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Biologically Inspired Design

Computational Methods and Tools

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In memory of my late parents, Urmil Goel and Satya Prakash Goel

Ashok K. Goel

I would like to thank the students I have had the opportunity and pleasure to teach. Their constant query of what, why, and how has kept me curious and energized to pursue my own line of what, why, and how

Daniel A. McAdams

Foreword: Curating Nature's Patent Database

The Moment of Truth

It is an odd hobby for a biologist, I admit, but I enjoy reading patents. Patents tell the meticulous story of how humans have solved the conundrums of their era, from catching mice to circling planets. This record of ingenuity is more than a legal necessity; it is an inspiration. Inventors read patents not just to avoid reinventing the wheel, but also to glimpse, from a mesa of inventive shoulders, the adjacent possible.

The volume you are about to read describes a Googlesque quest to develop another kind of patent database, one that describes nature's 3.8 billion years of adaptations. These adaptations are a record of life's long march to become well adapted to the particularities of this planet. While biologists ponder how adaptations help individual lilies, plankton, and pelicans survive, biomimics ask: "How might this adaptation, and the technology it inspires, help the human species fit in here over the long haul?"

In the last few decades, life's adaptations have inspired a series of game-changing technologies. A refrigeration-free vaccine inspired by the rugged Tardigrade, a coral-inspired way to sequester tons of carbon dioxide in concrete, and a material that captures fog as cleverly as a desert-dwelling beetle. Biomimics are working on ways to reduce pesticides in farmer's fields, ease traffic jams in cities, and prevent antibiotic resistance in our hospitals. Biomimetic products are doubling each year, and papers published in the field are doubling every 2–3 years, much faster than the 13-year doubling rate of other sciences (Lepora 2013). A 2010 economic study predicted that biomimicry could represent $1 trillion of global Gross Domestic Product by 2025,[1] and in 2012, biomimicry topped the

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[1] Fermanian Business & Economic Institute, Point Loma Nazarene University. Global biomimicry efforts: an economic game changer, (2010).

Society of Manufacturing Engineers' annual list of "innovations that could change the way you manufacture."[2]

Though the prospects for bioinspired design have never been better, the discipline's moment of truth is here as well. A chasm still exists for many innovators, and unless we can cross it, biomimicry will remain the domain of the few innovators skilled and interested enough to decipher the primary biological literature. This leaves a knowledge divide for the millions of non-biologically trained engineers, architects, product designers, planners, chemists, material scientists, even policy makers for whom nature's strategies would be a revelation.

It is not that relevant biological information does not exist; we are, in fact, awash in it. If you can afford to access the full-text literature databases, and if you are fluent in the jargon, you have a chance of keeping up with the science. But as a designer, you are apt to have neither literature access nor a Rosetta Stone. For biomimicry to realize its potential, we need a Biological Information System (BIS) that is as ubiquitous and accessible as the Geographic Information System (GIS). That platform needs to deliver curated knowledge at the moment of creation, in a form tailored to fit the working styles of the people who invent our world. Like GIS, the success of BIS will depend on software tools that intelligently make sense of the raw data, augmented by apps that further extend its usefulness.

Transferable Ideas and Downloadable Beaks

Building a biological intelligence tool for inventors is the quintessential exercise in spanning disciplines. Biologists and inventors not only speak different languages—they ask different questions. Biologists might write a paper about the evolutionary significance of sharkskin that reduces biofouling, but often the "how" information—the dimensions and placement of the denticles—is buried in a paper devoted to the "why." Uncovering these gems of innovation from the continual blizzard of papers is a challenge, requiring enabling technologies like those collected in this volume: a way to describe biological phenomenon in machine readable language, an engineering-to-biology thesaurus, natural language query, near-clairvoyant search algorithms, and more.

Mining the literature, even clairvoyantly, is just the beginning. My biomimicry consulting colleagues at Biomimicry 3.8 have spent 15 years bringing biology to the design tables of companies such as Boeing, General Electric, General Mills, HOK, Nike, InterfaceFLOR, and Procter and Gamble. We have learned that most inventors are not interested in reading biological papers. They prefer that we synthesize and translate the papers into a taxonomy of promising mechanisms. Ultimately, they want a set of transferable ideas—*design principles* that will help them approach their challenge in a completely novel way. Our researchers can

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[2] Society of Manufacturing Engineers http://www.sme.org/innovations12/#biomimicry.

easily read 10,000 papers to answer a question such as "How does nature contain liquids?" "How does nature manage vibration?" "How does nature store energy?" Building a taxonomy and extracting the design principles is a skill that takes years to master.

Once inventors are equipped with bioinspired design principles, there are still miles to go before these are translated into a product or process. This is where interactive tools could help, walking inventors through an iterative design process and giving them access to nature's ideas every step of the way. How, where, and when in the creative process this knowledge is delivered will mean the difference between inspiration and execution. Ideally, actionable plug-ins will be accessible right from the digital screens that designers, engineers, and architects use everyday, e.g., an AskNature button embedded in CAD/CAM or BIM tools.

