Rowland R (2017) Biomimicry step-by-step.
Bioinspired, Biomimetic and Nanobiomaterials
6(2): 102–112,
http://dx.doi.org/10.1680/jbibn.16.00019

Bioinspired, Biomimetic and Nanobiomaterials
Volume 6 Issue BBN2
Research Article
Received 29/05/2016 Accepted 09/01/2017
Published online 13/01/2017
Keywords: bioinspired/biomimicry/bionics

ice | science

ice Institution of Civil Engineers publishing

Biomimicry step-by-step

Regina Rowland BA, MGD, PhD*
Professor (FH), University of Applied Sciences Burgenland, Eisenstadt, Austria

The creativity found in nature is seemingly boundless. Designs and strategies that species have developed for survival emerged through aeons of evolution and have therefore been refined for high functionality within the given context. These survival strategies employed by single organisms and applied to whole ecosystems can be considered design ingenuity and are worth investigating as they represent an extensive pool of potential solutions to human problems. Many viable biologically inspired designs (BIDs) have already been emulated from nature and *biomimicry* offers one of the possible processes for mimicking nature's ingenuity and distinguishes itself from other bioinspired forms of innovation in two ways: it has a firm sustainability mandate that is embedded directly in the design process and it is applied to all kinds of disciplines beyond the usual technology focus of BID. The four phases of the biomimicry thinking design process are described, step-by-step, in this perspective, from the position of teaching it to developers of products and services, processes, structures and systems that are designed for sustainable futures. The perspective ends with a list of challenges observed while teaching the process to designers, engineers and managers.

1. Introduction

Biomimicry is one of several ways to innovate bioinspired forms, processes and systems into the human world and is underpinned by the premise that *life creates conditions conducive to life*.[1] Specifically, it is an analogy-based approach[2] to biologically inspired design (BID) and, as such, builds on the genre of biomimetic design and innovation.

Biomimetics has been defined as 'interdisciplinary cooperation of biology and technology or other fields of innovation with the goal of solving practical problems through the function analysis of biological systems [and] their abstractions into models'.[3] The beginnings of biomimetics and *bionics* – another 'technical discipline that seeks to replicate, increase, or replace biological functions by their electronic and/or mechanical equivalents'[3] – go back to the 1950s when the method of 'transferring the principles of biological systems to technical designs'[3] informed the development of aircrafts, vehicles and ships. Due to the influence of cybernetics in the 1960s, the central element of the field was defined as the *transfer of knowledge*. During the 1980s, the genre expanded into micro- and nanoscale dimensions and, since the 1990s, has stretched into the disciplines of computer science, nanotechnology, mechatronics and biotechnology. While biomimetics and bionics originated within the engineering fields of the 1950s,[4] and can thus be considered the fathers of BID, the genre of biomimicry emerged in the 1990s from the disciplines of biology, ecology and environmental sciences that formed the distinguishing features of biomimicry, such as the emphasis on innovation for sustainable futures. However, the interdisciplinary, collaborative and highly challenging BID process is common to many bioinspired approaches to innovation and is embedded in biomimicry practice. Another common element is the underpinning assumption or fact[5] that organisms and their 'biological structures are optimized to their needs'[3] and can therefore serve as models for inventions in human systems. Thus, developers could learn from nature's designs and the millions of species alive on the planet today. These organisms (bacteria, fungi, plants, animals and humans) have learned to survive and thrive within the given operating conditions on earth by completing 3·8 billion years of research and evolution.[1] Their designs have been perfected over aeons and allow them to perform adequately in the environments in which they live.[6]

In ISO 18458:2015,[3] biomimicry is defined as a 'philosophy and interdisciplinary design approach taking nature as a model to meet the challenges of sustainable development', which refers to systemic sustainability (integrating all aspects of sustainability, such as social, environmental, economic and so forth, for the purpose of creating conditions conducive to life). Sustainability in terms of biomimicry relates closely to the concept of thrivability[7] – a positivistic orientation towards breakthroughs and building on what works. In terms of social sustainability, the concept of thrivability includes the possibility that the human brain can (co-) evolve through its plasticity and build new neural pathways for generating leaderless social structures that function in the interoperative networked way ecosystems do. The Biomimicry Institute itself defines biomimicry as 'an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies'.[8] Biomimicry as a practice refers to a specific BID process – the transdisciplinary four-phased biomimicry thinking design process[9] – bringing together system thinking, design thinking and biology in service of the disciplines from which design challenges emerge.

