (cuticle)	Conventional humidity sensors	-	YES
28*	Novomer CO2-based plastics*	Plants (rubisco and Calvin cycle, CO2 fixation)*	Conventional oil-derived plastics	YES	YES
29	MUTE file sharing	Ants (search path behavior)	Other file sharing applications	-	YES
30	Shinkansen train	Kingfisher (beak) AND Owl (feathers)	Shinkansen 300 series nose // Shinkansen 300 series pantograph base	-	YES
31	Heliotrope sun tracker	Plants (heliotropism)	Mechanical sun tracker systems	-	YES
32	Duke superhydrophobic condenser	Lotus (leaf surface)	Standard condenser surface	-	YES
33	Bonn superhydrophobic coating	Salvinia (surface hairs)	Standard ship hull surface	-	YES

34	NanoChem BioPolymer thermal polyaspartate antiscalant	Oyster (oyster shell protein)	Polyacrylate antiscalant	-	YES
35	UF superhydrophobic hairy surface	Spider (hairs)	Uncoated surfaces, Teflon coatings, Wax coatings, Caulking, Lotus effect surfaces	-	YES
36	Fraunhofer IOF Trilobite camera	Wasp parasite [Xenos peckii] (eyes)	Conventional cameras, Other compound-eye cameras	-	YES
37	EPFL Salamandra robot	Salamander	Other locomoting robots	YES	YES
38	SNU flea robot	Flea (jumping)	Other robot actuation mechanisms	-	YES
39	Buckliball	Hoberman Twist-O Transforming Sphere	Other morphing structures, Other soft mechanical structures	YES	-
40	Infofuses	DNA	Other communications technologies, Other data storage and retrieval technologies, Cellular communications	-	YES
41	UNamur LED Overlayer	Firefly (lantern)	Unmodified LEDs	-	YES
42	UCB VELOCIRoACH	Cockroach (body, gait)	Other locomoting robots, Other legged/running robots	-	YES
43	HelsinkiUT Nacre coating	Abalone (nacre)	Other nanocomposite materials, Other artificial nacres, Steel, Ceramics	-	YES
44	UBath Gymnobot	Knifefish (dorsal fin)	Propeller-driven vessels	-	YES
45	GE Superhydrophobic metal coating	Lotus (leaf surface)	Other superhydrophobic materials, Unmodified metal surfaces, Standard de-icing methods	-	YES
46	Brinker Artificial pipeline platelets	Human (blood)	(Other methods of fixing leaky pipes), (Conventional pipelines), Remotely operated repair vehicles	-	YES
47	WhalePower tubercle wind turbine blades	Humpback whale (fin)	Conventional wind turbine blades	-	YES
48	NTU MASTER endoscopic robot	Crab (pincer)	Traditional stomach cancer tumor removal	-	YES
49	UCSB Nanoassembly method	Marine sponge (spicule construction)	Conventional semiconductor thin film production	YES	YES
50	TohokuU Amoeboid robot	Slime mold plasmodium (decision making)	Rigid robots, Centrally-commanded robots	YES	YES
51	UF - AFOSR Seagull UAVs	Seagull (wings)	Other unmanned aerial vehicles	YES	YES

52	UCB Shock absorber	Woodpecker (head)	Current flight recorder modules, Conventional hard resin protection methods	-	YES
53	UUtah Adhesive	Sandcastle worm (reef construction)	Current medical glues, Super glue, Metal bone setting hardware	YES	YES
54	BU Redowl sniper locator	Human (sound conduction and localization)	Other gunshot detection devices	-	YES
55	Harvard Nanofiber rotary jet spinning	Cotton candy machine (fiber spinning)	Nanofiber electrospinning	-	YES
56	PolyU Holinser forceps system	Dental forceps (manual manipulation)	(other tools?)	-	YES
57	AeroVironment Hummingbird NAV	Hummingbird (hovering flapping flight)	(other unmanned aerial vehicles?)	YES	-
58	UCB Hybrid nacre ceramic	Abalone (nacre)	Other materials, Metal alloys, Ceramics	-	YES
59	tenKsolar RAIS PV system	RAID (redundancy)	Conventional (series) solar panels, Electricity from typical coal or natural-gas power plants	-	YES
60	SNU UCR M-Ink	Biological structural coloration	Conventional pigments, Laser-beam surface patterning	YES	YES
61	UCB UPenn Redesigned RHex	Spiders (leg spines) AND Cockroaches (horizontal leg movement)	unmodified RHex, (other robots)	-	YES
62	NUS Robotic touch sensor	Human (fingerprints)	unmodified tactile sensors (smooth surface)	-	YES
63	UCB Gecko-inspired synthetic adhesive tape	Gecko (foot setae)	(adhesive tape)	-	YES
64	Duke Nosehouse	Nasal counterflow exchangers	(Conventional HVAC)	-	-
65	Caltech VAWT wind farm packing	Fish schooling (vortex interaction)	HAWT wind farms	-	YES
66	KAIST Robotic human intention reading algorithm	Human (mirror neurons and simulation theory)	(other robots that interact with humans ?)	YES	YES
67	Stanford PETE solar energy converter	Cogeneration systems (waste heat-to-electricity conversion)	Conventional solar cells	YES	YES
68	Lockheed Martin SAMARAI monocopter	Maple seeds (autorotation)	(other unmanned aerial vehicles?)	-	YES
69	MIT Brigham Porcupine quill adhesive	Porcupine	Sutures and staples	-	YES
70	Yale Rodolph robot	Bat AND Dolphin	Other robotic sonar systems, Robotic camera systems	-	YES