While designing a roofing system, for instance, a building engineer would be able to visually browse reinforcement strategies in the natural world, and download actual truss designs based on this information. While laying out the HVAC system, he or she could run a branching algorithm to generate a fluid distribution system that keeps frictional losses to a minimum. Framing designs could be light weighted with the use of software that equalizes stress along surfaces, inspired by the growth of trees and bones. A genetic algorithm that uses natural selection protocols could optimize the entire design, all within the same program.

These digital modules are what our colleagues at Autodesk have described as the difference between "concept" and "content." Rather than read about a *concept*, inventors want to access biological information as *content* that they can use immediately. They would like to be able to download a biological library of forms—3D models of life's most streamlined, lightweight, or multifunctional designs. Imagine if Eiji Nakatsu, the JR West engineer who mimicked the kingfisher's beak to create Japan's Shinkansen train, had been able to download a 3D model of the beak before building a physical model. He could have attached the beak model to the train body, stretched and scaled it, even tested it *in silico* with computational fluid dynamic tools.

Building a biological library of forms would help biologists as well as inventors. With today's reality-capture software for cameras, it is possible to imagine "scan jams" where volunteers would digitize the artifacts of the world's natural history museums, freeing them from molding drawers so they can enliven the next generation of sustainable designs.

The internal blueprints of biomaterials will prove equally important, especially as we move to computer-controlled additive manufacturing (3D printing). Organisms add structure to common polymers to achieve extraordinary functionality, e.g., beetles layer chitin composites in a plywood hatch to achieve strength and toughness. A different structural design is used to create color, resilience, or water repellency, all from the same material. A biomimetic structure-function catalog could allow additive manufacturers to streamline their supply chain as nature does, using a small palette of easily recyclable polymers in unique architectures to achieve a wide range of functions.

Of course, each discipline will have different inventive needs. Chemists might prefer a "substitution engine" that allows them to replace an industrial chemical synthesis with a biochemical alternative, achieving similar effect without waste or toxic by-products. Organizational managers will want yet another slice of biological information, pertaining to topics like communication, cooperation, networks, or resilience. For each category of human endeavor, new user-centric applications will need to be created atop the BIS data.

Helping Innovators Meet Their Mentor

At the end of the day, even the cleverest information tools will not guarantee that a new invention, even one inspired by nature, will be sustainable in terms of energy and material use, toxicity, end-of-life fate, etc.

To help innovators create in ways that are deeply biomimetic, we find it useful to use systems-thinking tools such as Biomimicry 3.8's Life's Principles[3] in the scoping, creating, and evaluating phases of invention. These are meta principles common to most species on earth, and include reminders such as "build from the bottom up," "use a safe subset of the periodic table," "perform chemistry in aqueous solution," "embed feedback mechanisms to continually evolve your design," etc. Interactive software tools that screen for how well a design is meeting Life's Principles could help innovators solve problems without creating new ones.

If you look at all the ways that nature can influence decision-making, you realize that biomimicry is more than just a new way to innovate. It is a new way to think. University and professional training courses that prepare designers and engineers to ask "How would nature solve this?" are vital, as are techniques, described here, that help students make the all-important cognitive leap from design principle to application. The professors pioneering in this field are in a unique role; they have an opportunity to encourage the highest and best use of this new and powerful methodology, hopefully to solve the worthy conundrums of our era.

A prescient Steve Jobs said: "I think the biggest innovations of the twenty-first century will be at the intersection of biology and technology. A new era is beginning." If the age of biology is to keep its promise, the people who make our world will need to become biologically literate. But they will not want to become biologists themselves. Instead, they will want to know the key principles, the best practices, the operating codes of the natural world. They will want to understand ubiquitous patterns as well as the strange and wonderful curiosities in nature's patent database. Ultimately, they will want to understand how life has managed to enhance this planet, and how our innovations might do the same.

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[3] http://biomimicry.net/about/biomimicry/lifes-principles/

A full-function tool to bring biological wisdom into human design is on its way, and the people in this volume will be instrumental in delivering it to us. They know that the key to wide-scale adoption of biomimicry is user-centric, curated knowledge, available at the moment of creation. Their efforts to help innovators learn from and emulate other species will one day be remembered as a pivotal leap in the evolution of our own.

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Janine Benyus
Co-Founder and Institute Board President,
Biomimicry 3.8

Preface

Biologically inspired design is a promising paradigm for design innovation as well as sustainable design. The scientific challenge now is to transform it into a repeatable and scalable methodology. This requires addressing several big challenges, including the following four: the first and foremost of course is to use the paradigm to address increasing numbers of real problems that translate into real products in the market. A second challenge is to document the best practices of successful applications of the paradigm and develop a theory of biologically inspired design. A third challenge is to develop computational methods and tools that can make biologically inspired design repeatable and scalable. A fourth challenge is to educate new generations of would-be-designers in the paradigm of biologically inspired design. These four challenges are interconnected and build on one another: success at one likely will spur success at others.

