Biomimicry: A Path to Sustainable Innovation

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Introduction

In his 1998 article, "Design for a Sustainable World," Victor Margolin argues that our ecological plight is beckoning designers to broaden their purpose beyond shaping commodities for clients.[1] Designers are poised to become agents of change that guide a sustainability transition. To do so, they must proactively mold the future profile of their profession by strategically adopting new forms of practice.[2] Biomimicry is an emerging paradigm that can help launch designers into their new role as sustainability interventionists. However, biomimicry does not necessarily render sustainable outcomes. To increase the likelihood of sustainable outcomes, practitioners must consider the form, process, and ecosystem levels of biomimetic design.

The purpose of this paper is to introduce scholars, students, and professionals in all fields of design to biomimicry and to its potential to yield sustainable outcomes when practiced in a deep, thoughtful way. The design community is an important leverage point for fueling dialogue about biomimicry because designers work "at the nexus of values, attitudes, needs, and actions" and, therefore, are uniquely positioned to act as transdisciplinary integrators and facilitators.[3]

What is Biomimicry?

Biomimicry involves learning from and emulating biological forms, processes, and ecosystems tested by the environment and refined through evolution.[4] Biomimicry can be applied to solve technical and social challenges of any scale.[5] Biology has inspired design since prehistoric man fashioned spears from the teeth of animals and mimicked the effective sneak-and-pounce hunting technique of large predators, but the development of a methodological framework for translating biological strategies into design innovations is a recent one. American inventor, Otto Schmitt, coined the term "biomimetics" in the 1960s to describe the transfer of ideas from biology to technology.[6] Three decades

1 Victor Margolin, "Design for a Sustainable World," *Design Issues* 14, no. 2 (1998): 83–92.

2 Alain Findeli, "Rethinking Design Education for the 21st Century: Theoretical, Methodological, and Ethical Discussion," *Design Issues* 17, no. 1 (2001): 5–17.

3 Daniel C. Wahl and Seaton Baxter, "The Designer's Role in Facilitating Sustainable Solutions," *Design Issues* 24, no. 2 (2008): 72.

4 Janine M. Benyus, "Spreading the Meme: A Biomimicry Primer," in *Biomimicry Resource Handbook: A Seed Bank of Best Practices* (Missoula, MT: Biomimicry 3.8, 2013), http://issuu.com/biomimicry38/docs/biomimicry_resource_handbook_excerpt (accessed August 14, 2013).

5 Janine M. Benyus, *Biomimicry: Innovation Inspired by Nature* (New York: William Morrow, 1997).

6 Otto H. Schmitt, "A Thermionic Trigger," *Journal of Scientific Instruments* 15, no. 1 (1938): 24; Jon Harkness, "A Lifetime of Connections: Otto Herbert Schmitt, 1913–1998," *Physics in Perspective* 4 (2002): 456–90.

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later, biomimicry was popularized by Janine Benyus, who broadcast its enormous potential to inform a new era of design in her critically acclaimed book, *Biomimicry: Innovation Inspired by Nature*.[7]

Biomimicry is a burgeoning field of study, as evidenced by a growing demand for training in biomimicry theory and practice[8] and a fivefold increase in biomimicry patents, scholarly articles, and research grants since 2000.[9] According to a report by the Fermanian Business & Economic Institute, biomimicry could account for $425 billion of the U.S. gross domestic product (GDP) and $1.6 trillion of global output by 2030.[10] The popularization of biomimicry is exciting not just because of its economic prospects, but because of its tremendous potential to inspire eco-friendly designs at this critical juncture in human history. Biomimicry forces a new set of questions that can be applied to the design process, as well as to the outcome. Biological designs are, for instance, resilient, adaptable, multifunctional, regenerative, and generally zero-waste. When deeply informed by biology, design thinking shifts away from an anthropocentric model and considers product life cycles and earth system limitations.

