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Nature as Inspiration in Materials Science and Engineering

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> The more our world functions like the natural world, the more likely we are to endure on this home that is ours, but not ours alone.
>
> Janine Benyus
> Co-founder of the Biomimicry Guild and
> President of The Biomimicry Institute

Biological systems have been in development for billions of years; solutions for many different classes of problems have been solved through optimization of nature's designs, development of materials and processes, and adaptation to changing conditions on Earth. Nature is a rich source of knowledge, and present-day human life has undoubtedly progressed because of our ability to be inspired by nature, and to then innovate solutions to our problems through biomimicry.

In 2008, Mueller[1] wrote about biomimicry as a "young science of adapting designs from nature to solve modern problems [which now] may be coming of age." While nature's designs are well established, our study of nature's designs in the context of biomimicry and bioinspiration might seem new, as Mueller suggests. In fact, bioinspiration is older than one may think; our inspiration from nature is so pervasive that many aspects of modern life are taken for granted, and bioinspiration thus seems like a newer field. When we consider specific sophisticated, modern conveniences such as traveling on an airplane, we actually find that bioinspiration, which occurred hundreds of years ago, set us down a path for innovation based on nature. Why do airplanes exist? Early pioneers of aviation saw birds flying and wanted to fly as well. One of the earliest records we have of bioinspired design is from Leonardo da Vinci (1452–1519). da Vinci designed flying machines and artificial wings (see Fig. 1) based on his dissections of birds. da Vinci was well ahead of his time in the translation of nature's designs for human use, but many of his inventions on paper never became realized in the physical world. Imagine earlier people who also saw birds in flight and wanted to fly, but their technology and knowledge did not even allow for drawing a design (paper was not invented until 105 AD!). Richardson[2] posits that many factors might have been responsible for the lack of materialization of da Vinci's drafted inventions: a culture that had not yet developed tinkering and experimentation as a means to test designs (a culture better developed later in the Industrial Revolution), the fear of competitors and adversaries stealing his ideas, high diversity of interests, and perhaps a personality that was easily bored once the design had been made on paper. da Vinci also had a reputation of not always delivering on time or, even worse altogether, of abandoning projects.

Interestingly, other famous inventors displayed similar behavior with regard to abandonment once a solution was formed. For example, the American inventor of instant photography and Polaroid (Polaroid Corporation, Waltham, MA), Edwin Land (1909–1991), "lost all motivation to write [down solutions to problems] or prove his vision to others" once he "could see the solution to a problem in his head."[3] In fact, "his wife, at the prodding of his instructor, would extract from him the answers to homework problems. She would then write up the homework and hand it in so [Land] could receive credit and not fail the course."[3] Nonetheless, Land never received a degree (other than honorary degrees). However, Land's innovative and inventive nature resulted in production of a great deal of intellectual property and in 40 publications.

Who knows how many patents da Vinci would have had if patent law had been formed in his time, but Land was granted 535 U.S. patents (second only to Thomas Edison who had 1097 U.S. patents). Moreover, Land's dedication to solving problems in commercialization was obsessive and resulted in many years of innovation and realizations of designs in cameras and products—at a cost of sometimes wearing the same clothes for 18 h and forgetting to eat.[3] Hence, being inspired is not enough—one has to have focus as well. Interestingly, Land was also inspired by nature but in the sense of vision and human perception of color. On vacation, Land's daughter asked why she could not see the photos he was taking with his film camera

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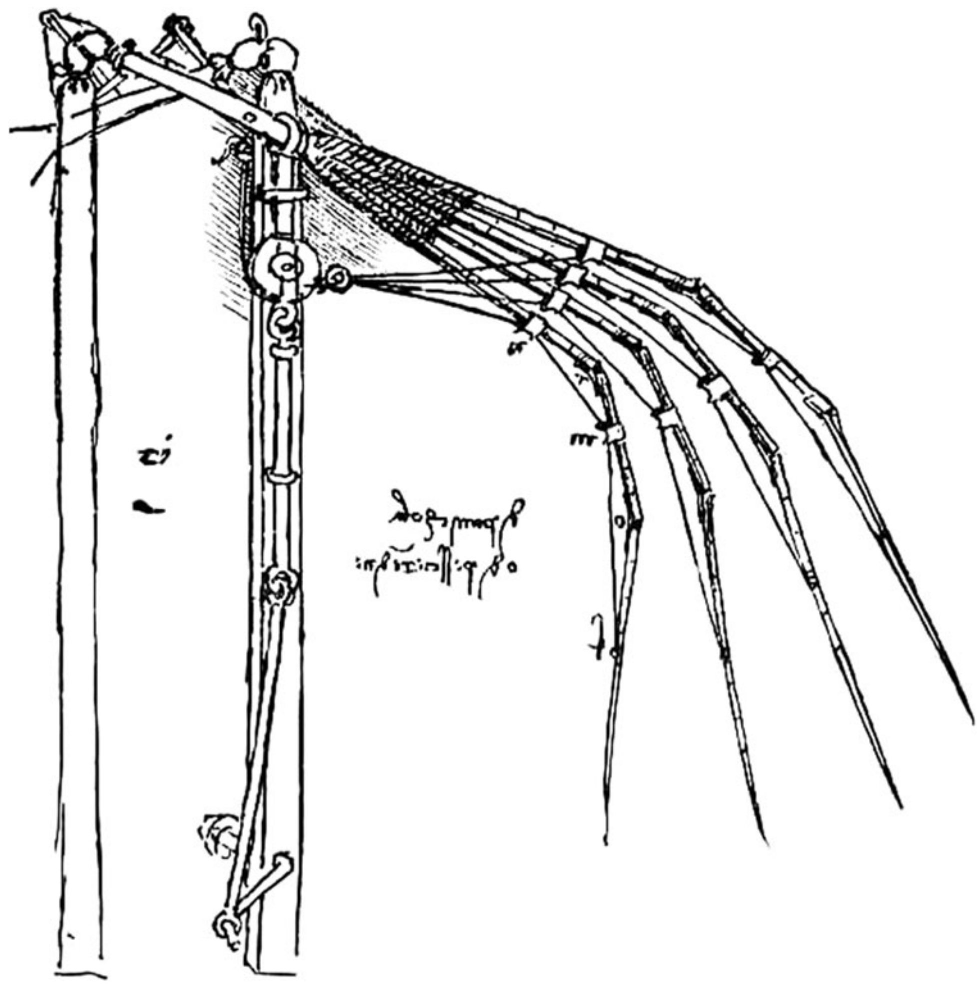

