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Bio-Inspired Design: An Overview Investigating Open Questions From the Broader Field of Design-by-Analogy

Bio-inspired design and the broader field of design-by-analogy have been the basis of numerous innovative designs throughout history; yet there remains much to be understood about these practices of design, their underlying cognitive mechanisms, and preferred ways in which to teach and support them. In this paper, we work to unify the broader design-by-analogy research literature with that of the bio-inspired design field, reviewing the current knowledge of designer cognition, the seminal supporting tools and methods for bio-inspired design, and postulating the future of bio-inspired design research from the larger design-by-analogy perspective. We examine seminal methods for supporting bio-inspired design, highlighting the areas well aligned with current findings in design-by-analogy cognition work and noting important areas for future research identified by the investigators responsible for these seminal tools and methods. Supplemental to the visions of these experts in bio-inspired design, we suggest additional projections for the future of the field, posing intriguing research questions to further unify the field of bio-inspired design with its broader resident field of design-by-analogy.
[DOI: 10.1115/1.4028289]

1 Introduction

Bio-inspired design is a cutting edge field of inquiry and practice, founded by thinkers such as Steele (bionics, 1950s), Schmitt (biomimetics, 1950s), and French (biologically inspired design, 1988) [1]. Many successful products have resulted from this approach or way of designing, drawing on form, function, and process-based inspiration from biology [2], and dating back to the 19th century, including barbed wire, Tiffany lamps, the Wright glider, the design of Central Park in Manhattan [3], and many more. Based on these and other bio-inspired designs, a number of foundational questions arise, including: how can we go about finding these elegant analogies without being well versed in biology and/or without counting on isolated experiences or chance?

To answer this question, researchers have worked to understand the cognitive mechanisms that underlie bio-inspired design, as well as developed tools and methods to support it. In this paper, we examine a set of seminal bio-inspired design methods and tools through the lens of the greater field of design-by-analogy (both in the cognitive psychology and engineering design communities) and review the existing literature on bio-inspired design cognition. Our goals are not to criticize existing methods, but rather, to relate and compare the literature, informing potential new research initiatives and identifying open questions and directions for the future of bio-inspired design research.

2 Research Methodology

2.1 Comparative Qualitative Research Method. Figure 1 depicts the comparative qualitative research methodology employed for analysis in this paper, defined by five steps: (1) examining the larger body of analogy literature and choosing a subset to identify cognitive mechanisms for design-by-analogy; (2) categorizing key findings from the analogy literature; (3) studying an existing set of seminal tools and methods for bio-inspired design, and the principles and considerations that underlie them; (4) reviewing the literature that addresses the cognitive psychology of bio-inspired design; and (5) analyzing gaps in the literature, questions yet to be addressed, and the future of the field of bio-inspired design.

2.1.1 Examining and Reducing Analogy Literature. We began by considering the research findings of those who study analogy. Identifying and investigating hundreds of contributions, the literature included in the analysis of this paper was chosen based on whether the publication advanced empirical understanding of how humans, often designers, work with analogy. Papers not included were those presenting tools or methods for design-by-analogy, unless in testing them, they uncovered and reported underlying cognitive mechanisms of design-by-analogy. The goal of this step was to characterize the current state of scientific knowledge around analogy, both generally and with respect to engineering design, in order to create a context within which bio-inspired design and its future as a field of inquiry is and should be considered.2

2.1.2 Categorizing and Synthesizing Key Findings From Analogy Literature. The subset of the larger body of analogy literature was categorized into key areas of research. These categories were considered iteratively and included input from a computational tool for structuring documents based on semantic similarity of their content. The purpose of this step is to explore multiple representations of the literature in order to uncover relationships, implications, and holistic perspectives on the state of the field. We chose our final categorization based on trends that emerged from the findings.

2.1.3 Studying Existing Seminal Tools and Methods for Bio-Inspired Design. A representative set of seminal tools for undertaking or supporting bio-inspired design was identified.

Contributed by the Design Theory and Methodology Committee of ASME for publication in the Journal of Mechanical Design. Manuscript received June 29, 2014; final manuscript received August 12, 2014; published online October 8, 2014. Editor: Shapour Azarm.

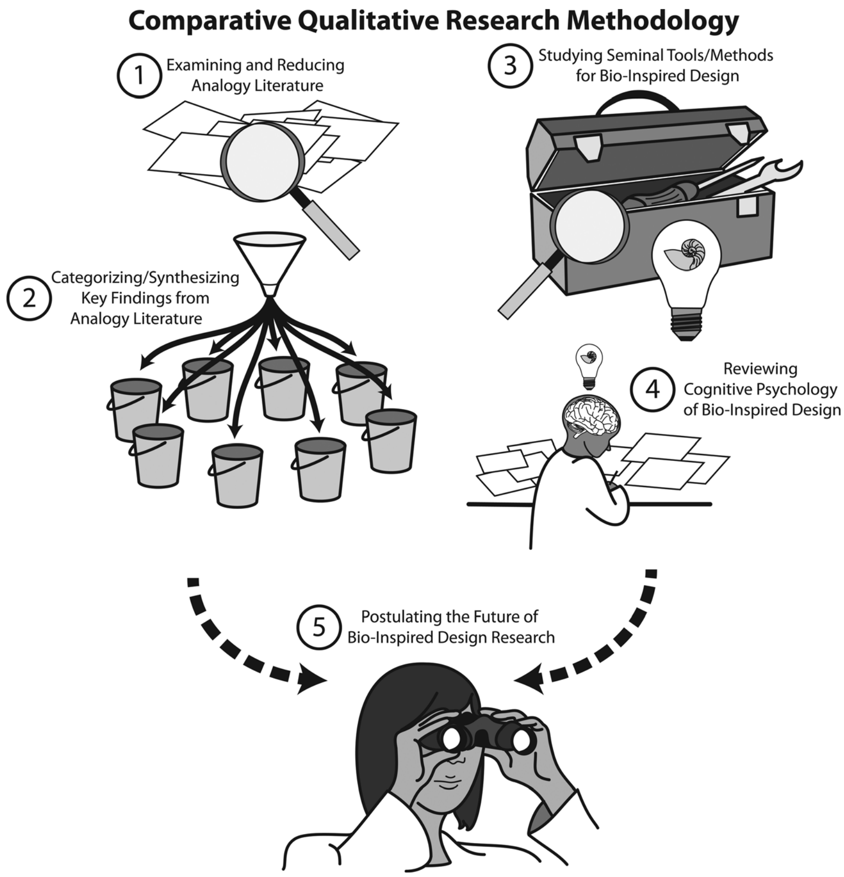


Fig. 1 Depiction of comparative qualitative research methodology

The creators of these methods and tools, Dr. L. Shu, Dr. D. A. McAdams, and Dr. R. Stone, generously shared their detailed materials, from which the authors have learned tremendously. The methods/tools are summarized with the intent of learning the ways in which bio-inspired design is currently performed and supported, understanding the underlying principles and considerations, and posing informed conjectures about some areas of future expansion of methods and tools for bio-inspired design.

2.1.4 Reviewing Cognitive Psychology of Bio-Inspired Design. The field of bio-inspired design research includes both efforts to develop tools/methods and study the cognitive mechanisms that underlie bio-inspired design. We reviewed studies from the latter effort to ascertain what is already known and what gaps exist, especially within the context of the broader analogy literature.

2.1.5 Postulating the Future of Bio-Inspired Design Research. Finally, we analyze the existing gaps in the literature, areas of contradiction, or lack of clarity, questions yet to be addressed, and more generally, the future of the field of bio-inspired design.

2.2 Quantitative Research Method. A quantitative analysis was performed to gain an understanding of the underlying structure, categories, and interrelationships of the literature based on solely the texts themselves. The process for quantitative structuring of this space was drawn from the previous work by the first author, in which text-based design databases were structured and explored [4,5]. A subset of 60 papers from the full literature review was used to get a general sense of the structure of the literature space, identify sparse regions, closely related categories, and gain a 2D spatial representation of the literature to date. The textual content of the papers was analyzed with Latent Semantic Analysis [6] to generate a similarity matrix, assigning a cosine similarity value to all pairwise comparisons of papers within the set. The similarity matrix was then used to generate structures of the data using Kemp and Tenenbaum's algorithm, for which the best fit was a grid structure out of eight different form types [7,8]. As postprocessing, the reference and a few key word identifiers were added to each paper "entity" within the structure, and regions were identified and overlaid by hand.

3 Review, Analysis, and Discussion

3.1 Methods and Tools for Supporting Bio-Inspired Design. From the well-known designs of Leonardo da Vinci (Fig. 2), bio-inspired design has emerged through the lens of visionaries and their establishment of identifiable areas of inquiry. Two such areas of relevance to bio-inspired design are biomimetics and bionics [9–11].