APPENDIX E

FULL-SCALE STUDY CONTINGENCY TABLE ANALYSIS

The contingency tables below display the joint (bivariate) frequencies for the full-scale study classification variables discussed in Chapter 4. Expected frequencies for each cell are shown in italics, with expected values less than 5 marked by an asterisk. Tables with such cells cannot be analyzed using the common Chi-square test for association. Instead, Barnard's multinomial exact test is used, with confidence interval constraints applied to the two nuisance parameters. The exact p-values are shown for each table.

Table 23. Contingency tables for all pairs of classification variables. Expected frequencies for each cell are shown in italics, with expected values less than 5 marked by an asterisk.

1) p = 0.020		Biological Cross-Disciplinarity		
		BCD	Non-BCD	Total
Inventors' Occupation	Academic	17 *13.19*	35 *38.81*	52
	Non-academic	0 *3.81**	15 *11.19*	15
	Total	17	50	67

2) p = 0.429		Driving Approach		
		Solution-driven	Problem-driven	Total
Inventors' Occupation	Academic	22 *20.62*	20 *21.38*	42
	Non-academic	5 *6.38*	8 *6.62*	13
	Total	27	28	55

3) p = 0.794		Analogy Multiplicity		
		Compound	Single	Total
Inventors' Occupation	Academic	2 *2.33**	50 *49.67*	52
	Non-academic	1 *0.67**	14 *14.33*	15
	Total	3	64	67

4) p = 0.893		Analogy Source Domain		
		Man-made	Natural	Total
Inventors' Occupation	Academic	5 *4.66**	47 *47.34*	52
	Non-academic	1 *1.34**	14 *13.66*	15
	Total	6	61	67

5) p = 0.795		Additional Function		
		Yes	No	Total
Inventors' Occupation	Academic	11 *11.64*	41 *40.36*	52
	Non-academic	4 *3.36**	11 *11.64*	15
	Total	15	52	67

6) p = 0.184		Improved Performance		
		Yes	No	Total
Inventors' Occupation	Academic	48 *46.57*	4 *5.43*	52
	Non-academic	12 *13.43*	3 *1.57**	15
	Total	60	7	67

7) p = 0.036		Driving Approach		
		Solution-driven	Problem-driven	Total
Biological Cross-Disciplinarity	Non-BCD	11 *7.24*	4 *7.76*	15
	BCD	17 *20.76*	26 *22.24*	43
	Total	28	30	58

8) p = 0.941		Analogy Multiplicity		
		Compound	Single	Total
Biological Cross-Disciplinarity	Non-BCD	1 *0.81**	18 *18.19*	19
	BCD	2 *2.19**	49 *48.81*	51
	Total	3	67	70

9) p = 0.128		Analogy Source Domain		
		Man-made	Natural	Total
Biological Cross-Disciplinarity ation	Non-BCD	0 *1.63**	19 *17.37*	19
	BCD	6 *4.37**	45 *46.63*	51
	Total	6	64	70

10) p = 0.047		Additional Function		
		Yes	No	Total
Biological Cross-Disciplinarity	Non-BCD	1 *4.07**	18 *14.93*	19
	BCD	14 *10.93*	37 *40.07*	51
	Total	15	55	70

11) p = 0.969		Improved Performance		
		Yes	No	Total
Biological Cross-Disciplinarity	Non-BCD	17 *17.10*	2 *1.90**	19
	BCD	46 *45.90*	5 *5.10*	51
	Total	63	7	70

12) p = 0.694		Analogy Multiplicity		
		Compound	Single	Total
Driving Approach	Solution-driv.	1 *1.45**	27 *26.55*	28
	Problem-driv.	2 *1.55**	28 *28.45*	30
	Total	3	55	58

13) p = 0.108		Analogy Source Domain		
		Man-made	Natural	Total
Driving Approach	Solution-driv.	1 *2.90**	27 *25.10*	28
	Problem-driv.	5 *3.10**	25 *26.90*	30
	Total	6	52	58