Other similar BID processes have been developed showing significant differences,[10] such as the bionic procedural,[11]

***Corresponding author e-mail address:** regina@reginarowland.com

hybridised bioinspired design and theory of inventive problem solving (Triz),[12] a toolset for systematic creativity in a six-step model,[13] the biomimetic as a design methodology model,[14] a design process providing iterative feedback and refinement loops[2] and a model focusing on the functional establishment of a pattern/model of biological models.[15] In spite of their differences, they have commonalities that are also inherent in the biomimicry thinking design process, shown in Fayemi *et al.*'s[16] problem-driven biomimetic process, highlighting the need for biological knowledge in various innovation process steps,[15,17–20] proposed different approaches to help close this knowledge gap without biologists and/or ecologists at the design table; however, none of these have tackled the issue of 'selection of the right biological model(s)'.[16] Likewise, in the biomimicry thinking design process, it is suggested to include the role of a scientist-at-the-design table for accurate emulation, and Biomimicry Taxonomy is offered as a tool to help non-biologists focus their research. Fayemi *et al.*[16] have developed and are still validating a new model, a translation tool that was designed to help designers and engineers 'pre-analyze biological systems … with a focus on the global system' (instead of specific functions) and select the right analogies by combining 'concepts of ideality, resources and system modeling'. The model is not meant to replace scientists-at-the-design table, but to postpone their involvement for a more focused choice of the kind of expertise needed during the BID process.

The biomimicry thinking design process can be applied to any kind of problem; its steps are not unique and were not invented by the co-founders of Biomimicry 3.8, Janine Benyus and Dayna Baumeister. However, one of their contributions to the genre of BID was to introduce this particular innovation process to various disciplines beyond the typical technology-oriented applications. In addition, they developed the philosophy of biomimicry, with its three essential elements of biomimicry, that include looking to nature as a model for inspiration (reconnecting with nature directly), a mentor to learn from (emulating nature's strategies for survival) and a measure for sustainability benchmarks (biomimicry ethos with a sustainability mandate) – it is this focus on sustainability built into the specific design process that represents a major distinguishing aspect of biomimicry. The steps through the four phases are outlined in this perspective by sharing the experience of teaching biomimicry to design, engineering and management students and conclude with listing some challenges observed throughout teaching BID from the perspective of design management. The discipline of design management has been defined as encompassing 'the ongoing processes, business decisions, and strategies that enable innovation and create effectively-designed products, services, communications, environments, and brands that enhance [the] quality of life and provide organizational success'.[21] As such, design management emerged in the nexus of business, organisational development and design and is based on social science practices with a focus on contextual (user-based) qualitative research – offering a way of innovating and researching which is different from the natural and applied sciences, such as physics or engineering. Biomimicry, taught through the discipline of design management as described in this perspective, is 'particularly valuable for its focus on *solution discovery*, as opposed to solution validation'.[22] Kolko's[23] *Exposing the Magic of Design* outlines this difference between scientific approaches, in particular the difference between deductive, inductive and abductive thinking, the last of which is characteristic of the genre of design where developers work on their hunches and test them through constructed feedback loops early in the innovation process to improve emerging prototypes (rather than starting with a hypothesis that is proven through quantitative research processes as is customary in the natural and applied sciences).

More information about biomimicry can be gathered from two organisations: Biomimicry 3.8,[25] the for-profit organisation, and the Biomimicry Institute,[8] the not-for-profit partner organisation.

2. Biomimicry foundation and practice

2.1 The philosophy: the three essential elements of biomimicry

The biomimicry philosophy is contained within three essential elements: (re-)connect, ethos and emulate.[9] The element of (re-)connect refers to people spending time in nature, realising themselves as part of nature, observing its patterns and processes directly and learning from these observations. Biomimicry practitioners build these activities into their daily lives in formal and informal ways. For example, a formal way of practicing is to complete *iSites*, structured ways of observing phenomena in nature directly, through quiet observation and reflecting on this observation in the form of field notes and sketching.

The biomimicry ethos concerns the requirement of working towards systemic sustainability and adhering to the 26 biomimicry life's principles representing common patterns in nature that apply to most, if not all, organisms in order to survive, thrive and evolve on the planet. There are six main principles, each including a set of subprinciples (Figures 1 and 2). The sustainability mandate here refers to innovations that create 'conditions conducive to life',[1] assuming that following life's principles will guarantee this outcome. It is worth mentioning that these life's principles seem easy to comprehend at first, but are actually difficult to emulate. In order to meet the sustainability mandate, they need to be specifically applied at deep levels of the emerging designs.

The element of emulation involves the four phases of the biomimicry thinking design process: scoping, discovering, creating and evaluating (Figure 3).

These three essential elements of biomimicry build the foundation on which the practice of biomimicry rests.