Fig. 1. An early proposed artificial wing design by Leonardo da Vinci. To innovate and construct bioinspired designs, da Vinci studied birds and their wings via dissection to understand "bone articulation, muscular extension and flexion, and hypothesized the construction of [this] artificial wing".[2]

instantly. Land set out to solve the instant photography problem and needed to invent a host of devices, techniques, and processes in order to make his daughter happy! The underpinning technology of instant photography was the film—deemed integral film: the color dyes and developers were all in one construct, which ended up forming the image through chemical reactions once the developer pack was burst and spread evenly across the dye layers. The dye layers in Polaroid color film were based on the physiology of cones in the human eye. Studies of animal eyes, color pigments within the eye, and studies on intact eyes in particular[4] at the time were enabling observations of the instant film revolution (and even today in modern complementary metal-oxide semiconductor digital imaging sensors).

Innovation does not always result in products but in new ways of thinking—for which da Vinci should also get credit. Land's Retinex theory of color vision started with his early works on the study of human perception of color[5,6] and then later developed into analysis[7] and algorithms used in computer color vision. Understanding how to think about the connection between the color sensing technology and the brain's interpretation of signals was an important part of developing photographic systems to achieve accurate color and white balance in Polaroid cameras and film. The color theory was not only used in the camera sector but also in psychology and computer systems.

A theme emerges from those invested in learning from the natural world: we must first seek to understand how nature's designs work, and in order to do so, we must reverse engineer and then re-engineer to suit our needs. As Janine Benyus has said: "[We need to] draw on nature's wisdom, not people's cleverness"[8] in order to innovate. So why would Mueller consider biomimicry and bioinspiration a young science? What Mueller is referring to is the systematic study of bioinspiration and biomimicry its own discipline. Our way of tackling bioinspiration has changed, with strong influence from Janine Benyus who initiated creation of the Biomimicry Guild. There are now new programs to become certified as a biomimicry professional. So how has the scientific community responded? There are more and more collaborations between biological scientists and engineers and between many other groups of people. The introduction of materials scientists and engineers was a natural phenomenon because the heart of materials science is the characterization of materials and their properties. Biological sciences are similar in that the physiology and biological processes are observed. The connection of many disciplines has led, and will continue to lead, to further bioinspired innovations. With formal training, such interdisciplinary studies will likely be accelerated and more fruitful.

In the field of materials science and engineering, we constantly try to understand the structure of materials and the interrelationships with processing and properties. Biological materials hold many secrets to materials design, which have been converted into successful technical materials [e.g., Velcro (Velcro USA Inc., Manchester, NH)]. The hidden, and not so hidden secrets, are what give motivation to the betterment of society through materials innovations. Along this thinking, TMS members formed the Biomaterials Committee and initiated the *Biological Materials Science Symposium* (BMS), which has grown steadily over the past 6–7 years to include many first-time TMS presenters from interdisciplinary fields. Efforts from the TMS Biomaterials Committee have resulted in publication of proceedings in journals such as *Acta Biomaterialia*, *Journal of the Mechanical Behavior of Biomedical Materials,* and *Materials Science and Engineering C: Materials for Biological Applications*, while many members also continue to contribute to *JOM*. The committee is dedicated to the training of members and especially students, and the BMS Symposium has always held openings for student-contributed presentations, offered travel awards, and presented cash prizes for its own separate student poster contest. Continuing education is another component of our efforts, and the "Biomimetic Workshop at the San Diego Zoo" held in 2011 was a resounding success with many attendees and industrial sponsors.

The articles in this issue touch on such curiosity-driven research to unlock nature's mysteries through characterization of materials and investigations of structure property relationships. A host of exceptional authors contributed to this excellent issue with topics ranging from understanding and characterizing materials made from keratin (McKittrick, Chen, Bodde, Yang, Novitskaya, and Meyers), the growth processes of cultured freshwater pearls (Murr and Ramirez), using concepts from animals to develop flexible dermal armor (Yang, Chen, McKittrick, and Meyers), all the way to developing an understanding of a multiscale model of how human bone fractures in various states of degradation (Zimmerman, Barth, and Ritchie). Finally, we conclude with thoughts on how we might envision future integration of life sciences with materials science and engineering (Miserez and Guerette).

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