Some scholars argue that the sustainability criterion is too limiting,[11] but "smart companies now treat sustainability as innovation's new frontier."[12] When tackled appropriately, it offers opportunities for lowering costs and generating additional revenues, and it enables companies to create new businesses to achieve competitive advantage. However, "imitation of the living world is not by default environmentally superior."[13] Therefore, informing designers, among others, about the circumstances under which biomimicry is most likely to lead to sustainable solutions is important so that they can engage with the future in a more direct way.[14] At its best, biomimicry is an elegant merger of sustainability and innovation that allows designers to continue earning a living within a system dominated by a consumer culture, while working alongside biologists to co-create a human civilization able to flourish within the ecological limits of our planetary support system.[15]

Biomimetic Design Practice

Biologists are key players in the biomimicry design process because it relies heavily on biological knowledge; however, the role of the designer remains central. This orientation is particularly true when it comes to abstracting biological strategies into more broadly applicable design principles and implementing them to solve human challenges.[16] The aim of biomimicry is not to create an exact replica of a natural form, process, or ecosystem; instead, it is to derive design principles from biology and use those principles as stimulus for ideation. That said, a final biomimetic solution should clearly evidence a transfer of functional or organizational

7 Janine M. Benyus, *Biomimicry: Innovation Inspired by Nature*. (New York: William Morrow, 1997).

8 Nathan F. Lepora, Paul Verschure, and Tony J. Prescott, "The State of the Art in Biomimetics," *Bioinspiration & Biomimetics* 8, no. 1 (March 1, 2013): 013001.

9 Fermanian Business & Economic Institute, *Bioinspiration: An Economic Progress Report* (San Diego, CA: Point Loma Nazarene University, 2013), http://www.pointloma.edu/sites/default/files/filemanager/Fermanian_Business__Economic_Institute/Economic_Reports/BioReport13.FINAL.sm.pdf (accessed May 28, 2014).

10 Ibid, 5.

11 Andrea E. Rawlings, Jonathan P. Bramble, and Sarah S. Staniland, "Innovation Through Imitation: Biomimetic, Bioinspired and Biokleptic Research," *Soft Matter* 8, no. 25 (2012): 6675.

12 Ram Nidumolu, Coimbatore K. Prahalad, and M. R. Rangaswami, "Why Sustainability Is Now the Key Driver of Innovation," *Harvard Business Review* 87, no. 9 (2009): 58.

13 John Reap, Dayna Baumeister, and Bert Bras, "Holism, Biomimicry and Sustainable Engineering," *ASME Proceedings*, no. IMECE2005-81343 (2005): 423–31; Julia Marie O'Rourke, "Environmentally Sustainable Bioinspired Design: Critical Analysis and Trends," May 2013, http://repositories.lib.utexas.edu/handle/2152/22289 (accessed May 25, 2014).

14 Victor Margolin, "Design, the Future and the Human Spirit," *Design Issues* 23, no. 3 (2007): 4–15.

15 Victor Margolin, "Design for a Sustainable World," *Design Issues* 14, no. 2 (1998): 83-92; Daniel C. Wahl and Seaton Baxter, "The Designer's Role in Facilitating Sustainable Solutions," *Design Issues* 24, no. 2 (2008): 72-83.

16 Janine M. Benyus, "Spreading the Meme: A Biomimicry Primer," in *Biomimicry Resource Handbook: A Seed Bank of Best Practices*> (Missoula, MT: Biomimicry 3.8, 2013), http://issuu.com/biomimicry38/docs/biomimicry_resource_handbook_excerpt (accessed August 14, 2013).

principle from biology. After all, the purpose of biomimicry is to tap the knowledge embodied by nature's 3.8 billion years of research and development,[17] and accomplishing this goal is not possible if the functional analogy between the natural model and the final design is lost in translation.

Biomimicry and Sustainability: The Direct Connection

Humans are currently using energy and resources unsustainably. Through biomimicry, designers can guide development of technologies that have net zero or net positive environmental consequences because biological solutions have been time-tested by billions of years of evolution and embody successful strategies for thriving on earth.[18] To demonstrate how biomimicry—repurposing nature's best ideas to solve human challenges—can help inform sustainable design, consider the following. TRIZ, a widely-used engineering problem-solving tool, was adapted to create BioTRIZ.[19] The original TRIZ, developed by Soviet inventor Genrich Altshuller and his colleagues in 1946, is a matrix where intersections represent engineering tradeoffs; for instance, to make a vehicle go faster, you need more power, which consumes more fuel.[20] At each intersection, a cell contains numbers that reference technological design principles for resolving a trade-off.[21] For example, if the vehicle's body is made more aerodynamic, you can make the vehicle go faster with the same amount of power and fuel. To create BioTRIZ, researchers analyzed 2,500 trade-offs and resolutions *in biology* and populated a matrix with biological instead of technological design principles.[22] Analysts found only a 12% overlap between trade-off resolutions recommended by BioTRIZ vs. TRIZ, which shows that biology solves problems differently than technology. In technology, the manipulation of energy may account for up to 70% of the solution, whereas in biology, energy never figures into more than 5% of the solution. Instead of manipulating energy, biological solutions tend to leverage information transfer and structure.[23]