3.1.1 Biomimicry (Method and Taxonomy) and AskNature (Computational, Web Tool). Biomimicry, as a term within bio-inspired design, has its roots in biomimetics and bionics. An early

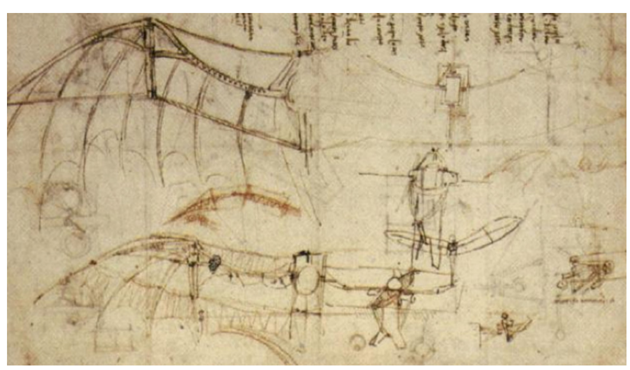


Fig. 2 Design for a flying machine, Leonardo Di Vinci, 1488 (Reprinted from source: Wikimedia Commons)

Fig. 3 Diagram illustrating biomimicry designlens, and its components: essential elements, life's principles, and biomimicry thinking (Reprinted from source: Biomimicry Institute 3.8 under Creative Commons License)[3]

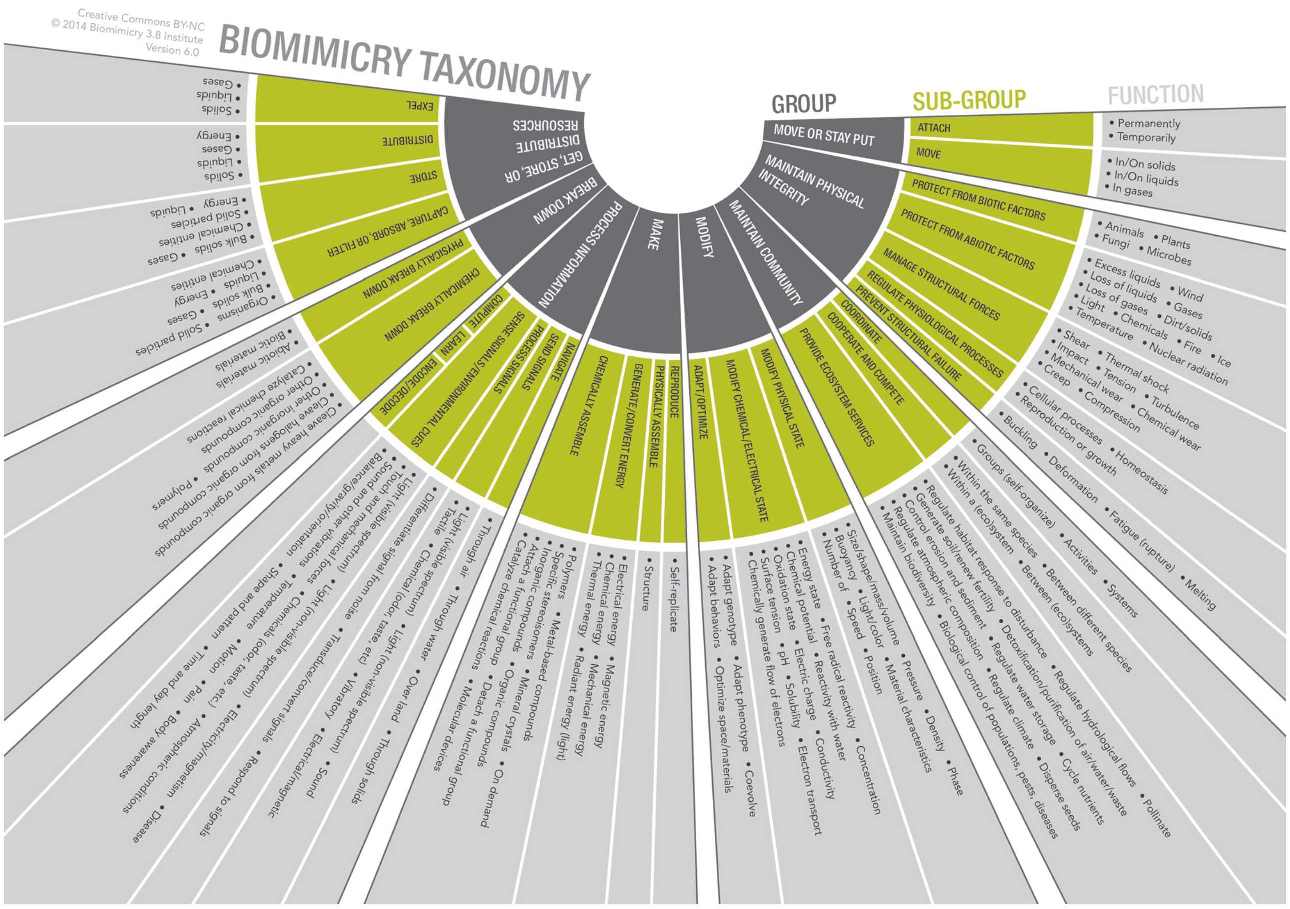


Fig. 4 Biomimicry taxomony, an underlying representational and search structure for AskNature (Reprinted from source: Biomimicry Institute 3.8 under Creative Commons License)[4]

use of the term appeared in a chemistry dissertation in 1982 [12]. More recently, Benyus defines biomimicry as a "…science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems" [2]. Benyus and colleagues developed taxonomies, methodologies (e.g., the biomimicry DesignLens and biomimicry thinking, Fig. 3), educational materials, and consulting services [33].[1]

This methodology includes an integral repository and online system known as AskNature,[2] an inspirational portal based on social networking and the sharing of biological knowledge. Figure 4 shows the underlying structure of the AskNature system known as the Biomimicry Taxonomy. This taxonomy abstracts

[1]http://biomimicry.net/

[2]www.AskNature.org
[3]http://biomimicry.net
[4]http://biomimicry.net

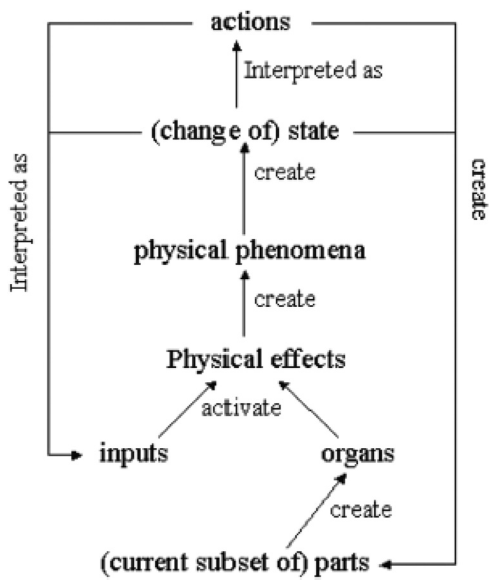


Fig. 5 SAPPhIRE causality model/representation to explain natural and artificial systems (Reprinted with Permission from Srinivasan, V., and Chakrabarti, A., 2009, "SAPPhIRE—An Approach to Analysis and Synthesis," paper presented at the Proceedings of ICED'09, the 17th International Conference on Engineering Design, Stanford, CA. Copyright 2009 by the Design Society) [15]

biological information in terms of high-level, intermediate-level, and granular functions, as well as some physical principles.

The authors observe that users approach the search engine similar to a web keyword search, as opposed to employing the taxonomy. For future directions, the authors state that considerations to assist users in taking advantage of the taxonomy will be examined to see if it increases user success rates.

3.1.2 IDEA-INSPIRE (Computational Tool). IDEA-INSPIRE is a computational tool developed by Chakrabarti et al. [13] to support generation of novel solutions for product design. Their method provides a systematic biomimetic search method that enables analogical reasoning at different levels of abstraction using inspirations from natural and artificial systems [13,14].

The method and software tool require a direct description of the design problem in one of two possible forms: (a) as a triplet: verb–noun–adjective/adverb (VNA) or (b) as a decomposition of the problem into subproblems to be searched. The causal description language, SAPPhIRE, Fig. 5, corresponds to the seven elementary constructs that enable system and state description: state-action-part-phenomenon-input-organ-effect has been implemented into the software called IDEA-INSPIRE that allows browsing of entries or forming searches of diverse complexity levels.

Future directions stated by the authors include expanding the databases to include more entries, developing strategies for more complex searches, exploring the process of triggering ideation, and further assessing the tool with more cases using more designers.

3.1.3 Biomimetic Design Through Natural Language Analysis (Method and Computational Tool). Chiu et al. [16] and Cheong et al. [17,18] identified design-by-analogy as an effective method for creativity, and that biology can be a powerful source for analogies. They proposed an approach to provide designers with useful words that enable effective search in the already available biological knowledge. The basic approach is proposed by Cheong et al. [17] for matching Functional Basis terms with meaningful biological keywords. Two works that predate this formal representation of the method with implemented biomimetic design examples can be found here [19,20].

The authors identified two areas of difficulty in using their method, which are fixation on particular phrases or words within the biological descriptions and difficulty transferring biological information to the target problem. They have explored ways to better support and structure the knowledge transfer process [21] and ways to identify a causal relationship in the biological stimuli to support analogical transfer [18]. They have found that designers need more explicit direction and strategies for performing the analogical transfer. The authors identify future directions of research that address the identification of relevant biological information as well as support the analogical transfer of the information to target engineering design problems.

3.1.4 Engineering-to-Biology Thesaurus (Tool) and Function-Based Biologically Inspired Design (Method). Nagel et al. devised an approach that uses functional modeling and the functional basis [26] to capture, in one form, the biological world in design. This approach differs with traditional design approaches because it starts from a biological system to extract analogical elements [22–25].

