In 2011 and 2012, we organized two workshops on computer-aided bio-inspired design sponsored by the United States National Science Foundation (NSF). These workshops brought together a few dozen leading researchers in computational methods and tools for biologically inspired design,1 and led to an edited volume [1]. The first chapter of the volume reports on the discussions at the two workshops. The success of the two workshops also led to this JMD special issue.

The special issue consists of 13 significant articles. The first section contains two survey articles. In “Where Are We Now and Where Are We Going?: The BioM Innovation Database,” Jacobs, Nichol, and Helms carefully and rigorously attempt to identify and archive the state of bio-inspired design practice as it exists in actual artifacts, products, and systems. Specifically, the authors address four questions. (1) Are products which are identified as being bio-inspired actually bio-inspired? (2) To what extent do bio-inspired designs mimic the forms, processes, and interactions of biological systems? (3) To what extent do bio-inspired designs exploit the scale and range of biological systems? (4) What patterns of design practice can we learn from successful bio-inspired design practitioners? Their process begins by collecting existing bio-inspired designs into a database that they can query for specific information about the design. Specific information is collected on 380 designs. The research team extensively interviewed bio-inspired design practitioners to create rich and detailed knowledge about the bio-inspired design. Although the processing and documentation of the state of bio-inspired design is ongoing, the research team did learn that more designs are solution based than challenge based, most designs claiming to be bio-inspired are, and most bio-inspired design teams are multidisciplinary and struggle with communication between the disciplines. Also, the research team discovered that bio-inspired design may be co-opted as a paradigm for acquiring knowledge about specific biological phenomena.

In “Using Stochastic MultiCriteria Acceptability Analysis in Keyword Corpus Search Results for Bioinspired Design” examines the use of text mining techniques for accessing biology articles from a corpus relevant to a design problem specified by keywords. They compare three classification techniques for the task: a Naive Bayes classifier, a k-Nearest Neighbor classifier, and a Support Vector Machine. Each of these techniques was first trained on data generated by human subjects. The three techniques were then tested on a corpus of single sentences selected from biology journals. Glier, McAdams, and Linsey found that the Naive Bayes classifier performed best with a precision of 0.86, a recall of 0.52, and an F score of 0.65.

In “Bio-Inspired Design: An Overview Investigating Open Questions From the Broader Field of Design-by-Analogy,” Fu, Moreno, Yang, and Wood examine bio-inspired design practices in the broader context of design-by-analogy strategies. The seminal works in bio-inspired design are reviewed through a comparative qualitative research method and a quantitative analysis. Five major research thrusts emerge from the published methods and tools for supporting bio-inspired design and are categorized as methods, taxonomies, tools, and computational tools. The bio-inspired design research thrusts are assessed against known cognitive and implementation factors in the broader design-by-analogy field and opportunities for future improvement are identified. The study of bio-inspired design is concluded to be a fruitful route to innovation and with strong foundation laid for further investigation of diverse and rigorous approaches.

Under Design Informatics, the paper by Glier, McAdams, and Linsey titled “Exploring Automated Text Classification to Improve Keyword Corpus Search Results for Bioinspired Design” examines the use of text mining techniques for accessing biology articles from a corpus relevant to a design problem specified by keywords. They compare three classification techniques for the task: a Naive Bayes classifier, a k-Nearest Neighbor classifier, and a Support Vector Machine. Each of these techniques was first trained on data generated by human subjects. The three techniques were then tested on a corpus of single sentences selected from biology journals. Glier, McAdams, and Linsey found that the Naive Bayes classifier performed best with a precision of 0.86, a recall of 0.52, and an F score of 0.65.

The short paper by Williams, Ertas, and Tate titled “Using Stochastic MultiCriteria Acceptability Analysis in
Biologically Inspired Design as a Multidisciplinary Tool to Assess Biology-to-Engineering Transfer Risk for Candidate Analogs" presents a multicriteria method for evaluating biological analogs to design problems. Their method combines stochastic multicriteria acceptability analysis originally developed in operations research with criteria derived from biologically inspired design to help designers sort, rank, and select candidate biological analogs.

The section on Empirical Studies contains four articles. In “Biomimetics: Structure-Function Patterns Approach,” Cohen, Reich, and Greenberg discover and list examples of structure–function patterns that repeat in biomimetic applications found through a TRIZ based method. Their goal is to find patterns that can serve as an index of clues that opens doors for further information elaborating the richness and complexity of these structure–function patterns. Using the TRIZ formalism to identify the underlying main function and related structure, they study the function–structure relation of 62 biological systems that are already related to biomimetic innovations and 78 additional biological systems not necessarily related to current biomimetic innovations. In the study, they found that structural patterns repeated themselves at macro- and nano-scales. In all, nine types of structures were found that effectively serve as “engines”—exploiting external fields of energy for performing dynamic functions or “brakes”—blocking external fields of energy that may damage the system, thus exhibiting static functions.