14) p = 0.853		Additional Function		
		Yes	No	Total
Driving Approach	Solution-driv.	5 *5.31*	23 *22.69*	28
	Problem-driv.	6 *5.69*	24 *24.31*	30
	Total	11	47	58

15) p = 0.411		Improved Performance		
		Yes	No	Total
Driving Approach	Solution-driv.	24 *25.10*	4 *2.90**	28
	Problem-driv.	28 *26.90*	2 *3.10**	30
	Total	52	6	58

16) p = 0.743		Analogy Source Domain		
		Man-made	Natural	Total
Analogy Multipliciry	Compound	0 *0.26**	3 *2.74**	3
	Single	6 *5.74*	61 *61.26*	67
	Total	6	64	70

17) p = 0.405		Additional Function		
		Yes	No	Total
Analogy Multipliciry	Compound	0 *0.64**	3 *2.36**	3
	Single	15 *14.36*	52 *52.64*	67
	Total	15	55	70

18) p = 0.677		Improved Performance		
		Yes	No	Total
Analogy Multipliciry	Compound	3 *2.70**	0 *0.30**	3
	Single	60 *60.30*	7 *6.70*	67
	Total	63	7	70

19) p = 0.542		Additional Function		
		Yes	No	Total
Analogy Source Domain	Compound	2 *1.29**	4 *4.71**	6
	Single	13 *13.71*	51 *50.29*	64
	Total	15	55	70

20) p = 0.712		Improved Performance		
		Yes	No	Total
Analogy Source Domain	Compound	5 *5.40*	1 *0.60**	6
	Single	58 *57.60*	6 *6.40*	64
	Total	63	7	70

21) p = 0.042		Improved Performance		
		Yes	No	Total
Additional Function	Compound	11 *13.50*	4 *1.50**	15
	Single	52 *49.50*	3 *5.50*	55
	Total	63	7	70

The data file and the R script for calculating the Barnard's exact p-values are given below.