This volume brings together a dozen chapters that together address all four of the above challenges at least to some degree, while emphasizing computational methods and tools for biologically inspired design. We are pleased to bring together these articles by some of the leading researchers and practitioners of biologically inspired design into a single volume.

Chapter 1 provides a brief review of two workshops sponsored by the United States National Science Foundation (NSF). These workshops served as the initial catalysis and formation of this book. Taken together, the two workshops brought together some 50 researchers in biologically inspired design, helped establish a stronger sense of research community, and led to the formulation of a research agenda outlined in the chapter.

Chapter 2 by Jon-Michael Deldin and Megan Schuknecht describe AskNature, Biomimicry 3.8 Institute's publicly available webportal that provides a functionally indexed database of biological design strategies and systems. Insofar as we know, this is the first scholarly article describing AskNature in detail, and thus adds an important piece to the growing literature on biologically inspired design.

In Chap. 3, Li Shu and Hyunmin Cheong describe a natural language approach to finding biological analogies and applying them to design problems. They review a decade long research program on developing the natural language approach to biologically inspired design, and also provide several examples of its application.

In Chap. 4, Jacquelyn Nagel presents an engineering-to-biology thesaurus, along with several examples of its use in addressing design problems. This kind of thesaurus can be a very useful tool for designers in finding biological analogies to their design problems.

Nagel, McAdams, and Stone in Chap. 5 describe the big picture of their several years of research on biologically inspired design. In particular, they present their information-processing theory of biologically inspired design, and illustrate it with several examples. They also describe a suite of tools that match several tasks in the process theory.

Goel, Swaroop Vattam, Bryan Wiltgen, and Michael Helms in Chap. 6 present their information-processing theory of biologically inspired design. They also compare their theory with similar theories such as Design Spiral and BioTRIZ, and examine what makes biologically inspired design different from other paradigms.

In Chap. 7, Jeannette Yen, Helms, Goel, Craig Tovey, and Marc Weissburg describe the evolution of a college-level interdisciplinary course on biologically inspired design. Their chapter reviews many lessons from teaching the course for several years. These lessons should be useful for potential teachers of similar courses.

In Chap. 8, Amaresh Chakrabarti focuses on analogical transfer from biology to engineering. He proposes guidelines for supporting this analogical transfer and describes an interactive tool that implements the guidelines. Comparative studies indicate that use of the tool increases the number of transferred designs.

Julie Linsey and Vimal Viswanathan in Chap. 9 study the cognitive challenges in biologically inspired design, focusing on design fixation. They describe several heuristics for addressing the challenges, including fixation. These heuristics should be useful for designing interactive tools for supporting biologically inspired design.

In Chap. 10, Wojciech Bejgerowski, John Gerdes, James Hopkins, Lengfeng Lee, Madusudanan Sathia Narayanan, Frank Mendel, Venkat Krovi, and Satyandra Gupta focus on bioinspired robotics. Building on several years of research, they present case studies ranging from bird-inspired robots to snake-inspired robots. They also describe a process by which biological features are selected and simplified for application using existing technologies for robot construction.

Julian Vincent in Chap. 11 specifies a need for identifying design principles that may help produce good technical designs without requiring biological expertise. He proposes four such principles derived from TRIZ: local quality, merging, dynamics, and prior cushioning. He calls for identification of design principles, especially those pertaining to information and material.

Frank Fish and John Beneski in Chap. 12 analyze the limits of design by evolution in biology and design by analogy in biologically inspired design. They argue that biological designs are not necessarily optimal with respect to any specific function. They advocate focusing on biological features that outperform currently available technologies for incorporation into technical designs.

We are grateful to Janine Benyus for writing the Foreword to this volume. Her work at Biomimicry 3.8 has long inspired the biomimicry movement, including our own efforts.

We are grateful also to the US NSF for sponsoring the workshops that led to this volume. In particular, we thank Christina Bloebaum for her support of this work as a Director of the Engineering Design and Innovation Program (now known as Engineering Systems Design) of the Civil, Mechanical, and Manufacturing Innovation Division of the Engineering Directorate at NSF.

We also thank the Springer publishing company, and especially Grace Quinn at Springer, for working with us on the preparation of this volume. We can only hope that scholars and practitioners of biologically inspired design, as well as design teachers and students more generally, will find this volume useful.

Ashok K. Goel
Daniel A. McAdams
Robert B. Stone

Contents

Chapter 1
Charting a Course for Computer-Aided Bio-Inspired Design

Robert B. Stone, Ashok K. Goel and Daniel A. McAdams

Abstract Bio-inspired design (BID) is an emerging research area in design, biology, computing, and engineering that seeks to systematically mine biological knowledge to solve design problems. To promote BID research, and especially research on computer-aided BID, the United States National Science Foundation (NSF) recently sponsored two workshops. These workshops served as the catalysis for this book. In this chapter, we review the discussions at the two workshops. We also sketch the outline of a research program on computer-aided BID that emerged from the workshops.