Biomimicry marks a divergence from the unsustainable Industrial Revolution, which was "an era based on what we can extract from nature."[24] Emulating biology is different from harvesting or domesticating organisms to accomplish a desired function. This difference might seem obvious; however, newcomers to biomimicry commonly seek "to use an organism to 'do what it does' instead of leveraging the design principles embodied by the organism. This is the equivalent of using fireflies themselves to produce light, rather than understanding and applying the complex chemistry involved in bioluminescence."[25]

17 Janine M. Benyus, *Biomimicry: Innovation Inspired by Nature* (New York: William Morrow, 1997), 3.

18 Janine M. Benyus, "Spreading the Meme: A Biomimicry Primer," in *Biomimicry Resource Handbook: A Seed Bank of Best Practices* (Missoula, MT: Biomimicry 3.8, 2013), http://issuu.com/biomimicry38/docs/biomimicry_resource_handbook_excerpt (accessed August 14, 2013).

19 Julian F. V. Vincent and Darrell L. Mann, "Systematic Technology Transfer from Biology to Engineering," *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 360, no. 1791 (2002): 159–73.

20 Ellen Domb, "Contradictions: Air Bag Applications," *TRIZ Journal,* 1997, http://www.triz-journal.com/archives/1997/07/a/ (accessed September 9, 2013),

21 Ibid.

22 Julian Sartori, Ujjwal Pal, and Amaresh Chakrabarti, "A Methodology for Supporting 'Transfer' in Biomimetic Design," *AI EDAM* 24, Special Issue 04 (2010): 483–506.

23 N. R. Bogatyrev and O. A. Bogatyreva, "TRIZ Evolution Trends in Biological and Technological Design Strategies," *Proceedings of the 19th CIRP Design Conference – Competitive Design, 30-31 March 2009* (2009): 293; Tom McKeag, "Framing Your Problem with the Bio-Design Cube," ZygoteQuarterly, no. 6 (2013): 104–09.

24 Janine M. Benyus, *Biomimicry: Innovation Inspired by Nature* (New York: William Morrow, 1997), 2.

25 Michael Helms, Swaroop S. Vattam, and Ashok K. Goel, "Biologically Inspired Design: Process and Products," *Design Studies* 30, no. 5 (2009): 606–22.

Biomimicry and Sustainability: The Deeper Connection

Beyond the direct connection between biomimicry and sustainability—the simple fact that in emulating biological systems we are emulating strategies time-tested by evolution—a much deeper connection also emerges. Biomimicry does not necessarily render sustainable outcomes, and we cannot overlook this fact.[26] A biomimetic solution could get high marks in functional performance but fail miserably in a sustainable life cycle analysis.[27] Thus, designers who want to use biomimicry to create more sustainable designs must strive to emulate biological lessons on three levels: form, process, and ecosystem.[28] This multilevel approach is most effective for achieving solutions that inspire awe in terms of sustainable performance:

1. *Form.* At the first level, emulating form, consider as an example the giant leaves of the Amazon water lily. The shape and support ribs of the leaves can inform a new innovation of lightweight but structurally strong building panels.[29] However, this innovation might or might not be sustainable. For example, if these panels are made of toxic materials that pollute the environment, the costs outweigh the benefits.
2. *Process.* At the second level of biomimicry, the focus is on emulating biological processes, or more specifically, how nature manufactures. Nature assembles structures at ambient temperature and pressure using non-toxic chemistry.[30] By contrast, most factories form product by carving, bending, melting, casting, or otherwise manipulating large blocks of raw materials at high temperatures and pressures. Compared to biological manufacturing, the factory approach shows tremendous room for improvement. It is much more energy-intensive, polluting, and wasteful.[31]