Authors Ngo, Turner, and Linsey examine differences in outcomes of problem- and solution-driven BID approaches in “Identifying Trends in Analogy Usage for Innovation: A Cross-Sectional Product Study.” This study uses 70 products that are classified as biologically inspired and characterizes the design team composition, analogy mapping approach, analogies used and design outcomes for each product. Findings suggest that there is no difference in product outcome between the problem- and solution-driven approaches. Additionally, no correlations are found between the design outcomes and team composition.

In “A Method of Finding Biologically Inspired Guidelines for Environmentally Benign Design and Manufacturing,” Reap and Bras posit that natural systems are inherently sustainable and thus should contain strategies and guidelines for designing engineered systems with minimum negative environmental impact. Toward that end, they identify characteristics, extract biological principles, and translate them into design guidelines. Importantly, they use the Constant Comparative Method to identify and extract fundamental characteristics and subsequently design guidelines from biology and ecology literature. Using this method, the guidelines found typically need to be restated or reformed to be more applicable for engineering systems. This type of reformulation of natural principles into engineering principles is common in bio-inspired design. For example, Nature’s principle of surface adhesion modification requires adaptation for engineering usage. Whereas water is a common contaminant carrier in Nature, in engineering applications, water is not always the most likely contaminant carrier. To reduce the cleaning burden in an engineering application, the guideline is restated as “Modulate adhesion using contaminant carrier phobic surface chemistry enhanced by micro and nano-scale structures.” Reap and Bras continue in the paper to review and compare their found guidelines with existing guidelines found elsewhere in the literature. In a case study they show direct quantifiable improvements in a carpet tile reuse and recycling network using their guidelines.

In “Effects of Abstraction on Selecting Relevant Biological Phenomena for Biomimetic Design,” Feng, Cheong, and Shu examine the role of abstraction in accessing biological analogs to design problems. They hypothesize that replacing biological nouns by their hypernyms (i.e., by more general forms of the nouns) may reduce the bias toward selecting biological analogs based on familiarity and superficial similarity. However, in two separate experiments they found that abstracting biological terms by their hypernyms did not demonstrate the anticipated benefits of abstraction on accessing relevant biology articles, suggesting the need for more research on the topic.

Finally, the special issue contains two articles in the section on Design Innovation. In “AmBot: A Bio-Inspired Amphibious Robot for Monitoring the Swan-Canning Estuary System,” Cui, Cheong, Adams, and Johnson present an example of a bio-inspired design. The robot is needed to collect water-monitoring data from the Swan-Canning River. The Swan-Canning River features relatively shallow and slow-moving water with sandy soils. The final robot must travel on land and water without damaging fragile ecosystems. The major challenge in developing this device lies in that the limited physical size of the robot allows only one type of propulsion system to be used both on land and on water. A feasibility assessment of existing bio-inspired robots revealed that the legged, finned, and snake-like robots were physically unfit for the monitoring task. Also, wheeled and tracked robots became easily bogged on sandy beaches. The robot ultimately developed is centipede inspired. Centipedes and their inspired robots are equipped with multiple legs, which effectively increase the contact area between the robots and ground, thus effectively reducing the pressure on each foot. Further, the multileg actuation provides efficient locomotion and maneuverability on sandy terrain. The centipede inspired robot, Analog multileg actuation into tracks and each leg-linkage is transformed into a track piece consisting of a base and a polystyrene-foam block. This made the tracks essentially both floats and paddles that are also capable of standing or walking the weight of the vehicle. A physical prototype is constructed and tested.

In “Performance Maps for a Bio-Inspired Robotic Condylar Hinge Joint,” Burgess and Etoundi share an example that mimics the design of the human knee. Offering more advantages than a simple hinge joint, the condylar joint allow motion that consists of both rolling and sliding. The ligaments that hold a human knee together are modeled as a four-bar mechanism and two actuators attached to the artificial ligaments provide hinge motion. The resulting design space for the condylar hinge is extremely large. Performance charts are developed that allow designers to better visualize the limits of performance of candidate joints and perform a tradeoff analysis on a number of performance aspects. A prototype hinge joint was manufactured and performance correlated with the presented performance maps.

In closing this editorial and opening the special issue, we are glad to report that biologically inspired design is at an exciting crossroads in the research community—it has grown from a collection of isolated efforts in different disciplines to an emerging community of multidisciplinary research teams with an increasing number of venues to share their findings and increasing interest by industry in applying the new approaches to support design practice. There is still much to do to cultivate the community of researchers and practitioners in biologically inspired design. Likewise, there is significant opportunity for researchers to define the future of the field. We hope you enjoy the glimpse of where biologically inspired design may be heading in this special issue.

Reference