Keywords Biomimicry · Biologically inspired design · Computer-aided design · Engineering design · Design computing

1.1 Introduction

Bio-inspired design (BID or biomimicry or bionics) is an emerging research area in engineering design, computing, and biology that seeks to systematically mine biological knowledge to solve existing design problems. However, the community

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of BID researchers at present is fragmented with no professional society, unifying funding source, or recurring conference.

As it stands, BID research is active across many disciplines and has had important and significant results. Nevertheless, BID remains largely a research activity contained in universities. BID is not yet an activity practiced by design engineers in the field. This “research-not-practice” status of BID exists because most BID is the result of researchers studying a biological entity or system such that their level of understanding allows an almost direct emulation but not necessarily new inspiration. This point solution status of BID sets a large, if a little ill-defined, scope for BID research: How do we transform BID from a point solution effort to fundamental theories and methods?

As a first draft of scoping BID research, some initial problems are apparent that served as motivation and agenda items for a workshop. How do we motivate and facilitate the interaction between engineering-oriented design researchers and science-oriented biology researchers—two fields with significantly different research cultures? How do we scope and scale biology in the context of abstracting engineering knowledge? How do we transmit biological knowledge to engineers and engineering knowledge to biologists without extensive discipline-specific training? How might computational theories of analogical reasoning inform the transfer of knowledge from biology to engineering and vice versa? How might artificial intelligence theories of knowledge representation and ontology support the construction of shared mental models among engineers and biologists? How might we teach biologically inspired design to engineers and biologists alike?

Of particular research interest to BID is how can we mine biology for solutions to problems for which we have no current solution. For example, some biological solutions exhibit superior sustainability to engineered solutions. Similarly, biological solutions often are complex both in their solution and the problem they solve. As the design problems solved become more complex, and the engineered solutions themselves also become more complex, biology may offer insights into how to solve the problem.

In this chapter, we provide an overview of two national science foundation (NSF)-sponsored workshops that started a discussion of these issues. The subsequent chapters in this volume discuss some of these issues in detail.

1.1.1 NSF Workshops

National science foundation funded two workshops to chart a course for BID. First, a one-day workshop in Palo Alto, California, was held on Sunday, March 20, 2011, in conjunction with the AAAI 2011 Spring Symposium on Artificial Intelligence and Sustainable Design.[1] A second, follow-up half-day workshop was held

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[1] http://designengineeringlab.org/BID-workshop/Workshop_1.html

Table 1.1 Presenters and presentation titles at workshop 1

Speaker	Title
Janine Benyus Biomimicry guild/Biomimicry Institute	Biomimicry: sustainable design inspired by nature
Satyandra Gupta University of Maryland	Bio-inspired robotics
Daniel A. McAdams Texas A&M University	Bio-inspired design
Ashok Goel Georgia Institute of Technology	Computational methods and tools for biologically inspired design
Julian Vincent University of Bath	Methods of bridging biological information and engineering information
David Rosen Georgia Institute of Technology	SSS approach and creativity metrics for bio-inspired
Shapour Azarm University of Maryland	Bio-inspired design optimization
Thomasz Arciszewski George Mason University	Bio-inspiration
Jeannette Yen Georgia Institute of Technology	Center for biologically-inspired design
Amaresh Chakrabarti Indian Institute of Science	Biologically inspired design: an overview of research at ideas lab, IISc

in College Station, Texas, on June 5, 2012, in conjunction with the Fifth International Conference on Design Computing and Cognition.[2]

The first workshop was a good match to the AAAI 2011 Spring Symposium as the symposium had a topic on the related issue of biologically inspired and evolutionary models of sustainable design.[3] The objectives for the first workshop were to

1. Identify the research community.
2. Identify the topical coverage (overlap/gaps) of research.
3. Explore the gaps in current research efforts as it relates to a systematic application of biological information for engineering design.
4. Formulate major themes under the BID research banner.
5. Articulate steps toward a sustainable research community for BID.

Table 1.1 summarizes the workshop presenters and the title of their presentations. The workshop was broken into three sessions where leading researchers in the disciplines that intersect to form the BID research community presented the state of the art in bio-inspired research topics.

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[2] http://designengineeringlab.org/BID-workshop/Workshop_2_%40_DCC.html

[3] http://www.vuse.vanderbilt.edu/~dfisher/AISD-Program.html

Table 1.2 Workshop 1 participants and affiliation

Name	Affiliation
Tom Arciszewski	George Mason University
Shapour Azarm	University of Maryland
Janine Benyus	The Biomimicry Group
Amaresh Chakrabarti	Indian Institute of Science (India)
Paul Egan	Carnegie Mellon
Douglas Fisher	Vanderbilt
Frank Fish	West Chester University
Robert J. Full	University of California, Berkeley
Erwin Gianchandani	Computing Research Association
Satyandra Gupta	University of Maryland
Norbert Hoeller	Sustainable Innovation Network
Chris Jenkins	Montana State University
Sangbae Kim	Massachusetts Institute of Technology
Venkat Krovi	University at Buffalo
Julie Linsey	Georgia Institute of Technology
Mary Lou Maher	University of Maryland
Julia O'Rourke	The University of Texas at Austin
David Rosen	Georgia Institute of Technology
Megan Schuknecht	AskNature.com
Justin Seipel	Purdue University
Jami Shah	Arizona State University
Jacquelyn Stroble	James Madison Univeristy
Srinivasan Arjun Tekalur	Michigan State University
Craig Tovey	Georgia Institute of Technology
Mohamed B. Trabia	University of Nevada, Las Vegas
Irem Tumer	Oregon State University
Swaroop Vattam	Georgia Institute of Technology
Julian Vincent	University of Bath (UK)
Anosh Wadia	Texas A&M
Jeannette Yen	Georgia Institute of Technology