   Encouraging a large-scale shift from traditional to biomimetic manufacturing will be difficult, given the markedly different infrastructure required. A team might envision a biomimetic solution that is environmentally sustainable, in theory, but if no appropriate manufacturing techniques are at hand, realizing that solution might be impossible. The development of infrastructure required to manufacture environmentally friendly, cost-effective biomimetic products is lagging behind.[32]

   Nearly all biological materials are constructed of a combination of carbon, hydrogen, oxygen, nitrogen, phosphorous, and sulfur. It is the way these ingredients are combined that gives biological materials a great variety of useful functions. Industrial manufacturers take a different approach. Instead of combining a few benign

26 John Reap, Dayna Baumeister, and Bert Bras, "Holism, Biomimicry and Sustainable Engineering," *ASME Proceedings,* no. IMECE2005-81343 (2005): 423–31.

27 Ibid.

28 Janine M. Benyus, "Spreading the Meme: A Biomimicry Primer," in *Biomimicry Resource Handbook: A Seed Bank of Best Practices* (Missoula, MT: Biomimicry 3.8, 2013), http://issuu.com/biomimicry38/docs/biomimicry_resource_handbook_excerpt (accessed August 14, 2013).

29 David Attenborough, *The Private Life of Plants: A Natural History of Plant Behaviour* (Boston: Compass Press, 1995).

30 Exceptions always arise to a general rule. For instance, bombardier beetles defend themselves against predators by ejecting a steaming hot spray of noxious chemicals. The spray is generated internally when two chemicals, hydroquinone and hydrogen peroxide, stored in separate reservoirs in the beetle's abdomen, are mixed in a third chamber with water and catalytic enzymes. This brings the water to a boil. Although in this case a biological organism uses extreme heat to manufacture, note that bombardier beetles generate this heat by way of a simple chemical reaction, rather than using large amounts of electricity or other external energy sources.

31 Jeremy Faludi, "Biomimicry 101," *World Changing. Change Your Thinking,* (October 13, 2005), http://www.worldchanging.com/archives/003625.html (accessed August 14, 2013).

32 Hugh A. Bruck, et al., "Training Mechanical Engineering Students to Utilize Biological Inspiration During Product Development," *Bioinspiration & Biomimetics* 2, no. 4 (2007): S198–209.

elements in a multiplicity of ways to achieve a range of functional properties, we seek out rare and toxic elements like carcinogenic hexavalent chromium that inherently exhibit desired functional properties. To further illustrate this key difference consider the following: A beetle's shell provides strength, breathability, color, and waterproofing but is made from only chitin and protein, which, in turn, are made from ony the six elements previously named.[33] In contrast, a chip bag is made of several different materials that each fulfills a separate function. The beetle's shell is biodegradable, but the chip bag ends up in a landfill. To produce our own multifunctional materials from a small chemical palette, we still have much to learn about biological construction. In addition, biological manufacturing has a higher fault tolerance. Even with minor defects, natural systems are usually still fully functional. The tolerance for a discernable degree of variation would allow for fabrication noise, offering ways to create successful designs with lower production cost.[34]

One example of a promising approach to improve manufacturing is 3D printing, which involves forming a solid object from a digital model by laying down successive layers of material. This approach mimics nature's additive, material-efficient manufacturing processes. Advances in 3D printing are unbelievably exciting, but 3D printing processes urgently need tweaking before this technology can be considered eco-friendly. Opportunities for enhancing the technology require looking at other aspects of biological manufacturing. Right now, 3D printing uses toxic resins, ceramics, and powdered metal as feedstock,[35] but research currently is being conducted to investigate the viability of using benign, locally sourced feedstocks, such as waste woodchips, used paper, plastic scrap, clay, or carbon dioxide.[36] At the end of the 3D-printed product's lifecycle, it could be disassociated using naturally occurring enzymes, returning it to printing feedstock for 100% recycling.[37] We can also improve 3D printing if we stick material layers together using attractive forces, such as hydrogen or ionic bonds, because such forces would eliminate the need for toxic glue between the additive layers of a 3D-printed object. Another pressing problem is the amount of energy the printing process consumes. Currently, 3D printers consume an estimated 50 to 100 times more electrical energy than injection molding to create a product of the same weight.[38]

33 H. R. Hepburn and A. Ball, "On the Structure and Mechanical Properties of Beetle Shells," *Journal of Materials Science* 8, no. 5 (1973): 618–23.