Future directions stated by the authors include exploring more specialized biological texts that encompass more specific information than the general texts, as well as employing clustering analysis to extract more complex relationships between terms.

3.1.5 Design by Analogy to Nature Engine (DANE) (Computational Tool). DANE provides a framework and access to a design case library containing structure–behavior– function (SBF) models of biological and engineering systems [27]. It also allows the designer to author SBF models of new systems and enter them into the library. Based on the information provided in DANE, users may search and access systems through a functional representation embedded in the library. Search results are presented to users in various multimedia forms.

Future directions stated by the authors include iterative deployment of the tool and expansion of the library through use by target end users.

3.1.6 TRIZ-Based Methods for Bio-Inspired Design. There have been a number of efforts to advance and formalize biomimetics. One such approach takes advantage of the normative TRIZ structure [9,28,29]. TRIZ has been extensively applied in different fields where the representation is in terms of function, generalized problem-formulation parameters, and contradictions [30].

One particular approach seeks to connect biomimetics systematically with TRIZ by redefining the 39 generalized parameters and contradiction matrix into a simplified BioTRIZ matrix [31] of 6×6 fields of principles. Through this approach, operations appropriate to biomimetics and bio-inspired analogies are mapped directly to TRIZ principles. One future direction stated by Vincent and Mann [30] includes examining the evolution and constraints that biology has addressed that may have been overlooked by or be predictive of future trends in technology.

3.1.7 Summary: Bio-Inspired Tools and Methods. The seminal bio-inspired design methods and tools reviewed in Secs. 3.1.1–3.1.6 can be found in summary in Table 1 below.

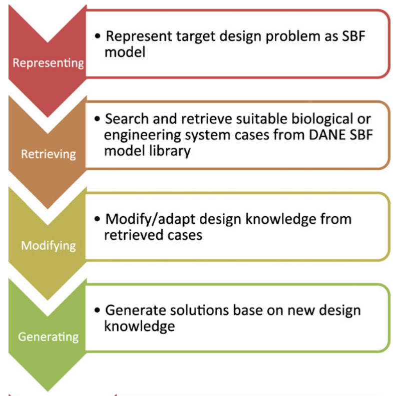
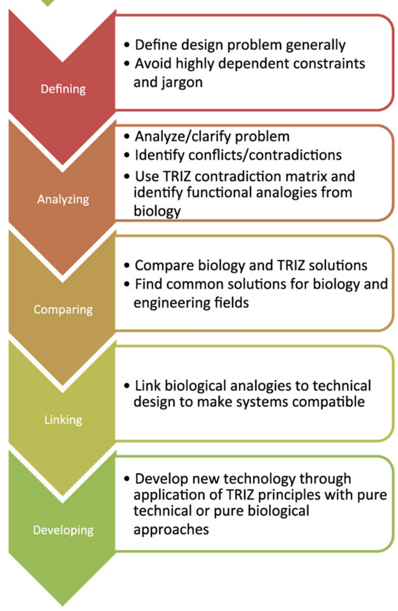
3.2 Results and Discussion of Quantitative Analysis of Literature. As outlined in Sec. 2.2, a quantitative analysis was performed to gain an understanding of the overall underlying structure, categories, and interrelationships of the literature based on solely the texts themselves. The computational methodology used to generate these results was published in Ref. [4]. Figure 6 shows the results of this process.

As observed from the regions indicated with shaded rectangles and larger-sized text for region labels, the quantitative analysis using purely textual content of the subset of papers led to clustering into very similar categories and areas of inquiry as those found when iteratively defining them qualitatively. Some interesting

Table 1 Summary of bio-inspired tools and methods

Bio-inspired technique—method	Representation	Elements—characteristics	Process	Literature—sources
Biomimicry and AskNature	Functional hierarchy/taxonomy, categories, and strategies for accessing biological inspiration	Function driven design Based on repository of examples/strategies Requires minimal preparation to use Open source	Scoping: • Define context • Identify function • Integrate life's principles Discovering: • Discover natural models • Abstract biological strategies Creating: • Brainstorm bio-inspired ideas • Emulate design principles Measuring: • Evaluate using life's principles	Deldin and Schuknecht [33][5]
IDEA-INSPIRE	Software based search and retrieval of both natural and artificial systems and strategies, founded on SAPPhiRE model (VNA) and/or functional modeling	Requires some preparation and learning to formulate design problem in terms of SAPPhIRE model (VNA triplets) Allows browsing of entries or forming searches of diverse complexity levels Based on repository of examples/strategies Requires access to proprietary software	Familiarizing: • Browse database of natural and artificial systems • Develop familiarity and intuition for the material Formulating: • Formulate/define design problem in terms of verb-noun-adjective (VNA) triplet(s) Constraining: • Provide constraints to assist the software (optional) Retrieving: • Receive software search results Mapping: • Map search results to solutions for design problem	Chakrabarti et al. [13]
Biomimetic design through natural language analysis	Method and computational tool for searching existing biology texts for relevant solutions/strategies	Function driven design Requires access to proprietary software	Selecting: • Select original functional keywords based on design problem Expanding: • Expand keywords using hypernyms, synonyms, and troponyms Searching: • Life texts and identify relevant matches • Find frequent words • Find verbs modified by frequent words Organizing: • Organize and correlate search results (verbs) Iterating: • Iterate on search through Life texts	Shu [34] Cheong et al. [17]
Engineering-to-biology thesaurus and function-based biologically inspired design	Translation of engineering to biology at a functional level and methodology to employ thesaurus in design process	Function driven technique Requires knowledge/learning/preparation of functional modeling Method drives functional modeling of biological system Thesaurus can be used for engineering to biology or biology to engineering translation Open source	Identifying: • Find good reference for biological system • Ascertain core functionality of biological system • Use thesaurus to understand relationship of biological flows to engineered flows Defining: • Define research question of functional model of biological system • Define biological category and scale of functional model Developing: • Develop functional model of biological system using functional basis • Use thesaurus to choose functions for realistic representation of system Validating: • Validate functional model with biology expert for correct use/interpretation of terms against research question, category and scale	Nagel et al. [22] Nagel et al. [23] Nagel and Stone [24]Nagel et al. [25]

Table 1 ***Continued***

Bio-inspired technique—method	Representation	Elements—characteristics	Process	Literature—sources
DANE	Database for searching and authoring SBF design cases/models	SBF driven design Requires knowledge/learning/preparation of SBF modeling Based on repository of cases/models Requires access to proprietary software		Vattam et al. [27]
BioTRIZ (and BEAST)	TRIZ-based biological solution search strategy	Conflict/contradiction driven design Requires knowledge/learning/preparation of TRIZ contradictions/conflicts and matrix Open source with proprietary software support available		Vincent and Mann [30] Craig et al. [28] Bogatyrev and Bogatyreva [31] Nix et al. [29]

observations that are distinct from the qualitatively generated categories include:

- Commonness/familiarity and distance of analogy seem to be semantically quite similar according to the structure, as they are grouped together based on their textual content; this could indicate that these areas have much more room for expansion and distinction from one another in terms of future research efforts;
- It is evident from this representation that there is overlap between regions; for example, there is overlap between fixation and expertise. This indicates that these two factors have been studied together in a number of papers, and signals that there is an opportunity to test the interactions of any combination of the major factors identified as categories in this structure/review;
- One area that was not explicitly discussed as a cognitive element, but rather an implementation/pragmatic factor, is connection to industry and design practice, which links to accessibility of the work to the general public;
- As would be expected, papers coming from the same research group were clustered together. More interestingly, however, is the clustering of temporally similar research—that is, older papers clustered on the right side of the structure, most likely due to the development of research questions and new knowledge over time, in that the seminal works studied foundational questions; it is exciting to consider that a structuring method such as this could indicate not only regions of the literature but also lineage of the knowledge over time.

[5]http://biomimicry.net/

3.3 Key Research Findings and Cognitive Elements From Analogy Literature. In examining the empirical studies of analogy and cognitive mechanisms impacting the use of analogy, we not only sought to extract the crucial findings of each contribution but also the forward looking questions for future research from the investigators. The categories that strongly emerged are reviewed in this section: fixation, incubation, memory, analogical reasoning processes, modality in representation, analogical distance, commonness of analogy, and expertise.

