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Biologically inspired design

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ABSTRACT

The bioworld is an immense repository of successful solutions to overcome diverse problems. This repository can be used for biologically inspired design (BID). In this lecture, I point out various aspects of BID, including (i) identification of bioworld systems of relevance for engineering, with emphasis on multifunctionality, multicontrollability, sustainability, and circular economy; (ii) correlation of engineering problems with solution strategies available in the bioworld; and (iii) descriptions of two pathways for systematic adaptation of bioworld solutions to solve engineering problems.

Keywords: circular economy, contraindicated performance, formal design, multifunctionality, multicontrollability, problem-driven BID, solution-driven BID, sustainability

Good morning, colleagues. On Monday, March 13, you heard Daniel Inman speak about designing uncrewed air vehicles with inspiration from avian flight. The following day, you heard Zoubeida Ounaies on living multifunctional materials. Since good things always come in threes, this lecture is about biologically inspired design (BID).

Until 2008, I was a regular faculty member with instructional and research activities that regular faculty members at regular universities undertake. I had a thoroughly regular existence. And then, quite suddenly, I became acutely conscious of what we call climate emergency today. That forced me to take off my regular glasses and look at human activities from a fresh viewpoint. I will share with you what I came across, what I learned, and what I thought of.

I will explain that systems in the bioworld are relevant to engineering. Then I will describe relevant attributes of the bioworld, and and go on to identify correlations between engineering problems and bioworld solutions. Finally, I will acquaint you with pathways for adaption of systematic procedures for undertaking BID activities. Much of what I will tell you is available in a short book that I co-wrote three years ago with Torben Lenau.[1]

Definitions. This lecture is divided into six modules. The first module is on a few definitions. The concept of SUSTAINABILITY ideally requires the indefinitely long maintenance of natural resources for ecological balance. That is, present-day needs are satisfied and resources needed for the next generation are preserved. The term BIOMIMICRY encompasses basic research as well as application-oriented research on bioworld outcomes and processes. It also incorporates sustainability. Biomimicry is concerned with the design of both products and manufacturing processes.

BID's scope encompasses design strategies to reproduce desirable outcomes, mechanisms, and structures in the bioworld. The conceptualization and design of aeroplanes exemplifies BIOINSPIRATION. Birds fly. Aeroplanes fly. The mechanisms are totally different. The outcomes are the same. Next, BIOMIMETICS aims to reproduce bioworld mechanisms. As an example, the hook-loop mechanism which allows burrs to stick to animal fur is reproduced in Velcro™. Finally, in BIOREPLICATION a bioworld structure is reproduced. The exocuticle of an emerald ash borer has been copied to serve as a decoy.

Three requirements have been prescribed by the International Standards Organization for a design to be claimed as BIOMIMETIC. First, a FUNCTION ANALYSIS must be performed on a bioworld system. Second, the essential mechanism(s) in that system must be identified and converted into ENGINEERING PRINCIPLE(S). Third, those principles must be applied in the DESIGN of a product or process.

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A MULTIFUNCTIONAL system can perform two or more functions that are largely unrelated. A Swiss Army knife is an excellent example. Some systems are MULTICONTROLLABLE. Examples are metasurfaces that can be electrically, magnetically, and thermally controlled.

Nature of Design. The second module is on the nature of design. Design can be informal as well as formal. As engineers and scientists, we are familiar with both, but perhaps less with formal design used in industrial studios. INFORMAL DESIGN produces one-off products, exemplified by the swords of blue steel made in medieval Damascus. Informal designers, such as village potters, may produce just a few different types of items for local use.

FORMAL DESIGN is essential in industrialized societies, because users, designers, and manufacturers can be located far away from each other. Therefore, formal design requires market research, it requires documentation, and it requires communication among all stakeholders (including conceptualizers, designers, manufacturers, and users).

Formal design requires a specific mindset called DESIGN THINKING, which focuses on user needs. Therefore, there is a DESIGN PATHWAY with six steps. The first step is to generate a set of possible solutions. It need not be a small set. The second step is to identify a few acceptable solutions, from the user's point of view as well as from manufacturability. The third step is to grade the acceptable solutions according to their manufacturability. The fourth step is to compare them from the points of view of the users. The fifth step requires the formulation of a design proposal, prototyping the chosen design, and testing it. The sixth step is to transmit documentation to the manufacturer. This pathway is usually not lineal and generally has loops.

Designers need to define the DESIGN OBJECT quite at the beginning of the design activity. One would think that the design object is simply a product (or a process). Is it? No. The design object comprises the product or process, its components, merchandizing services, maintenance services, operational infrastructure, and end-of-life disposal services. Think of designing an automobile. You have to consider the kinds of tires available for replacement, the entertainment options to provide, and the availability of a dealer network; plus, the availabilities of trained mechanics and replacement parts, the network of fuel providers, and even junkyards in that region. Thus, a product or process exists in an ecosystem, just as an animal or a plant or a virus exists in the bioworld.

So where does BID fit in formal design? BID is to be used for systematic idea-generation to engender a set of possible solutions. There are two types of idea-generation methods. The first is very creative. There are no rigid rules. People simply brainstorm. Idea-generation methods of the second type are structured or systematic. There are rigid rules. BID is constrained to consider ideas arising from bioworld studies.

Finally, the DESIGN TEAM is multidisciplinary, because it comprises artists, physicists, chemists, materials scientists, engineers, etc. A BID team will also have a general biologist or more.