Table 24. Product example classification data as appears in EPSdata.txt

Occup	BCD	Driver	Mult	Domain	AF	IP	Count
Acad	Non-BCD	Solu.	Single	.Nature	No-AF	No-IP	1
Acad	Non-BCD	Solu.	Single	.Nature	No-AF	IP	7
Acad	Non-BCD	Solu.	Single	.Nature	AF	IP	3
Acad	Non-BCD	Solu.	Single	Man	No-AF	IP	1
Acad	Non-BCD	Prob.	Single	.Nature	No-AF	IP	10
Acad	Non-BCD	Prob.	Single	.Nature	AF	IP	2
Acad	Non-BCD	Prob.	Single	Man	No-AF	IP	2
Acad	Non-BCD	Prob.	Single	Man	AF	No-IP	1
Acad	Non-BCD	Prob.	Single	Man	AF	IP	1
Acad	Non-BCD	Prob.	Comp.	.Nature	No-AF	IP	1
Acad	Non-BCD	unknown	Single	.Nature	No-AF	IP	2
Acad	Non-BCD	unknown	Single	.Nature	AF	IP	1
Acad	Non-BCD	?Inquiry	Single	.Nature	No-AF	IP	1
Acad	Non-BCD	?Inquiry	Single	.Nature	AF	IP	2
Acad	BCD	Solu.	Single	.Nature	No-AF	No-IP	1
Acad	BCD	Solu.	Single	.Nature	No-AF	IP	7
Acad	BCD	Solu.	Single	.Nature	AF	No-IP	1
Acad	BCD	Solu.	Comp.	.Nature	No-AF	IP	1
Acad	BCD	Prob.	Single	.Nature	No-AF	IP	3
Acad	BCD	unknown	Single	.Nature	No-AF	IP	4
Mixed	Non-BCD	Prob.	Single	.Nature	No-AF	IP	1
Mixed	BCD	Solu.	Single	.Nature	No-AF	IP	1
Mixed	BCD	Prob.	Single	.Nature	No-AF	IP	1
Nonacad	Non-BCD	Solu.	Single	.Nature	No-AF	IP	4
Nonacad	Non-BCD	Solu.	Single	.Nature	AF	No-IP	1
Nonacad	Non-BCD	Prob.	Single	.Nature	No-AF	IP	4
Nonacad	Non-BCD	Prob.	Single	.Nature	AF	No-IP	1
Nonacad	Non-BCD	Prob.	Single	.Nature	AF	IP	1
Nonacad	Non-BCD	Prob.	Single	Man	No-AF	IP	1
Nonacad	Non-BCD	Prob.	Comp.	.Nature	No-AF	IP	1
Nonacad	Non-BCD	unknown	Single	.Nature	No-AF	No-IP	1

```r
# Import libraries and packages
### Package ‘Exact’ is available from http://CRAN.R-project.org/package=Exact
library(MASS)
library(Exact)

# Read in data from EPSdata.txt
EPS = read.table("EPSdata.txt", header = T)

# Define trimmed data for classification labels which are excluded from analysis

### Trim data to remove “Mixed” Inventors’ Occupation examples
### EPStrim1 will contain data from only 67 of the 70 examples
EPStrim1 = EPS[EPS$Occup != "Mixed",]

### Trim data to remove undetermined Driving Approach examples
### EPStrim3 will contain data from only 58 of the 70 examples
EPStrim2 = EPS[EPS$Driver != "unknown" & EPS$Driver != "?Inquiry",]

### Trim data to remove both “Mixed” Inventors’ Occupation examples and
### undetermined Driving Approach examples
### EPStrim3 will contain data from only 55 of the 70 examples
EPStrim3 = EPS[EPS$Occup != "Mixed" & EPS$Driver != "unknown" & EPS$Driver !=
           "?Inquiry",]

# Create all 2x2 contingency tables (21 tables) using the xtabs function
### Create all tables with Inventors’ Occupation as left-axis variable
etable12 = xtabs(formula = Count ~ BCD + Occup, data = EPStrim1, exclude = c("Mixed",
           "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)
etable13 = xtabs(formula = Count ~ Driver + Occup, data = EPStrim3, exclude =
           c("Mixed", "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)
etable14 = xtabs(formula = Count ~ Mult + Occup, data = EPStrim1, exclude = c("Mixed",
           "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)
etable15 = xtabs(formula = Count ~ Domain + Occup, data = EPStrim1, exclude =
           c("Mixed", "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)
etable16 = xtabs(formula = Count ~ AF + Occup, data = EPStrim1, exclude = c("Mixed",
           "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)
etable17 = xtabs(formula = Count ~ IP + Occup, data = EPStrim1, exclude = c("Mixed",
           "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)

### Create remaining tables with Biological Cross-disciplinarity as left-axis variable
etable23 = xtabs(formula = Count ~ Driver + BCD, data = EPStrim2, exclude = c("Mixed",
           "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)
etable24 = xtabs(formula = Count ~ Mult + BCD, data = EPS, exclude = c("Mixed",
           "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)
etable25 = xtabs(formula = Count ~ Domain + BCD, data = EPS, exclude = c("Mixed",
           "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)
etable26 = xtabs(formula = Count ~ AF + BCD, data = EPS, exclude = c("Mixed",
           "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)
etable27 = xtabs(formula = Count ~ IP + BCD, data = EPS, exclude = c("Mixed",
           "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)

### Create remaining tables with Driving Approach as left-axis variable
etable34 = xtabs(formula = Count ~ Mult + Driver, data = EPStrim2, exclude = c("Mixed",
           "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)
etable35 = xtabs(formula = Count ~ Domain + Driver, data = EPStrim2, exclude =
           c("Mixed", "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)
etable36 = xtabs(formula = Count ~ AF + Driver, data = EPStrim2, exclude = c("Mixed",
           "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)
etable37 = xtabs(formula = Count ~ IP + Driver, data = EPStrim2, exclude = c("Mixed",
           "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)
```

```r
### Create remaining tables with Analogy Multiplicity as left-axis variable
etable45 = xtabs(formula = Count ~ Domain + Mult, data = EPS, exclude = c("Mixed",
           "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)
etable46 = xtabs(formula = Count ~ AF + Mult, data = EPS, exclude = c("Mixed",
           "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)
etable47 = xtabs(formula = Count ~ IP + Mult, data = EPS, exclude = c("Mixed",
           "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)

### Create remaining tables with Analogy Source Domain as left-axis variable
etable56 = xtabs(formula = Count ~ AF + Domain, data = EPS, exclude = c("Mixed",
           "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)
etable57 = xtabs(formula = Count ~ IP + Domain, data = EPS, exclude = c("Mixed",
           "unknown", "?Inquiry-driven"), drop.unused.levels = TRUE)

### Create remaining tables with Additional Functionality as left-axis variable
etable67 = xtabs(formula = Count ~ IP + AF, data = EPS, exclude = c("Mixed", "unknown",
           "?Inquiry-driven"), drop.unused.levels = TRUE)
etable76 = xtabs(formula = Count ~ AF + IP, data = EPS, exclude = c("Mixed", "unknown",
           "?Inquiry-driven"), drop.unused.levels = TRUE)

# Construct list of contingency tables
etable = list(etable12, etable13, etable14, etable15, etable16, etable17, etable23,
         etable24, etable25, etable26, etable27, etable34, etable35, etable36,
         etable37, etable45, etable46, etable47, etable56, etable57, etable67)

# Display all 21 contingency tables in console
etable


# Calculate and display Barnard's exact p-values, with interval approach
for(xt in etable) {
     print(exact.test(xt, model="Multinomial", interval=TRUE)$p.value)
}
```

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