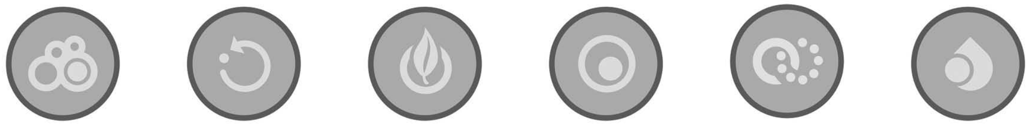
34 Tim Starkey and Pete Vukusic, "Light Manipulation Principles in Biological Photonic Systems," *Nanophotonics* 2, no. 4 (2013): 289–307.

35 Brian C. Howard, "Improving 3-D Printing by Copying Nature," *National Geographic Daily News*, July 7, 2013, http://news.nationalgeographic.com/news/2013/07/130707-3d-printing-biomimicry-green-design-science/ (accessed August 29, 2014).

36 Christian Baechler, Matthew DeVuono, and Joshua M. Pearce, "Distributed Recycling of Waste Polymer into RepRap Feedstock," *Rapid Prototyping Journal* 19, no. 2 (2013): 118–25; Klaudius Henke and Sebastian Treml, "Wood-Based Bulk Material in 3D Printing Processes for Applications in Construction," *European Journal of Wood and Wood Products* 71, no. 1 (2013): 139–41.

37 Brian C. Howard, "Improving 3-D Printing by Copying Nature."

38 Hod Lipson and Melba Kurman, *Fabricated: The New World of 3D Printing* (Indianapolis, IN: Wiley, 2013).



EVOLVE TO SURVIVE	ADAPT TO CHANGING CONDITIONS	BE LOCALLY ATTUNED AND RESPONSIVE	INTEGRATE DEVELOPMENT WITH GROWTH	BE RESOURCE EFFICIENT (MATERIAL AND ENERGY)	USE LIFE-FRIENDLY CHEMISTRY
Continually incorporate and embody information to ensure enduring performance.	Appropriately respond to dynamic contexts.	Fit into and integrate with the surrounding environment.	Invest optimally in strategies that promote both development and growth.	Skillfully and conservatively take advantage of resources and opportunities.	Use chemistry that supports life processes.
Replicate Strategies that Work Repeat successful approaches. **Integrate the Unexpected** Incorporate mistakes in ways that can lead to new forms and functions. **Reshuffle Information** Exchange and alter information to create new options.	**Incorporate Diversity** Include multiple forms, processes, or systems to meet a functional need. **Maintain Integrity through Self-Renewal** Persist by constantly adding energy and matter to heal and improve the system. **Embody Resilience through Variation, Redundancy, and Decentralization** Maintain function following disturbance by incorporating a variety of duplicate forms, processes, or systems that are not located exclusively together.	**Leverage Cyclic Processes** Take advantage of phenomena that repeat themselves. **Use Readily Available Materials and Energy** Build with abundant, accessible materials while harnessing freely available energy. **Use Feedback Loops** Engage in cyclic information flows to modify a reaction appropriately. **Cultivate Cooperative Relationships** Find value through win-win interactions.	**Self-Organize** Create conditions to allow components to interact in concert to move toward an enriched system. **Build from the Bottom Up** Assemble components one unit at a time. **Combine Modular and Nested Components** Fit multiple units within each other progressively from simple to complex.	**Use Low Energy Processes** Minimize energy consumption by reducing requisite temperatures, pressures, and/or time for reactions. **Use Multi-Functional Design** Meet multiple needs with one elegant solution. **Recycle All Materials** Keep all materials in a closed loop. **Fit Form to Function** Select for shape or pattern based on need.	**Break Down Products into Benign Constituents** Use chemistry in which decomposition results in no harmful by-products. **Build Selectively with a Small Subset of Elements** Assemble relatively few elements in elegant ways. **Do Chemistry in Water** Use water as solvent.

Figure 1
Life's Principles. Life's Principles is a systems-thinking tool that contains common principles embodied by most species on Earth. Its purpose is to help practitioners create designs that fit seamlessly within the larger natural system. Permission to reprint image granted by Biomimicry 3.8.