Following the presentations, three breakout groups were formed to generate answers (and thus recommendations) for three general questions:

1. If BID is going to contribute to sustainability it needs to…?
2. If BID is going to contribute to complex system design it needs to…?
3. If BID is going to contribute to design education and pedagogy it needs to…?

The three breakout groups were led by Mary Lou Maher, Jami Shah, and Craig Tovey, respectively. The final session of the workshop featured debrief reports by each of the breakout groups and a general discussion session for all participants. The workshop included 30 researchers from the disciplines of engineering design, computer science, and biology in addition to the three organizers. The participants are listed in Table 1.2.

The second workshop, held in College Station, Texas, leveraged the computational design community at the 2012 Design Computing and Cognition

Table 1.3 Presenters and presentation titles at workshop 2

Speaker	Title
Rob Stone Oregon State University	Review of workshop 1 activities and findings
Ashok Goel Georgia Institute of Technology	Grounding bio-inspired design in cognition and computation
Julie Linsey Georgia Institute of Technology	Word tree express—a tool for design by analogy and bio-inspired design
Filipo Salustri Ryerson University	Analogy and systems are at the heart of BID
Marc Weissburg Georgia Institute of Technology	Pedagogical challenges to BID innovation
Rob Stone Oregon State University	Gathering designer feedback to generate requirements for intuitive biologically-inspired design tools

Conference to evaluate the first workshop's findings and generate a draft description of a program for research funding for BID. The objectives for the second workshop were to

1. Review the findings from the first workshop.
2. Introduce new ideas and research directions for BID through invited talks and a poster session with participants.
3. Draft a BID program description for a funding agency.

The outcome of the second workshop is captured in the later section entitled "Proposed NSF Program in BID." Table 1.3 summarizes the workshop presenters and the title of their presentations. The participants of the second workshop are listed in Table 1.4.

In addition to the individual presentations, the second workshop held breakout sessions with the goal of defining a potential NSF research program for funding BID research. The leaders of the breakout sessions included Alice Agogino, Tom Arciszewski, David Brown, Julie Linsey, and Marc Weissburg.

1.2 Current Research from the Disciplines

We begin with a brief summary of the state of the art from various subdisciplines of BID, with pointers to workshop presenters whose presentations elaborate each of those points.

Table 1.4 Workshop 2 participants and affiliation

Name	Affiliation
Alice Agogino	U. California at Berkeley
Kinda Al Sayed	University College London (UK)
Fernando Alvarez	Universidad de Bogotà (Columbia)
Tom Arciszewski	George Mason University
Ryan Arlitt	Oregon State University
David Brown	Worcester Polytechnic Institute
Christopher Earl	Open University (UK)
John Gero	George Mason University
Michael Helms	Georgia Institute of Technology
Julie Linsey	Georgia Institute of Technology
Mijeong Kim	Kyung He University (South Korea)
Pertti Saariluoma	University of Jyväskylä (Finland)
Filipo Salustri	Ryerson University (Canada)
Noe Vargas-Hernandez	U. Texas—El Paso
Pieter Vermaas	TU-Delft (Netherlands)
Marc Weissburg	Georgia Institute of Technology

1.2.1 Bio-Inspiration

One of the key aspects of BID is utilizing the similarities noted in nature for a particular problem to design and to bring inspiration to the designer. Inspiration through the forms of nature can come in three different types: visual, conceptual, and computational. Visual inspiration is widely used and understood. Pictures or other visuals of a biological system are used to create engineering systems that share the same visual appearance. Conceptual inspiration is the use of the knowledge found in biology to form design rules, heuristics, principles, or patterns. This type of inspiration requires an understanding in both nature and engineering. Algorithmic bio-inspiration is searching through nature to find algorithms like evolutionary computation and knowledge representations such as generative representations.

There are three different sources of bio-inspiration: evolution which is the gradual improvement in living systems in response to environmental stimuli, coevolution or coadaptation of a species in response to evolution of other species in the habitat, and morphogenesis—evolutionary development of an organism or its parts (Areiszewski).

Another search for bio-inspiration has been in the development of 3D manufacturing. While there are a large number of polymers used in engineering to complete various tasks, nature uses a small set. Taking inspiration from nature and using a smaller set more efficiently can be beneficial in manufacturing (Benyus).