3.3.1 Fixation. Jansson and Smith define fixation as "blind adherence to a set of ideas or concepts limiting the output of conceptual design" [32]. Design-by-analogy is highly impacted by the effects of fixation, as it is always possible that analogical inspiration or stimuli can become a source of fixation for the designer, inhibiting her from searching the design space as broadly as she otherwise might have (Table 1). Thus, we must be informed about the ways in which we expose ourselves to external stimuli for

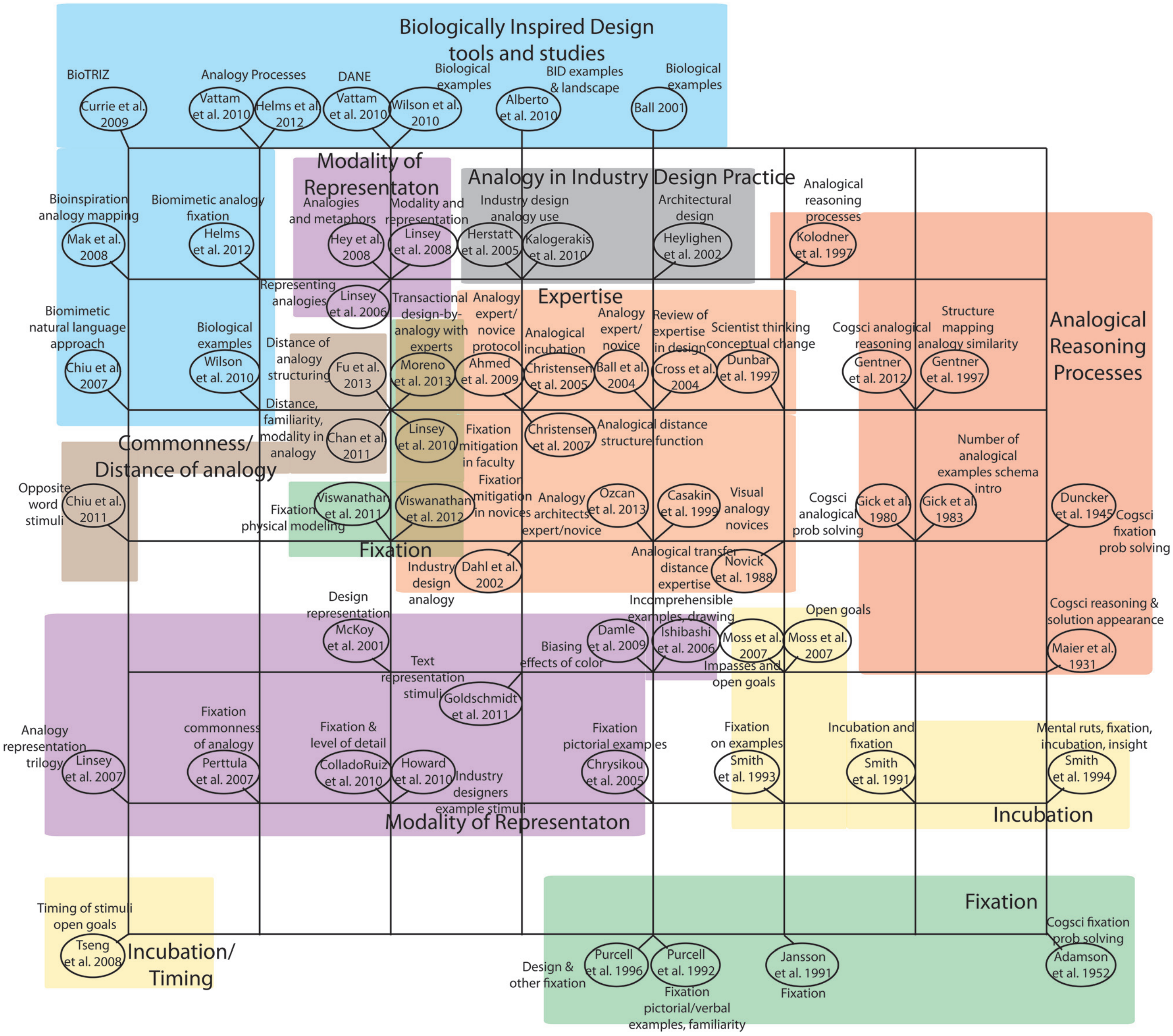


Fig. 6 Quantitative structuring analysis of 60 paper subset of literature

design-by-analogy in order to mitigate the negative effects of fixation. In Table 2, we review the current understanding of the phenomenon of fixation, and present questions and future research suggested by investigators who have studied fixation.

There is much left to understand about fixation and its effects on analogical thinking and designing. Moreno et al. provide a comprehensive review of design fixation, how it has and can be measured, and the state of the art for breaking fixation using design-by-analogy methods [50]. As with all of the subfields reviewed here, fixation is influenced by many confounding factors, like modality of representation, clarity, and experience/expertise/familiarity with the content of the stimuli, etc. The study of these interactions will paint a much clearer picture of the theory of fixation in the use of analogy in design.

3.3.2 Incubation. Smith and Blankenship describe incubation as a period of problem solving that occurs after initial failed attempts to solve a problem and after which an insight occurs suddenly and unpredictably, allowing the designer or problem solver to reach a solution; they were able to observe this phenomenon in a series of experiments [40]. Incubation is attributed to "unconscious work" on a problem, carried out while the designer is engaged in a different task than that of solving the design problem, or changing contexts. Table 3 summarizes the major findings on incubation in design cognition and design-by-analogy.

Incubation and open goals have the potential to be one of the most influential components of failed or successful design-by-analogy and should be considered not only in experimental design when studying analogy but also as a manipulable variable that may have an unexpected influence on results.

3.3.3 Memory. Unassisted design-by-analogy comes about through accessing, abstracting, and transferring knowledge already in the designer's possession from one domain to another, and thus is very closely entwined with aspects of human memory. Table 4 summarizes the major findings on memory in design cognition and design-by-analogy.

The way in which analogical information is encoded into memory could be highly affected by modality, learning styles, commonness of the information, fixation as an obvious barrier to retrieval, and even demographic factors that highly correlate with memory, like age of the designer. These factors should be examined as they relate to the performance in analogical reasoning and design activities.

3.3.4 Analogical Reasoning Processes. Table 5 summarizes the major findings on analogical reasoning processes in design cognition and design-by-analogy.

Appreciating these structures of understanding of analogical reasoning can allow us to systematically explore the space of

Table 2 Summary of major findings on fixation in design-by-analogy research

Authors/reference	Major findings/contributions	Key take away
Bogatyrev and Bogatyreva [32] Jansson and Smith [35]	Designers copied features from example solutions, even when explicitly instructed not to;	Designers don't have control over or awareness of when, how, and upon what they fixate
Smith et al. [36]	Fixation is often unintentional, and perhaps unavoidable Designers fixated on features that defied the guidelines of the design problem	
Chrysikou and Weisberg [37]		
Chrysikou and Weisberg [37]	Mechanical engineers and industrial designers fixate in different ways, with ME's becoming fixated on a particular unusual principle used to solve a problem, while ID's may become fixated on being "different"	Training, area of expertise, and experiences with existing concepts/ artifacts can change how one fixates
Purcell and Gero [38]	If information was unfamiliar, fixation effects did not occur; If familiar, strong fixation effects were observed[6]	
Purcell and Gero [39]	"Functional fixedness," was observed, the inability to rerepresent the functionality of an object into a new functional application due to fixation on its original contextual use	
Knoblich et al. [40]	To mitigate fixation, taking a break between an initial unsuccessful attempt at solving a problem and a second attempt can lead to unexpected insight (incubation)	Incubation can break fixation
Smith and Blankenship [41]	Effects of incubation, or "open goals" in problem solving were confirmed, and explain that it often occurs without conscious awareness for the designer	
Moss et al. [42] and Linsey et al. [43]	Multiple representations and rerepresentation of the design problem can help to break fixation	Fixation can be broken or mitigated by rerepresentation of the design problem
Linsey et al. [44,45] Smith et al. [36]	Defixating instructions or materials can mitigate fixation effects, but perhaps only for expert designers	
Viswanathan and Linsey [46]	Detailed information in the form of physical models or benchmarking products led to fixation, but "soft information," with more abstract yet still relevant information does not.	There are mixed reports of the fixation effects of physical models
Collado-Ruiz and Ostad-Ahmad-Ghorabi [47]	Fixation thought to be inherent to physical representations is in fact due to the Sunk Cost Effect, or reluctance to deviate from a design path upon which significant resources have been expended	
Viswanathan and Linsey [48]	Having designers copy examples that they could not understand assisted them in finding a new representation of the information in order to understand it	Fixation is not always necessarily a bad thing
Ishibashi and Okada [49]	SCAMPER method can enable designers to fixate usefully to refine concepts further, while also defixating by posing questions that can allow them to jump to other areas of design space	

research inquiries by examining each aspect of the elements identified by the investigators in this section. These structures also indicate potential alternative approaches for representing knowledge, sharing knowledge to designers, searching knowledge for analogies, and providing aids to map similarity features of analogies to target problems.

3.3.5 Modality in Representation. Modality in representation refers to the form that an example or analogical stimuli might take on, corresponding to the variety of sensory perceptions that might be involved in processing them. For example, a physical model or prototype representation of an analogical stimulus can be perceived through touch, sight, and even sound or smell, while text based or pictorial descriptions of the same stimulus can only be perceived through sight, and take a significantly different kind and possibly even effort of cognitive processing. Markman discusses the cognitive foundations of mental models and representation in Ref. [65]. Table 6 summarizes the major findings on modality in representation in design cognition and design-by-analogy.

It is apparent from these diverse findings that the theory of modality in representation of analogical stimuli has yet to be unified, and likely depends on many other factors, such as commonness, quality of rendering, clarity of text, analogical distance, etc. Nonetheless, the current findings and diversity of modal representations need to be considered as tools and methods are developed for analogical reasoning and design.

3.3.6 Analogical Distance. A key attribute of analogies to consider when choosing external stimuli or inspiration is analogical distance. Most often this variable is conceptualized as a dichotomy of near-field or far-field, where near-field, or "within domain," references a source and target from the same or very similar domains that may share a significant number of surface features, while far-field, or "between domain," refers to a source and target that originate from different domains and share little or no surface features. Table 7 summarizes the major findings on analogical distance in design cognition and design-by-analogy.