3. *Ecosystem.* Even emulating both form and process does not guarantee development of a product with a net zero or net positive environmental impact.[39] The design might still be lacking in terms of how it fits within the larger ecosystem. All organisms are part of a biome that is part of the bio-sphere. As such, every organism's continued prosperity is dependent on the health of the biosphere.[40] The highest level of biomimicry, emulating the ecosystem, is most difficult because it requires skilled systems thinking to make sure the design fits seamlessly within the biosphere. The US-based firm, Biomimicry 3.8 (the 3.8 stands for 3.8 billion years of evolution), developed a tool called Life's Principles that helps evaluate a biomimetic design's ecosystem-level sustainability. Life's Principles summarizes repeated patterns and principles embodied by organisms and ecosystems on earth. These patterns and principles are thought to support a sustaining biosphere.[41] In total, the tool outlines six major principles and 20 sub-principles (see Figure 1). Inconsistencies with Life's Principles are indicators of a potentially unsustainable innovation and identify opportunities to further optimize your design. These inconsistencies are easier to detect and resolve when the tool is used as a benchmark throughout the entire design process and when the team makes an effort to integrate Life's Principles along the way.

39 O'Rourke, "Environmentally Sustainable Bioinspired Design," 69.

40 William McDonough, "Cradle to Cradle Design" (lecture presented at the TED Conference, Monterey, CA, 2005), https://www.ted.com/talks/william_mcdonough_on_cradle_to_cradle_design (accessed May 10, 2014); Michael Braungart and William McDonough, *Cradle to Cradle: Remaking the Way We Make Things* (New York: North Point Press, 2002).

41 Janine M. Benyus, "Spreading the Meme: A Biomimicry Primer," in *Biomimicry Resource Handbook: A Seed Bank of Best Practices* (Missoula, MT: Biomimicry 3.8, 2013), http://issuu.com/biomimicry38/docs/biomimicry_resource_handbook_excerpt (accessed August 14, 2013).

Biomimetic designs, like all designs, can be used in a variety of ways, including those that are potentially dangerous and counterproductive. Another aspect of ecosystem-level biomimicry focuses on ensuring that biomimetic designs are used in ways that are socially beneficial. Regulating how innovations are used is not always possible, but designers still need to do what they can to ensure solutions that are deployed do "what is possible and useful" rather than "what is possible, but harmful."[42]

The Defense Advanced Research Projects Agency (DARPA) has been the biggest financial supporter of biomimicry research, as well as of the development of biomimetic concepts.[43] DARPA recognizes that, if understood properly, biological strategies could inform new defense capabilities. DARPA's Defense Sciences Office (DSO) focuses on "understanding and emulating the unique locomotion and chemical, visual, and aural sensing capabilities of animals."[44] DARPA's DSO funded the development of BigDog, a dynamically stable quadruped robot that can run over rough-terrains and carry heavy loads. BigDog mimics quadruped mammal leg articulation, with compliant elements that absorb shock and recycle energy from one step to the next.[45] DARPA regards and values BigDog as a robotic mule to accompany soldiers in terrains too rough for conventional vehicles. Biomimetic robotic technologies like BigDog can be used in both productive and destructive ways.[46] They can venture into remote or dangerous areas, preventing possible human injury or death. They can dismantle mines or locate survivors after a chemical disaster. On the other hand, robots can be used to illegally surveil or kill innocent civilians.

Design affects how we interface with the world, so we should balance the profound innovation possible through biomimicry with a lens of environmental and social scrutiny. This analysis requires effort on the part of the designer to selectively transfer desirable aspects of the natural model to the final design and to advocate for its being used for positive ends. That said, the lofty ideal of net social and environmental contribution should not dissuade designers from using the biomimicry approach. A biomimetic design that does not achieve net positive effect but does improve environmental or social performance by any increment compared to the status quo is worth pursuit. Every biomimetic design is at least one stride ahead in the marathon toward a better relationship with each other and our natural environment.

Conclusion

Given our ecological plight, now is the time for designers to broaden their purpose beyond just shaping commodities according to client specifications. Designers have a unique opportunity to act as sustainability interventionists. To do so, they must adopt new

42 I. C. Gebeshuber, P. Gruber, and M. Drack, "A Gaze into the Crystal Ball: Biomimetics in the Year 2059," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 223, no. 12 (December 1, 2009): 2899–918.