Studies have shown that 70 % of engineering problems are solved by energy rather than by information. On the other hand, nature solves problems by using information rather that energy, making the system more efficient (Vincent).

Novelty is how unique the solutions are, while variety is how many of the solutions were new. A study containing a control group, a BID group, and an engineering group allowed the analysis of the groups' solutions using these metrics. The study showed that BID increases novelty but not necessarily variety. There was noticeable fixation in the engineering group that was not seen in the others (Rosen).

One can also use a creativity metric to analyze designs. By examining the novelty and the usefulness of a design, a creativity score can be determined. Biological systems may be a way to inspire more creative solutions when undergoing design problems (Chakrabarti).

1.2.2 Bridging Biology and Engineering

Historically, BID has been rather anecdotal rather than systematic; therefore, a way to make BID more systematic is needed to increase the benefits gained from BID. There are two main methods to enhancing BID, stimuli, and transfer guidelines. Stimuli is broken up into two different categories, structured and unstructured. Structured information allows for a simpler search and easier transfer of knowledge. However, the arrangement of the information into a structure can be difficult and time-consuming. Unstructured information requires no effort to arrange the information; however, the "search" carried out by the designer and the transferring of the idea tend to be more difficult and time-consuming. Transfer guidelines are broken into four general steps: formulate search objectives, search for biological analogs, analyze biological analogs, and transfer relevant knowledge to the target domain. Using the SAPPhIRE model, seven levels of abstraction can be obtained. These abstractions can be used to inspire ideas. The SAPPhIRE model excels at empirical findings and exploring the number of ideas which lead to a higher levels of SAPPhIRE and greater novelty. One can also use design creativity as a metric of the novelty and the usefulness of a design. Currently, not all levels of SAPPhIRE have been explored and studies are being done to examine these. Use of the SAPPhIRE model has shown that a systematic framework helps increase the overall number of ideas (Chakrabarti).

Bio-inspired design is responsible for many useful, innovative designs: The lotus leaf inspired self-cleaning water repellent surfaces, and the cocklebur inspired velcro. These are just a few examples of the power of BID. Engineering design is more problem driven, and the concepts are dominated by knowledge of similar systems. One can recast BID as a problem-driven effort by combining it with function-based design methods to create function-based BID. Function can be used as the analogical connection between what an engineering system needs to do and how the natural system completes that function. By using normal functional modeling techniques, naturel systems can be modeled. This modeling framework allows an analogous connection needed between engineering systems and natural systems. A practical challenge of this approach is that engineers and biologists use different terminologies when describing solutions to function; therefore, an engineering-to-biology thesaurus is needed. The current BID methodology uses the functional basis terms with biological function/flow correspondents. The main steps for this start with creating a functional model for the design problem using a terminology known as the functional basis. The next step is translating the functional model into the associated biological keywords. After this is done, one can search a specific biological knowledge repository or use Google, biology texts, or other publications (McAdams).

Goel has done work in developing information processing theories and computational methods for BID. This work starts with conducting empirical studies of BID, then developing general information processing accounts of BID, next constructing computational tools and techniques for aiding BID, and finally deploying and evaluating the tools in realistic settings. One of their findings is that BID often involves compound analogies, entailing intricate interaction between problem decomposition and analogical reasoning. A second finding is that BID engages not only in analogical transfer of functionally indexed mechanisms but also in transfer of problem decompositions. A third finding is that biological analogies are useful for several tasks of BID in addition to design concept generation, such as design analysis and explanation.

Other work bridges biological information with engineering information. Rosen has been researching and developing a strategy–state–structure ontology to create a formal language that represents designs. Strategy is function plus behaviors; therefore, this would include a taxonomy of functions and behaviors that could be used together to form strategies (Rosen).

At the University of Maryland, Gupta has been conducting studies with bio-inspired robots. Bio-inspired robots are robots with the main inspiration coming from a bird, animal, or fish. There are many applications of bio-inspired robots that include but are not limited to medical, reconnaissance, mine detection, entertainment, and space exploration. The traditional approach in creating these robots is taking inspiration from nature and adding modeling- and simulation-based optimization to create designs for these robots. Traditional manufacturing techniques are then examined to determine which designs can be executed. There are many successful robots larger than 100 mm; however, miniature robots (between 100 mm and 5 mm) usually come with limited capabilities. By finding new novel manufacturing concepts, highly capable yet miniature bio-inspired robots could be implemented. The first step is to approach design differently—to simplify by only retaining features of the biological creature that are useful and to identify high-value characteristics. Another need in the design phase is to amplify the useful biological characteristics to improve the performance of the robot. The second step is to approach the modeling and simulation of these robots differently using metamodel synthesis. The last is to approach assembly differently (Gupta).