There is a need for a more rigorous definition of "near-field" and "-field" if a unified theory of analogical distance is to be established. This subfield is impacted by modality of representation, mental models of analogy, timing of introduction of the stimuli, and fixation effects, and thus interactions

[6]This result was derived from a preliminary study, which the authors were not able to replicate the fixation effects observed by Jansson and Smith; this was potentially due to the participants being novices in the study by Purcell and Gero which they were not in the former study, or due to the correlation within the examples of familiarity of aspects of the designs with frequency of occurrence, causing confounding effects in the results.

Table 3 Summary of major findings on incubation in design-by-analogy research

Authors/reference	Major findings/contributions	Key take away
Knoblich et al. [40]	Incubation was effective as a means to solving design problems after an impasse	Incubation is effective in helping designers overcome impasses
Smith and Blankenship [41] and Moreno et al. [51]	Hints to the solution of the problem aided in outcomes when presented implicitly during incubation, or "open goals"	Incubation helps designers apply relevant information to solve their problem
Moss et al. [52]	Incubation distinct from reminiscence, which is the successful retrieval of information from memory that initially could not be retrieved	Incubation is expressly linked to fixation and memory, and has interaction effects with distance of analogy
Knoblich et al. [40]	Incubation has been observed most successfully after fixation has been induced	
Bogatyrev and Bogatyreva [32]	Fixation may have long term effects from years of education or experience—a property that may also be tied up with incubation and the passing of time	
Smith [53]	Open goals were beneficial for employing far-field analogical stimuli; near-field stimuli was more beneficial if seen before solving began	

Table 4 Summary of major findings on memory in design-by-analogy research

Authors/reference	Major findings/contributions	Key take away
Tesng et al. [54]	Designers working in teams draw on their personal knowledge, and thus it is more unlikely in unassisted design-by-analogy that cross-domain transfer of knowledge will occur since it is limited by the designers finite familiar knowledge set	Unassisted cross-domain transfer of knowledge is difficult to achieve due to specific expertise and memory
Kalogerakis et al. [55]	Far-field analogies more difficult to retrieve from memory	Memory and distance of analogy are linked—far-field analogies are impeded by memory effects
Gick and Holyoak [56]	Far-field analogies can be difficult to notice as relevant to one's target problem	
Casakin and Goldschmidt [57] and Clement [58]	Retrieval can be facilitated if the analogy is encoded into memory in a way that allows key relationships to be applied to both source and target domains	There are ways to work with the properties of memory to facilitate design-by-analogy

Table 5 Summary of major findings on analogical reasoning processes in design-by-analogy research

Authors/reference	Major findings/contributions	Key take away
Clement et al. [59]	Analogical reasoning involves three main parts: retrieval, mapping, and evaluation	Analogical reasoning processes have been characterized by the phases, influencing factors, constraints and purposes served.
Clement et al. [59]	Three main kinds of factors influence success of analogical reasoning: the characteristics specific to the mapping itself, the characteristics of the human, and the characteristics of the task	
Gentner and Smith [60]	Mapping has three psychological constraints: the alignment has to be structurally consistent, the source and target need to have shared relations, and the more interconnected the underlying set of high order relations are, the better the match will be evaluated	
Gentner and Markman [61]	Analogy serves three purposes in ideation: identifying problems, communicating concepts, and solving problems	
Christensen and Schunn [62]	Distinction between metaphor and analogy in ideation; metaphors are used to frame the problem and understand the design situation; analogies are used in the conceptual design phase to map from source to target	In the context of ideation, metaphor is distinct from analogy
Hey et al. [63]	Four ways in which an analogy can be transferred or mapped: transferring an extant solution or technology from one domain to another, transferring the structure from source to target, partial transferring of functionality from source to target, and using analogy as an inspiration or stimulus for an idea	Types of analogical transfer can be characterized in multiples ways, but broadly speaking, range from surface level to deep analogy
Herstatt and Kalogerakis [64]	Two types of analogical transfer: "transformational" and "derivational"	

of these subfields of analogy must be studied in controlled ways.

3.3.7 Commonness of Analogy. Commonness of analogy is defined as how prevalently analogies are found in designers' worlds and increases with the probability that a designer would have had prior exposure to the analogy or with significant features or knowledge-domain content of the analogy. Purcell and Gero explain that, psychologically, the degree to which an example design or analogical stimulus activates relevant prior knowledge of a designer, for example, from everyday experience, coursework, or design practice, is the indicator of its commonness [38]. Table 8 summarizes the major findings on commonness in design-by-analogy research.

Table 6 Summary of major findings on modality in representation in design-by-analogy research

Authors/reference	Major findings/contributions	Key take away
Markman [66]	The best schema for analogical stimuli are two dissimilar examples that capture high level essential relations pertinent to the solution while excluding unimportant domain-specific information	Too much superficial detail in representation of analogical stimuli can have negative effects on design outcomes
Gick and Holyoak [67]	Stimuli with a high degree of superficial detail, which tends to be true of (i.e., detailed prototypes) restricted retrieval of far-field analogies from memory	
Christensen and Schunn [68]	Color has an effect in sketching during ideation that causes designers to fixate early on the details of the design	
Gick and Holyoak [56]	Visual analogies have been shown to improve problem solving in design in both experts and nonexperts, though more for nonexperts	Some researchers found visual analogies to be most beneficial to design
Damle and Smith [69]	Pictorial stimuli led to higher quality and more novel designs than text stimuli	
Purcell and Gero [38]	Modality was modulated by the commonness of the analogy; pictorial stimuli had no positive effect if stimulus was unfamiliar/uncommon, but familiar stimuli led to design fixation and increased variety of designs; textual representations of the same stimuli produced significantly less fixation	Others have found that text based stimuli is most beneficial to design
McKoy et al. [70]	Text stimuli led to greater originality of design outcomes when compared to no stimulus	
Moss et al. [42] and Linsey et al. [43]	Multiple representations were best for more fully enabled analogical reasoning	Still others found that multiple modalities were best for design

Table 7 Summary of major findings on analogical distance in design-by-analogy research

Authors/reference	Major findings/contributions	Key take away
Gentner and Smith [60]	Possibility for creative insights is highest when two domains being related by analogy are dissimilar to one another on the surface	The larger faction of researchers argues that far-field analogies are most beneficial to innovation in design
Goldschmidt and Sever [71]	Originality of design outcomes was positively correlated with the number of far-field analogies used during ideation	
Dahl and Moreau [72]	With biological examples used as stimuli, far-field examples increased idea novelty compared to the control, whereas near-field examples decreased idea variety	
Hey et al. [63]	The probability of breakthrough innovation is positively related to the distance of analogy used during ideation	
Wilson et al. [73]	Oppositely related word stimuli lead to novel design outcomes because they make designers reconceptualize the meaning of the words to integrate them into design concepts	
Tseng et al. [54]	Analogical distance was positively related to solution novelty; far-field analogies foster better communication with stakeholders	
Chiu and Shu [74] and Dunbar [75]	Disagree that far-field analogies are always the best choice to enhance ideation outcomes	Other researchers disagree that far-field analogies are always most beneficial
Kalogerakis et al. [55]	Analogies to solve problems were a mix of near and far-field; far-field analogies can be difficult to retrieve from memory	
Gick and Holyoak [56]	Far-field analogies can be hard to notice as relevant to the target domain	
Gentner and Markman [61]	Analogy served three functions within design process; analogies for identifying problems tended to be near-field; those used to explain concepts were mainly far-field	Others found that benefits of analogical distance depend on other factors, and neither near or far-field are necessarily always best
Fu et al. [5] and Weisberg [76]	Analogical distance often contextually defined; there is a potential “sweet spot” of analogical distance, where “too near” analogies may be trivial or fixating, and “too far” analogies may be difficult to usefully apply to the target domain	
Smith [53]	Benefits of distance of analogy depended on the timing of the introduction of the stimuli; far-field showed benefits once open goals were established; near-field, showed benefits when introduced before initial problem solving began	

Commonness is an aspect of analogy that is less studied than other subfields, but highly relevant to the success of designing with analogy. Commonness of analogy is referentially defined, influenced by the particular designer’s context, training and experience, making it decidedly linked to expertise. In addition, there is indication that successful retrieval, abstraction, mapping/transfer of the analogical content from source to target is sensitive to the commonness of the stimuli, subject to the pitfalls of fixation, difficulty in understanding the content of the source due to lack of familiarity or experience with it, or lack of clarity in the representation of the stimulus.