43 Elizabeth R. Johnson, "Reinventing Biological Life, Reinventing 'the Human,'" *Ephemera* 10, no. 2 (2010): 177–93.

44 DARPA, "Defense Sciences Office," 2008, http://www.darpa.mil/Our_Work/DSO/ (accessed September 15, 2014).

45 Boston Dynamics, "BigDog: The Most Advanced Rough-Terrain Robot on Earth," *BostonDynamics*, http://www.bostondynamics.com/robot_bigdog.html (accessed September 15, 2013).

46 Our focus here is on the technology itself. We do not provide comment on the essentiality of a military because that would reach far beyond the scope of this paper. We also assume in this discussion that the robot was made in an environmentally sustainable way, which in many cases has not yet been accomplished.

forms of practice that yield sustainable solutions. Biomimicry is one such emerging practice, which involves repurposing biology's best ideas to solve human challenges.

Biomimicry has generated designs that are environmentally and socially sustainable. Consider the success of Stabilitech, a U.K. company that has created a biomimetic technology that allows storage and handling of biological samples without refrigeration. Traditionally, biological materials, such as vaccines, have to be kept refrigerated until delivery to the patient to prevent degradation. Healthcare facilities in developing countries lacking reliable refrigeration infrastructure were forced to discard half of supplied vaccines because of problems with temperature control.[47] Some organisms—like spikemoss, tardigrades, and brine shrimp—are able to temporarily halt their metabolism in response to adverse environmental conditions, such as extreme dryness and cold temperatures.[48] By mimicking the principles of biological mechanisms, Stabilitech successfully developed non-toxic and inexpensive chemical excipients that stabilize biological materials in ambient temperatures.[49] Now viable vaccines are made available to a greater number of people in developing countries for a lower cost. And the technology is sustainable. According to a Stanford University pilot project, shifting the storage of biological samples from frozen storage to room temperature could result in energy savings of 200,000 million BTUs for refrigeration and a reduction of more than 18,000 tons in associated reduced carbon dioxide emissions over the next ten years.[50]

Design practitioners can set an example for others by practicing a deep form of biomimicry, which considers emulation of form, process, and ecosystem. This multilevel approach should not be limiting—it is not an all-or-nothing proposition—but is most likely to lead to solutions that awe in terms of sustainability. Much remains to be investigated and learned about biomimicry for the paradigm to mature. As more design practitioners adopt biomimicry, this development can happen more quickly. Through trial-and-error, biomimetic design practitioners can evolve best practices. As in nature's way, maladapted strategies should rapidly disappear or transition into better-adapted ones. Every attempt at biomimicry provides value in the form of lessons learned, and regular practice will encourage a sense of responsibility to care for nature, as a mentor and source of inspiration for innovative solutions.[51]

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47 Michael Jennings and Monika Wcislo, "European Commission Offers $2 Million Prize for a Leap Forward in Vaccine Technology," *News Alert* (2012), http://ec.europa.eu/research/index.cfm?pg=newsalert&year=2012&lg=en&na=na-160412 (accessed October 5, 2013).

48 John H. Crowe, Folkert A. Hoekstra, and Lois M. Crowe, "Anhydrobiosis," *Annual Review of Physiology* 54, no. 1 (1992): 579–99; James S. Clegg, "Cryptobiosis—A Peculiar State of Biological Organization," *Comparative Biochemistry and Physiology Part B: Biochemistry and Molecular Biology* 128, no. 4 (2001): 613–24; http://www.asknature.org/strategy/5647adb99bf90b1c723987c7683ea169#.U3GD115Ktkw (accessed May 13, 2014); http://www.asknature.org/strategy/e13202f222f17c78af45111d9553db19#.U3GDeV5Ktkw (accessed May 13, 2014).

49 Jeffrey Drew, "Desiccated Product." U.S. Patent Application 11/815,947, filed February 9, 2006; Sherry Ritter, "Inspired by the Water Bear," *Biomimicry Education Network,* 2012, http://ben.biomimicry.net/coolbio/2012/inspired-by-the-water-bear/ (accessed May 10, 2014).

50 Gregory Jensen, "Room Temperature Biological Sample Storage," *Sustainable Stanford Quick Fact Sheet*, 2009, http://www.i2sl.org/documents/toolkit/bulletin_rtss_508.pdf (accessed October 10, 2013).

51 Jeannette Yen et al., "Evaluating Biological Systems for Their Potential in Engineering Design," *Advances in Natural Science* 3, no. 2 (2010): 27–40.