1.2.3 Techniques and Tools for Bio-Inspired Conceptual Design

The development of design tools to help designers use BID effectively is crucial to being able to teach BID in a classroom and implement BID in the workplace. Asknature.org is an important tool for BID. Asknature.org takes organizes bio-literature by function and allows the user to search through. The Web site is public domain, part search engine and part social network, and helps people using BID connect with each other. As of now, asknature.org contains 1,300 strategies for design. These strategies contain links to biologist Web pages or Google Scholar articles to help the user be able to research the strategy. Support from Autodesk Inventor has been crucial as it implements BID into a commonly used design tool. A current redesign of AskNature is underway to follow the path of idea from nature–transferable idea–possible products–actual products–digital downloads–Autodesk Inventor. This would allow an easier transfer of flows from BID into products. Another possible tool would be implementing native ecosystem data in city planning. By setting new ecological performance standards, architects and city planners would use the ecosystem data to develop a city that is more sustainable and functions together (Benyus).

Another tool of importance is the engineering-to-biology thesaurus. This thesaurus helps engineers include bio-inspiration in the engineering design process by relating the engineering functions and flows in the functional basis to biological functions and flows. In this manner, the designer is allowed to use their functional model to relate key functionality to the way nature also solves it (McAdams). Another tool for BID is the creation of databases to organize information.

Goel described two knowledge bases: DANE and Biologue. Both DANE and Biologue use structure–behavior–function models of biological and engineering systems. DANE, which has already been released (http://dilab.cc.gatech.edu/dane/), is a functionally organized database of biological solutions. This is useful to designers because it allows them to look up the function they are trying to solve and relate that to biological solutions. The more recent Biologue system is a database that allows the indexing of biology-related documents using the structure–behavior–function model. Using this, a designer can compare the functions of what they are designing and also compare the structures and behaviors of their design to biological systems.

Of note, bio-inspired optimization techniques are also used in design. Genetic, ant, particle swarm, bee, and firefly algorithms all contain specific uses to help engineers optimize in design. By studying the ways grouped animals move and interact, techniques can be developed to mimic those interactions and create better optimization techniques and algorithms. These techniques can be used to help overcome challenges often found while trying to optimize designs. Such challenges include complexity, scalability, and convergence. There is a need to extend the applicability of genetic algorithms for design optimization with regard to uncertainty, system product design, and multi-objective genetic algorithms

(MOGA). Pros and cons exist for all of the BID optimization algorithms. The desirable traits are that the algorithm is population based, can optimize non-convex discontinuous functions, can handle discrete–continuous/combinatorial design problems, and obtain global optimums. However, sometimes these optimization techniques result in local optimums that can be undesirable. Nevertheless, there are complications with these algorithms that include complexity, scalability, and convergence (Azarm).

Vincent discussed another important BID tool, Bio-TRIZ. Bio-TRIZ is a reduced form of TRIZ that relates the TRIZ inventive principles to biological contradictions. Studying 5,000 examples, the conflict matrix was reduced from 39 conflict elements to 6 elements that appear in both biology and engineering, and a 6 × 6 contradiction matrix that contains all 40 of the inventive principles was created. These 6 conflict elements are substance, structure, time, space, energy/field, and information/regulation. Biological solutions were then studied to fill in inventive principles aspect of the matrix (Vincent).

1.2.4 Education in Bio-Inspired Design

The Biomimicry Institute (TBI) has been working on implementing BID into earlier education (K1-12) as well as into a professional masters program. An important part of featuring BID in a classroom setting is combining biologists, biomimetic scientists, engineers, and designers together. Academic settings tend to be very different from work settings. Therefore, working to close the difference between academic and work settings would lead to better transition from BID in the classroom to BID in the workplace (Benyus).

Since 2005, Georgia Institute of Technology has offered a BID interdisciplinary course for engineers, biologists, and other scientists. This course features ∼30 engineering students and ∼15 biology students that take part in semester-long, self-defined design projects that include the help of faculty mentors. This has been created to help promote BID practice and explore how BID aids in developing products. The main goal of this course is to encourage ways of thinking about and to explore nature that helps facilitate a designer's ability to implement biological strategies in engineered products and sustainable systems. The development results in a fifteen-week course that includes the principles of biologically inspired design, biomimetic materials, biologically inspired sensing and movement, system design and optimization, and green technology. These lectures contain both content and practice to help the students grasp the material. The final is a presentation by the students on a novel BID (Yen).

An important aspect of BID is implementing it in a classroom setting so students can not only learn and understand it but also implement it in industry. The University of Maryland has offered bio-inspired robotics undergraduate classes. These classes offer an excellent opportunity to teach students how to design a complex and modern mechatronics system. The content of the course includes the fundamentals of robotics, including kinematics, inverse kinematics, dynamics, trajectory generation and controls, bio-inspired robots where design concepts, sensors, and actuators are covered, and ending with robot building tutorials using mechanical design, servo motors, microcontrollers, and programming. The class is project based with bio-inspired robot outcome (Gupta).

1.3 Recommendations

Biologically inspired design has been practiced on an *ad hoc* basis throughout human history. The breakout sessions at the first workshop were designed to explore the research needed to move BID from *ad hoc* to *intentional* in its application. The breakout sessions at the second workshop were targeted toward defining an NSF program for funding BID research.