3.3.8 Expertise. Expertise has been studied extensively with respect to analogy in conceptual design. Here, we include a

Table 8 Summary of major findings on commonness in design-by-analogy research

Authors/reference	Major findings/contributions	Key take away
Chan et al. [77], Duncker [78], and Maier [79]	After prior experience with an artifact, people have difficulty seeing alternative uses for it, called "functional fixedness"	Less common stimuli were found to be more beneficial to design than more common stimuli
Viswanathan and Linsey [48]	Having artists copy novel (or uncommon) artwork enabled them to flexibly rerepresent artwork of others and increased novelty of art produced	
Weisberg [76]	If analogical stimuli is both uncommon and far-field, it has a positive effect on the novelty of design outcomes	
Adamson [80]	Commonness is inversely related to probability of fixation on the stimuli	Some researchers disagree, finding an inverse correlation between commonness and probability of fixation

Table 9 Summary of major findings on expertise in design-by-analogy research

Authors/reference	Major findings/contributions	Key take away
Perttula and Sipila [81]	Novices in design tend to approach ideation with a depth-first strategy, whereas experts tend to use a breadth-first strategy	Novices show distinct differences from experts in design-by-analogy execution, and generally have more difficulty with it
Gick and Holyoak [56] and Cross [82]	Novices may have more difficulty with analogical mapping than experts	
Novick [83]	Novices have greater difficulty with retrieval and mapping concepts from disparate domains	
Kolodner [84]	With engineers, experts use significantly more analogies than novices; novices tend to analogize over specific, concrete examples, whereas experts use a more schema-driven approach, analogizing of multiple examples to achieve a more general design solution	In different and particular domains of knowledge, experts and novices use analogies differently. Generally, across fields, experts demonstrate behavior that leads to more success in design-by-analogy
Ball et al. [85]	In architecture, novices lean toward "mental leaps" without awareness of their feasibility, whereas experts lean toward "mental hops"; intermediate level designers tended to directly copy the examples	
Ozkan and Dogan [86]	In transactional design, design-by-analogy, as exercised by experts, can lead to successful design outcomes	
Moreno et al. [87]	In aerospace, novices tended to transfer information based on geometric attributes, often without particular applicability or appropriateness for the given design problem; experts used analogies from problem identification, solving, and reasoning about the functionality and predicted behavior of a proposed component	
Gick and Holyoak [56]	Visual analogies tend to be more beneficial for novices than for experts, though they aid both in problem solving	Novices and experts are similar in some respects, including benefiting from visual analogies and susceptibility to fixation
Linsey et al. [44,45]	Novices and experts fixate to the same degree on features of an example solution, but experts can produce more nonredundant ideas and can mitigate their fixation with the help of defixation materials	

review of the findings with the intention of examining the implications on how designers learn at different levels of experience in the use of analogy in the design process, and how to model our methods, interactions, and artificially intelligent approaches to aid design-by-analogy. Cross has written an extensive review of the literature on expertise in design, to which we refer the reader for more detail on the subject [81]. Table 9 summarizes the major findings on expertise in design-by-analogy.

It is evident that the spectrum of expertise results in different behaviors in design activities, which is important to consider as we develop educational modules in BID, or even experienced designers in techniques that are new to them. The field of expertise is touched by all of the aforementioned subareas of the study of analogy in Sec. 3.3, since experts and novices are all designers at difference levels of experience. The most impactful aspect of the study of expertise is its extension to improving design education and support tools/methods.

3.4 Cognitive Studies on Bio-Inspired Design. Certainly, there are cognitive mechanisms that are unique to bio-inspired design, and a number of investigators have worked to uncover these. Of course, their findings enrich the understanding of design-by-analogy and could extend to the broader context; considering that all findings of empirical laboratory experiments are limited to the context, problem, conditions, participants, assumptions, and many other elements with which the studies were designed and executed, this is true of any cognitive study in analogy or not. Table 10 summarizes the major findings on cognitive aspects of bio-inspired design.

These cognitive studies are a snapshot of investigations into cognitive elements of analogy research and point to important findings relative to the more general analogy literature. They also, implicitly, demonstrate gaps and opportunities for further studies. For further reading on biologically inspired design and an alternate presentation of the field, refer to the work of Shu et al. [100].

4 Future Directions for Bio-Inspired Design Research

We summarize our analysis and impressions of the state-of-the-art knowledge in biologically inspired design in Fig. 7 and present the corresponding nomenclature. The evaluations in Fig. 7 were collectively agreed upon through consensus by the authors after examining and using the methods. Due to the review-based nature of this paper, inter-rater agreement was not deemed necessary for this analysis.

Table 10 Summary of major findings on cognitive aspects of bio-inspired design

Authors/reference	Major findings/contributions	Key take away
Shu [21]	Students had difficulty mapping analogies from biology to engineering domain, fixating on applying strategies only to specific parts of the design problem; more generalized descriptions of biological phenomena could help with transfer	Designers, and novices in particular, have difficulty abstracting strategy level principles during BID, showing particular susceptibility to fixation on superficial details
Ahmed and Christensen [88]	Designers fixate on irrelevant superficial content of biological knowledge when mapping, and had difficulty identifying the relevant analogy; novice designers tended to map specific features of stimuli, as opposed to identifying an overall analogy and employing it in multiple ways	
Cheong et al. [89]	Abstraction of biological nouns led novice designers to fixate on other nonabstracted words, e.g., verbs in text descriptions, and reduced ability to understand biological phenomena	
Feng et al. [90]	Problem-based versus solution-based approaches to BID: solution-based approaches tended to constrain rest of design process, while problem-based approaches led to fixation on the biological solution. Other observed pitfalls included improper analogical transfer and poor problem definition	
Helms et al. [91]	Success of BID is highly influenced by the designer's own prior knowledge of biology, which can both help or hurt the process	BID outcomes are affected by aspects of design-by-analogy, including distance of analogy, modality of representation, and expertise, surely among many others
Dahl and Moreau [72]	Biological examples improved novelty without inhibiting variety; far-field biological examples led to more successful higher levels of abstraction, believed to cause greater variety; near-field and far-field biological stimuli both caused fixation, with near-field participants fixating on surface and structural aspects; far-field participants fixated on structural aspects	
Merrill [13] and Currie et al. [92]	Investigated how different modes of representation affect the nature of design outcomes in the context of bio-inspired design	
Sarkar and Chakrabarti [93]	In a BID course, analogies were used in almost all phases of design process; analogies classified into five types: direct transfer, schema induction, problem transformation, deferred goal, and compositional analogy	Analogical reasoning processes and aspects of the mechanics of using BID in problem solving have been explored, uncovering deeper mechanisms to study
Vattam et al. [94]	5 main design activities to code BID data: problem discussion/analysis, biological phenomenon discussion/analysis, relating to/recalling existing solutions, generating new solutions, and evaluating solutions/analogies; design evaluation and critical thinking led to strategy level analogies from biology, as opposed to lower level superficial or function analogies	
Cheong et al. [95]	Three key attributes of evolution of design problem; (1) design problem can/may change throughout design process, regardless of success/failure of ideation activities; (2) Existing solutions to design problem affect how it is formulated; and (3) value of cross-domain analogy/knowledge transfer not only comes from transferring concepts, but also innovative design problem formulation	
Helms and Goel [96]	To teach BID to undergraduate of engineering and biology majors, familiarize students with techniques to help transfer knowledge from biological to engineering domain through lectures on BID practice and examples, analogy exercises, mentorship, and more	Strategies and recommendations for how to (and how not to) best perform and teach BID have been suggested based on the literature
Weissburg et al. [97] and Glier et al. [98]	Directed method for BID had no benefit to design outcomes when compared to using no formal ideation method	
Glier et al. [99]	Provide thorough account of cognitive challenges when performing BID, including difficulties with retrieval, inaccurate mental models, improper feature transfer/focus, ignoring of distant analogies, and fixation. Future BID methods/tools should encourage designers to develop multiple concepts based on each biological source, present diverse stimuli with shared underlying principles, provide uncommon solutions, incorporate structures of categories of the information, and provide abstractions of the biological information	

4.1 Summary of Nomenclature and Definitions. Building from the literature investigation, cognitive and related factors involved in design-by-analogy may be summarized and defined explicitly, as listed in Fig. 7. The following terms represent a summary of the nomenclature and definitions for these factors, as extracted from the extensive literature and understanding of the field.

Fixation: "Blind adherence to a set of ideas or concepts limiting the output of conceptual design" [32].

Incubation: A period of problem solving that occurs after initial failed attempts to solve a problem and after which an insight occurs suddenly and, perhaps, unpredictably, allowing the designer or problem solver to reach a solution(s) [40].

Memory: The mental capacity to recall previously learned information or knowledge.

Expertise: The level of experience, training, and knowledge that a designer has with respect to a particular field, practice (design), or tool.

Modality in representation: The form that an example or (analogical) stimuli might take on, corresponding to the variety of sensory perceptions that might be involved in processing them.

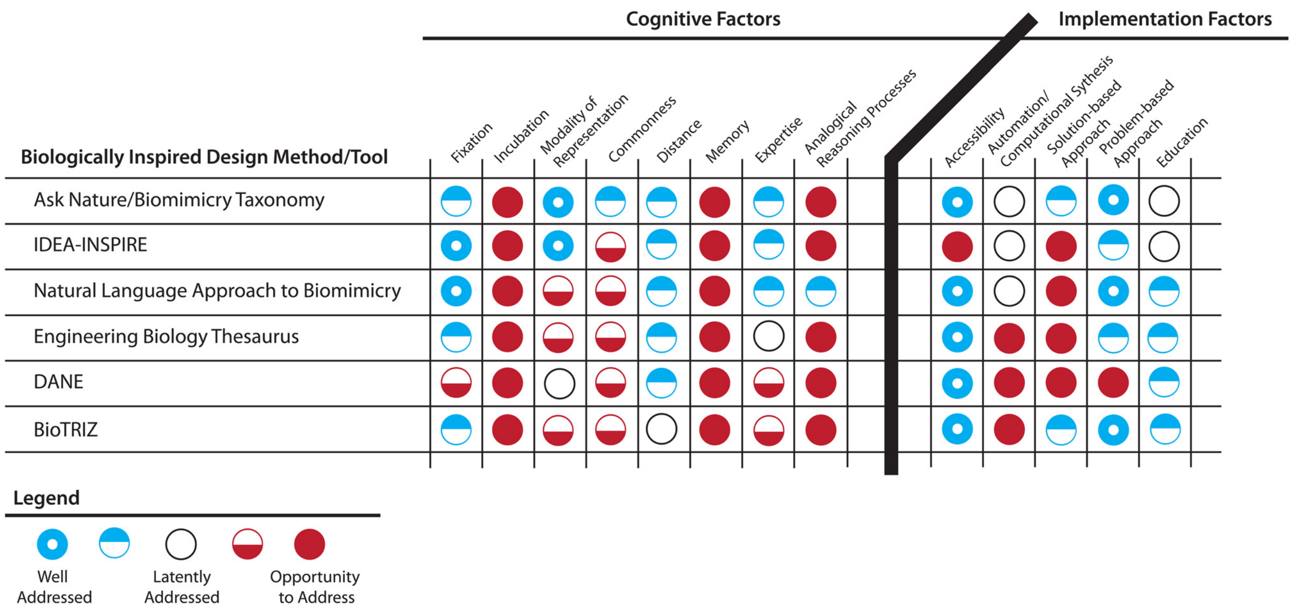


Fig. 7 Visual summary of state of research questions in bio-inspired design methods and tools

Analogical distance: Conceptual distance between the source and target of analogy.