Rationale for BID. Why should one adopt bioworld solutions? To answer this question, let us look at the Theory of Evolution. Charles Darwin actually used the word EVOLUTION sparingly. He used the phrase DESCENT WITH MODIFICATION. Descent means heritability: what you get from your parents, and how are their contributions amalgamated. Modification means mutation. Some features are not inherited from the parents. A mutation may have reproductive success, and may therefore spread. A series of consecutive mutations can give rise to a new species.

Every successful mutation is a solution to a problem! About 9 million species are estimated to exist in the bioworld. So, the bioworld is a collection of millions, even billions, of solutions.

We have to be careful, however. Bioworld solutions just have to be adequate. They need not be the best solutions, because evolution is constrained. Mutations are changes, not *de novo* entities. But we have the opportunities to combine and enhance bioworld solutions.

Bioworld Characteristics. Bioworld solutions should be sought, because they may have certain attractive characteristics. The first attractive characteristic is ENERGY EFFICIENCY. Neither very low nor very high temperatures are found in the bioworld. Neither very low nor very high pressures are found in the bioworld. Therefore, the adoption of a bioworld solution could enhance energy efficiency. Next, the bioworld has CIRCULAR ECONOMY OF MASS. The outputs and waste of a species become nutrients for one or more species. This leads to an important dictum for all engineers: *Waste is a design flaw.* Third, bioworld systems are often MULTIFUNCTIONAL.

Therefore, fewer organs have to be formed, housed, and controlled. In industry, multifunctionality means that the same part or subprocess can be used in many products. That promotes standardization, reduces inventory costs, enhances repairability, and prolongs useful life. MULTICONTROLLABILITY builds resilience via redundancy, and can be essential for critical facilities such as hospitals, missile guidance systems, and spacecraft.

But bioworld solutions are often SUBOPTIMAL. The wings of an owl are suitable for flying silently but not rapidly. The wings of a swan are noisy but can life a heavy body. So the adequacy of a bioworld solution is context-specific. Adequacy should not be confused with optimality, which means that a bioworld solution may have to be modified for industrial application. That provides an opportunity to add functionalities. As an example, consider the Biomimetics 200™ series of tennis racquets made by Dunlop. The racquet's carbon frame has a honeycomb structure, giving it strength and it is still light weight. Its frame is covered by a sharkskin-type fabric to reduce drag. Its grip has structures like the feet of a gecko to improve adhesion.

The sixth characteristic of bioworld solutions is often CONTRAINDICATED PERFORMANCE. A bird is heavier than air but it still can fly. Shells are made of chalk but can withstand high pressure. The mycelium of mushrooms is fibrous but makes the soil rigid.

So, you see that bioworld solutions have much to offer.

Solution-driven BID. Next, I move on to one of the two ways to undertake BID. It is SOLUTION-DRIVEN BID. Somebody happens to notice a bioworld phenomenon and then finds an industrial use for it. Wilhelm Barthlott, a botanist, noticed that lotus leaves don't get wet, which became the initiator of water-repellent surfaces. Exploitation of the lotus-leaf effect is a prime example of solution-driven BID.

A solution-driven BID activity is conducted in seven phases. In the first phase, a bioworld phenomenon is identified. The biological functionality is described in the second phase, and the underlying biological principle is extracted in the third phase. In the fourth phase, the usefulness to humans is specified. Engineering problems are searched for during application-specific brainstorming sessions, in the fifth phase. One of those engineering problems is selected in the sixth phase, and the underlying biological principle is applied to the selected engineering problem in the seventh phase. A design proposal is created, a prototype is constructed, and the concept is tested.

Problem-driven BID. The second way of undertaking BID is initiated by an engineering need, i.e., an engineering problem to be solved. Very importantly these days, that problem may arise from a commitment to sustainability.

A PROBLEM-DRIVEN BID activity is very similar to a traditional engineering design activity, but it is constrained in that solutions must be based on biological principles. This activity has five phases. In the first phase, a clear picture of the engineering problem must be produced. This phase is divided into three tasks. In the first task, the problem has to be described, but without details, using illustrations and only a few words. A quad chart may be made to explain the context, core functions, main specifications, and performance criteria. In the second task, the engineering problem is analyzed to identify the main function and all sub-functions enabling the main function. The means for each subfunction are then identified. In the third task, a translation is performed from engineering to biology, to find means for some or all subfunctions from the bioworld as follows: First, synonyms are found for each sub-function by using a thesaurus. Then, engineering terms are converted into biological terms. As biology is rich in Latin terms, a dictionary may be used to find Latin equivalents.

The second phase is a search for biological analogies, using commonplace search engines, library search engines, and biological databases. Biologists should be consulted, if none is on the design team. And don't forget to use artificial-intelligence tools such as ChatGPT, which may soon replace general biologists! Once a candidate organism has been found, a look at related or similar species is recommended. In the third phase, a more intensive search of biological literature is carried out and general biologists are consulted to extract key biological principle(s). In the fourth phase, the biological principles are converted into abstract engineering principles. Finally, in the firth phase, a design proposal is created, a prototype is constructed, and the concept is tested.

To conclude, I have provided a synoptic view of biologically inspired design, and I hope that I have enticed a few colleagues to incorporate some aspects of the bioworld in their own research, particularly with an eco-responsible focus.

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Reference

1. Lenau, T.A., Lakhtakia, A., [Biologically Inspired Design: A Primer], Morgan & Claypool, San Rafael, CA, USA (2021).