1.3.1 A Design Theory for Bio-Inspired Design

Bio-inspired design seeks to exploit biology for several different kinds of design such as sustainable design, creative design, and complex system design. Of course, these different kinds of design are mutually compatible and consistent: We can have complex systems that are sustainable, sustainable designs that are creative, and so on. Nevertheless, the three kinds of design have different emphases and foci.

The goal of bio-inspired sustainable design is to use biology as an inspiration for designing technological products that are ecologically sustainable. Although biological systems are not always optimal, the argument goes that they typically use only local and abundant resources and are often very efficient in terms of use of resources such as energy and water. Of course, this does not guarantee that bio-inspired products will be necessarily sustainable, but it promises that they may be more sustainable than equivalent products available in the market today. Consider the following specific cases:

The Biomimicry Institute's work on BID is driven by the growing need for sustainable design. An example of sustainable design at TBI is the novel design of a water bottle with "ribs" on its plastic surface mimicking the ribs on trees and providing strength to the bottle. This allows the bottle to use less plastic, which makes it lighter than similar water bottles (Benyus).

Recent work on BioTRIZ indicates that for many functions for which technological products typically use energy, equivalent biological systems use information instead. This suggests that we seek biological sources as inspiration to design a new generation of technological products that use information in place of energy to achieve as many functions as possible (Vincent).

Another line of research seeks to identify design patterns that biological systems use to achieve ecological sustainability. For example, the Namibian beetle uses an interleaved pattern of the biological effects of hydrophobia and hydrophylia for harvesting water from dry air. Bio-inspired designers have now used the same pattern for fog harvesting. This suggests building a classification of functionally indexed design patterns for sustainable design (Goel).

The goal of bio-inspired complex system design is to use the characteristically complex interactions found in nature as a guide to engineered systems that are complex and integrated among their constituent components. Although biologists welcome complexity, engineers typically are concerned about it and do what they can to avoid it. Approaching complex system design from a biologist's perspective that complexity could be a positive aspect and allow a mechanism for coping with product failures appears a promising avenue with the following observations:

On the engineering side of complex systems, one has relatively simple units leading to an emergent phenomenon that includes many interacting parts exhibiting nonlinear behavior, uncertainty, and multiple scales. The biology side of complex designs contains heterogeneity, multiple different parts that fit together and provide different outcomes dependent on initial conditions, and multi-functionality.

Biologists can help shift the paradigm of perceived complexity versus real complexity. This shift can help show engineers how to manage complexity in their systems which could lead to innovative products and elegant designs and help predict the performance of complex systems.

Nature has the ability to self-repair, adapt, add redundancies, accommodate failure, regenerate and reconfigure parts, as well as others. Engineering systems do not accept the notion of failure as a positive feature, but small, intentional failures to avoid a catastrophic failure can be a good thing.

1.3.2 A Funding Program for Bio-Inspired Design Research

As part of the second workshop, the participants reviewed the findings of the first workshop and produced variants of a proposed call for proposals. For purposes of context, it was assumed that the umbrella agency for such a program would be the United States NSF. The variant ideas were aggregated into the following brief description of an NSF program:

The NSF invites proposals for research in BID. Biologically inspired designs and processes have much potential to solve urgent and complex challenges faced by the United States and the planet such as those found in military, urban infrastructures, climate change, sustainability, and space exploration domains. Proposals must be from suitable multi-disciplinary teams (i.e., members might include biologists, computer scientists, engineers, or psychologists), addressing small- to medium-scale designs (such as household products or automotive systems), have demonstrated educational and computational potential, and be well evaluated. Suitable research areas include but are not limited to:

- BID system usability, interface design, visualization, and search;
- Identification of the role of biologically inspired tools and design methods for each stage of the design process, for example, problem framing, conceptual design, refinement, production (DfM for BIDs), marketing, reuse/recycle;
- Knowledge-base/database building and integration, ontologies (construction, use, and evaluation), and test beds (computational and physical);
- Evaluation of analogy utility (before, after, and during use) of BIDs, design methods, and the manufacturability of resulting designs;
- Roles of the scales (both spatial—from micro- to macro-, to systems of systems—and temporal—to promote desired emergent behavior over time) of biological knowledge for problem identification, design decomposition, generation, evaluation, and explanation;
- Impact of BID on communication in multiple disciplinary teams, for example, novice–expert studies, development of a community of practice and networks, sociology of disciplinary norms;
- Teaching approaches and curricular development.

The work must be extensible and must be shared in order to promote BID community building.

1.4 Summary

In summary, it is clear that recent research efforts across the disciplines of engineering design, computer science, and biology have attempted to address the various problems associated with not only developing biologically inspired designs, but also teaching students how to develop biologically inspired designs. However, it is also evident that there is a need for additional work on refining the proposed methods and tools as well as developing new methods to address current limitations. The recommendation of the workshop organizers is that a new cross-cutting NSF program in BID be established that seeks to fund transformative research as described in the program brief above. Such a program is expected to support high-risk/high-reward research that otherwise has no current home in the NSF.

Suggested Readings

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