Commonness: How often the analogies are found in designers' worlds and design environments, or how familiar designers are with an analogy, its features, and its attributes, which increases with the probability that a designer would have had prior exposure and/or experience with the analogy.

Analogical reasoning processes: The cognitive steps and characteristics that humans employ when working to find/retrieve, translate/abstract/transfer and evaluate information/knowledge being mapped from a source application to a target application.

Accessibility: How available the tool or method is to the academic or public community for use in design practice, education, or research.

Problem-based approach: The design problem, and associated representations, serves as the starting point and focus of using a method/tool.

Solution-based approach: The biological phenomena serve as the starting point and focus of using the method/tool.

Computational synthesis/automation: How automated the solving of the design problem is using the tool/method, or how much human input/work is required to reach a result.

Education: The structured process by which learning of knowledge, skills, and/or understanding occur.

4.2 Discussion of Better Addressed Areas of Inquiry. Based on our analysis, there are a number of methods and tools that thoughtfully address particular areas of inquiry when examined through the lens of the design-by-analogy literature. Modality in representation is well addressed by most methods, which offer text, images, diagrams and even videos of the biological information. While other modes of representation could be developed, the examined methods often allow a designer to expose themselves to multiple choices within these modality types, enabling the designers to perceive the information in the modality that is most natural or apt for them to learn the content. As the analogy literature states, designers at different levels of expertise or types of expertise respond to modality in representation in different ways. Allowing for this diversity of thought, perception, and learning style to be accommodated in the user interfaces and presentation of the analogies is a flexible way of addressing this aspect of analogical cognition. One way that this could be expanded upon is to add different modalities to other parts of the user interface and conveyed analogies, not just the presentation of the end content for use in analogy—for example, giving designers the option to explore a design space visually with graphical representations instead of through text fields/representations. As this aspect of analogical reasoning does not have a cohesive theory or implications for best practices in design, the current methods and tools in bio-inspired design do a reasonable job of incorporating what is currently understood about this attribute in a flexible and responsive way. Based on experiencing the methods/tools, it was found that the engineering-to-biology Thesaurus, the Natural Language Approach to Biomimetic Design, and BioTRIZ could all have benefitted from more modalities of representation in their implementations, which could be a possible area of future exploration for these works. Benefits of maintaining single modality implementation include strong reception by learners/thinkers who are most amenable to the modality used, as well as reduced cognitive load in processing the information.

Another area that is more implicitly addressed is the aspect of commonness of analogical information. The analogy literature indicates that commonness, while it has not been studied extensively, is inversely related to quality of design outcomes; that is, less common analogical stimuli have more positive effects on design outcomes. Reasons for these effects include designers' difficulty with reconceptualizing the purpose of an artifact, process, system or information, or fixating on former representations of the stimuli. However, stimuli that are too uncommon have the potential to be so unfamiliar to the designer that they are incomprehensible, and thus analogical transfer will be greatly inhibited. The texts used to populate many of the taxonomies/repositories/etc., in bio-inspired design are biological textbooks and other seminal texts of the field; therefore, if one had been exposed to biological knowledge prior to using the tool or method, the information would be likely captured in the basis corpus used to build the method/tool. This could be positive, in that it does not require the designer to be an expert in field of biology in order to access the information, and there is a possibility that the designer may have even been exposed to the information, if even at a surface level, before in their secondary or college education. However, there is the potential that there is an ideal window or range in the spectrum of commonness of analogy that could be tested, understood, and taken advantage of within the tools or methods to lead designers to the greatest success rates in practicing bio-inspired design. In terms of the actual experience of the tools/methods during the design process, some of the information presented was more easily understood, abstracted and transferred to concepts than other information. It was unclear if this originated from commonness of the concepts being presented, or the way in which the information was presented (i.e., word choice, inclusion of visual explanations, translation to lay-person's terms).

Distance of analogy has been studied more thoroughly, both in the analogy literature and in the implementation of bio-inspired design tools and methods. Similar to commonness of analogy, it could be best characterized as a continuum as opposed to the traditional dichotomous conceptualization of distance (within/outside domain or near/far). Many of the bio-inspired tools and methods examined for this paper included ways of accessing further or closer distanced analogies by enabling different levels of abstraction in querying, different scale of biological systems, or different ways of traversing the design analogy space. Certainly, when the assumption that the transfer of analogical information is already crossing the boundary between the fields of engineering and biology, it is difficult to conceptualize what kind of biological phenomenon would be closer or further in a particular space with a particular target design problem in mind, but different representations and knowledge-domain perspectives could be provided to study this question. This question could then be explored more intentionally and systematically in the bio-inspired design tools and cognitive studies.

4.3 Discussion of Areas of Opportunity for Inquiry. Many of the bio-inspired design methods and tools address a number of aspects of design-by-analogy quite intentionally. However, there is a good deal of opportunity for expanding methods to incorporate more knowledge or aspects from the greater analogy literature.

Memory is highly linked to area of expertise in terms of identifying and connecting relevancy to a target problem through prior knowledge or experience with a subject area (biology). Other than attempting to generalize or abstract biological information for nonexperts, memory and access to long-term memory are not explicitly addressed by any method or tool. All of the methods/tools reviewed here did not address memory, as far as the authors could tell. Some open questions and opportunities to address memory more explicitly with cognitive experiments that could in turn impact the shaping of tools and methods might include the following:

- We all have experiences with biology—how do we engage the memory and experiences of designers to combine with biological phenomena?
- How might long term memory (prior experience with biological knowledge without developing expertise in the area) affect a designer's ability to transfer biological phenomena to design problem applications?
- What are ways in which we can encode and categorize biological information into our memories for better odds of analogical transfer at a later time?
- How are learning styles and approaches (visual learner versus auditory learner, etc.) impacting our ability to abstract and transfer biological information to a new domain?
- Would transformation techniques for mapping biological information to domain-knowledge representation assist in analogical transfer?
- While many of the reviewed bio-inspired design methods include functional representations and interpretations, could biological analogies be represented in terms of affordances, product-service system representations, and physical phenomena or physical effects of existing devices, systems, or processes?

Incubation, or "unconscious work" on the problem after initial failed solving attempt(s), is also not explicitly addressed by any of the methods or tools. This result might be more of an external factor to the tools; for example, the time during ideation at which the tool or method is introduced or engaged could be key to the successful implementation of the tool/method. As with the topic of memory, all of the methods/tools reviewed here did not seem to address incubation. Nonetheless, targeted and systematic incubation could be developed through studies, such as through the following research questions:

- When should bio-inspired methods/tools be used during the conceptual design process to achieve the highest rate of success with analogical reasoning and design?
- Should there be training both with particular methods and with abstracting and transferring biological information to a new domain?
- What are key stages of bio-inspired methods and processes to construct reflection times and introduce timing for separating designers from the problem being solved? What are the durations of these incubation periods? Should distractors or other activities be introduced to remove intrinsic stresses of the problem solution process?

Expertise can be viewed in several ways—it could be the area of expertise of a designer in terms of experience or education, the level of experience of a designer, or even the familiarity with a particular framework of thinking that might require more or less training to use a particular tool (i.e., deep or shallow understanding of functional modeling or physical phenomena). Many of the methods require familiarity or even expertise with particular frameworks, for example, SBF, function structures, query formulation, TRIZ matrices, principles and conflicts or even simply the abstraction of a design problem. The experience of using the methods/tools confirmed this analysis—DANE and BioTRIZ required familiarity with relatively complex models of thought that could be and were difficult for designers who were unfamiliar with these models. Once mastered, however, these models are insightful and useful for problem solving. The engineering-to-biology thesaurus required some expertise for knowing where and how to make use of biological functionalities once translated from the engineering domain. AskNature, IDEA-INSPIRE, and natural language approach to biomimetic design all required little expertise with models or biology to learn and use the tool/method. In general, most methods do not take into account the level of experience of the designer with practice in design—this could be an area for further expansion of the tools; perhaps they could become more complex or in depth as designers gain more experience with them, or in general, they could be tailored to what we understand about differences in spectrum of expertise for thinking and learning.

- What types of training are we employing to assist designers to understand the basis of the tool/method for BID that they are using? What is most effective and how long does it take to learn and wield given methods and tools? Can we decouple the challenge/effects of a particular tool/method interface or required skillset from the challenge of transferring the biological analogical information to the target problem?
- What are ways that we can make BID methods and tools more dynamic and adaptable with respect to the level of experience of the designer, both with design practice and with the field of biology? Can we construct an environment that develops in complexity in concert with the designer's increasing level of expertise/experience?
- How can BID methods be developed to adapt to the background and experience of designers, or be tailored by designers for their preferred or personally developed design methodologies and design philosophies?
- How should BID methods be deployed across design and industry organizations, especially with respect to different ranges of expertise, skill sets, and educational backgrounds?
- What social psychology factors and interface issues between social psychology and engineering should be identified and studied to deploy, effectively, BID methods in functional team environments and processes?

- What kinds of strategies will be most intuitive to learn for a novice? What modalities of representation of examples and analogical stimuli will they be most open to, or most likely to fixate upon? What happens if we try to train a novice to design like an expert early—will it change/inhibit/accelerate their trajectory to expertise? Are there attributes of novice design behavior that are desirable? How can we use what we know thus far about expertise in analogical design for the creation of computer supported design, and who should we be mimicking and/or creating these tools for? When does an expert become a novice and vice versa, depending on the degree of expertise and the problem domain?

In all of these methods, fixation is addressed well in some ways and not as well in others. It is evident that nearly all of the methods can provide information to a designer that can help break fixation through rerepresentation of the design problem or encouragement of searching significantly different areas of the design space. However, fixation could be apparent and also a concern in the reviewed methods that provide only one biological phenomenon for potential analogical transfer for a given function (derived from a target problem/application). We know from the cognitive psychology literature that more than one example leads to much greater success in analogical transfer and can reduce/prevent/mitigate fixation. Some methods do provide multiple examples, such as IDEA-INSPIRE, which lists biological/engineering entries as inspiration for the problem posed. This issue could be solved by the expansion of methods to a larger set of biological phenomena, a future aim that is explicitly stated in many of the methods. For methods that require significant investment into one potential biological phenomenon by, for example, creating a functional or SBF model of it, there could be fixation due to sunk cost [47] or too much detail too early in ideation:

- How do we go about choosing what biological phenomena are best to populate the repository/taxonomy/etc.? What are the appropriate depth and granularity representations for these phenomena?
- What is the best level of detail with which to work when examining the biological stimuli to foster analogical transfer and reduce fixation? Too much detail may obscure the ability to abstract and transfer the information to a new domain, but too little may lead to significant loss of information about structures, systems, or attributes, limiting the aspects over which the designer can choose to analogize and perform similarity mappings.
- What processes may be developed for readily expanding and refining biological analogies, their representations, and the continuous discoveries and understanding? May processes be computationally automated to capture and translate biological information sources? Could crowd-sourcing, as is currently being explored in one form by AskNature, be utilized to capture and expand repositories of biological analogies?
- Significant fixation mitigation approaches have been developed for ideation methods. Do these mitigation approaches integrate with current BID methods?
- Ideation methods in engineering design and other fields are being developed and studied at a tremendous rate over the past two decades. How are BID methods positioned and coordinated within the suite of ideation methods, especially to overcome fixation [101]?

With respect to our understanding of analogical reasoning processes, we know that designers use analogies for more than just inspiration for solving a design problem directly through transfer; analogies are used for identifying problems, as well as communicating ideas during ideation. It could be that there are more dynamic ways for framing the use of biological information during ideation. Another consideration is cognitive load on the designer; some methods not only require the user to transfer knowledge from one domain to another but also to learn a new method/tool with which they may not already be familiar. On a philosophical level, Ball challenges us to consider if it is even possible to isolate one aspect of a biological system for analogical transfer while discarding the remainder of the system within which it is embedded [102]; he notes that Vogel has pointed out that all of biology's artifacts are created by factories that are smaller than the artifacts themselves. The current BID tools and methods focus on ideation, and analogical mapping is at the idea level. We know that mimicking biological structures is very difficult, and the transition of an idea to reality, implementation and a realizable fabricated form is not addressed by most methods. Based on the experience of using the methods/tools, it was clear that the mechanics of abstracting and transferring the biological information to the design problem was not within the scope of factors considered when designing the tool/method, with the exception of the work by Shu and coworkers [18,21] and Chakrabarti and coworkers [103,104].

- Are there different ways to present biological analogical information to facilitate different types of analogical reasoning, such as transformational versus derivational [64] or functional versus structural versus inspirational [63]?
- How could BID methods assist designers in attempting to perform the steps beyond concept generation?
- How could BID methods be enhanced, expanded, or integrated with modeling approaches, visualization, simulation, experimentation, and production processes?

4.4 General Discussion of Implementation and Pragmatic Factors. A number of factors that are more external to the cognitive psychology literature of analogy were examined as part of this study. These attributes affect the success and implementation of a method or tool, and thus are important to highlight and progress forward. Accessibility, or how available to designers and researchers the method or tool is for use, is one of the most important of these attributes. This attribute is often a difficult subject, as the philosophy of how to handle intellectual property is controversial and highly debated, especially at the interface of academic research and commercial interests. In the case of academic research pursuits, the more accessible the details, steps, and materials for using a tool or method, the more we can benefit from its potential to support innovation. IDEA-INSPIRE and BEAST could not be experienced or analyzed to the same extent as the other methods/tools due to accessibility restrictions.

Accessibility is also related to the general area of mapping design research to practice. There exist many principles and approaches for successfully transferring design research to practice, such as in the context of BID methods and tools which have been primarily developed in academia [105]. Research and practical opportunities exist for studying and applying these principles to the bio-inspired design field.

There are ways in which computational synthesis and automation could ease some of the challenges of BID. Most of the methods/tools reviewed here do not attempt to automate the design process, though some are more automated than others. For example, the engineering-to-biology thesaurus is very much an analogue tool, which is highly effective for pointing the designer in the direction of new and insightful biological search terms that may be relevant to the functionality they seek, but does not address the actual search of texts or resources using these terms. On the opposite end of the spectrum, tools like IDEA-INSPIRE, natural language approach to biomimetic design and AskNature provide a graphical user interface in which the designer can enter search terms and retrieve biological information for mimicry or inspiration. None of these actually suggest solutions to design problems or evaluate how useful/helpful each piece biological might be, which would be two areas for further automation and computational synthesis of the BID process.

Problem-based versus solution-based approaches refer to whether the design problem serves as the starting point for search and ideation (problem-based) or the biological information serves as the starting point for search and inspiration (solution-based). The methods and tools reviewed here do facilitate both kinds of approaches, but not all of them do so. This integrated facilitation might be a consideration for the future of all BID methods, as designers could benefit from more flexibility in how and when the tool or method could be used during their design process, making it a more versatile and thus potentially a more highly employed design innovation aid. Most methods/tools reviewed here were much more problem-based. Two methods that allowed for more solution-based approaches included AskNature, which allows the designer to browse the database of biological phenomena without a problem in mind, and BioTRIZ, which can provide meta-analogies through browsing of the TRIZ principles without a problem in mind.

Finally, education is an important area to consider when it comes to the development of these tools. Many questions related to education were raised in Section 4.3, including considerations for how to train novices in BID, how to support education with these new methods and tools, how to train designers to use these new methods and tools, and how to adapt to designers as their expertise grows and changes. Significant research within the cognitive study of bio-inspired design focuses on this educational aspect [106], and it seems to be a well-recognized and used venue for testing and iterating on the development of these tools and methods.

5 Conclusions

Biologically inspired design has the potential to be a fruitful route to innovation. The tools and methods reviewed and examined in this paper build a strong foundation for supporting this way of designing with diverse and rigorous approaches. By presenting an overview of the analogy literature and examining the state of the art in bio-inspired design methods and tools through that lens, we present the current state of the field and pose open questions to unite BID with its umbrella field of design-by-analogy, and push progress forward in academic research pursuits by postulating challenges and potential future directions. Results indicate that many exciting near-term and long-term opportunities to explore still remain in understanding and supporting bio-inspired design. Looking forward, a cognitive foundation for the mechanisms and particular properties of BID must be deeply understood through empirical study, in order to build tools and methods that dovetail intuitively with human cognition. In BID cognition, there are many open research questions, including understanding what distance of analogy means and how to measure it, effects of memory and incubation, and the interaction effects of factors like commonness, modality of representation, and expertise. As tools and methods are developed, scaling factors for obtaining large databases of stimuli and accessibility of the outcomes should be major considerations. Integrating our understanding of analogical reasoning processes into the methods and tools could lead to higher success and lower fixation rates in BID. The frontier of bio-inspired innovations and supporting processes is just emerging with potential that is boundless.

Acknowledgment

The authors would like to thank Dr. Amaresh Chakrabarti, Dr. Li Shu, Dr. Daniel A. McAdams, and Dr. Rob Stone for sharing their insights, detailed methods and tools, Bradley Camburn, Kevin Blake Perez, Zack Huang, Leonardus Adi Prasetya, and Dr. Cassandra Telenko for their discussions and insights on this work. This work was funded by the SUTD-MIT International Design Centre (IDC).[7]

[7]http://idc.sutd.edu.sg

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