2.2 The framework for the practice

The biomimicry practice follows a well-organised but flexible transdisciplinary team-based design process applicable to any kind of tangible or intangible design challenge. The process may take

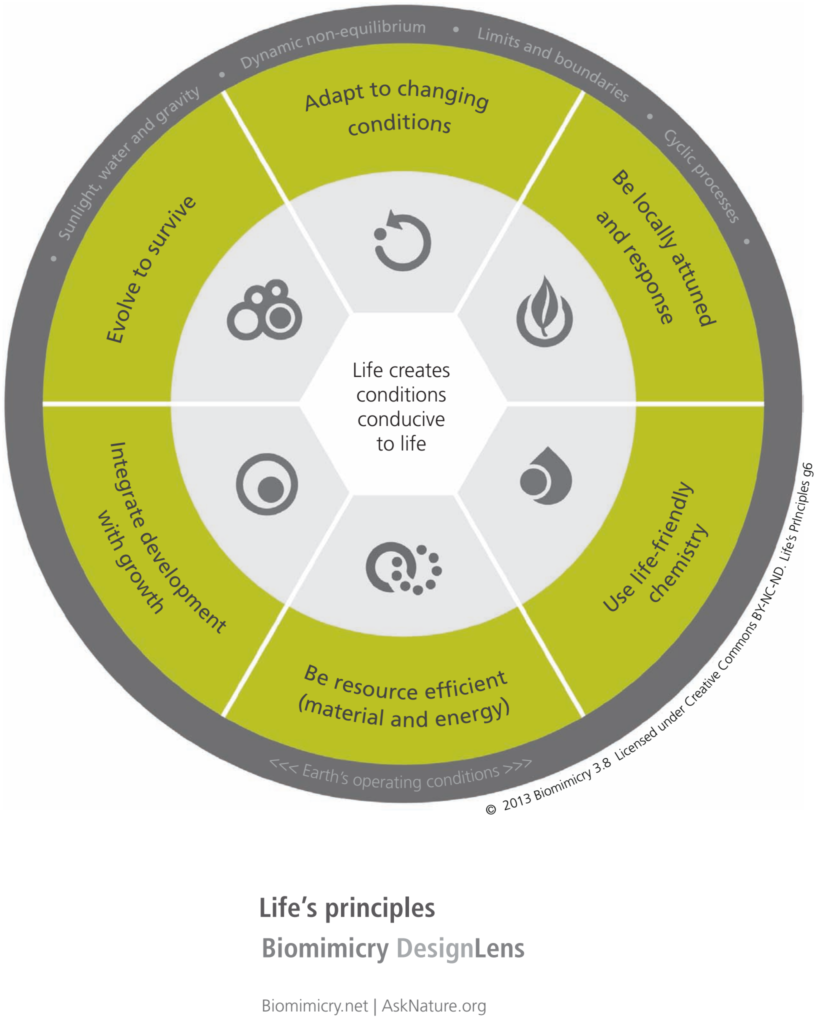

Figure 1. The six main biomimicry life's principles © 2013 Biomimicry 3.8. CC BY-SA

one of two particular paths: biology to design (Figure 4), where the process begins with an inspirational biological insight that is then applied to a design (also called biology push and understood as a bottom–up process),[3] and challenge to biology (Figure 5), where a particular design challenge has been identified for which a bioinspired solution is sought[9] (also called biology pull and understood as a top–down process).[3]

The challenge-to-biology design process is best applied in problem-driven collaborative environments. This approach includes upfront research about well-defined functions – an analogy-based approach[2] – that are present in biological systems and lead to the desired solution in the human context in which the design is supposed to solve a specific problem. The strategies and their mechanisms for these functions are then emulated through certain innovation steps. While the challenge-to-biology design process is generally described as flowing sequentially through the four phases of scoping, discovering, creating and evaluating in a more or less linear fashion, the actual live process is also highly iterative. The design team moves back and forth through the phases until all aspects of the innovation are aligned and the design is determined to meet the design criteria. The desired outcomes are considered achieved when the criteria are fulfilled, life's principles have been thoroughly considered and the application has been demonstrated wherever possible (meeting the sustainability mandate). It is worth mentioning that meeting all the principles is nearly impossible given the current knowledge base, social norms and available materials; nonetheless, there must be proof in the end that solid attempts have been made to meet the sustainability mandate.

2.3 The four phases of the biomimicry thinking design process for the challenge-to-biology approach

2.3.1 Step 1: scoping phase

During the scoping phase, the design challenge is contextualised and eventually communicated through a design brief that includes (*a*) the description of the chosen design challenge, (*b*) the description of the context in which the challenge arises as a problem and in which its potential solution must perform, (*c*) a

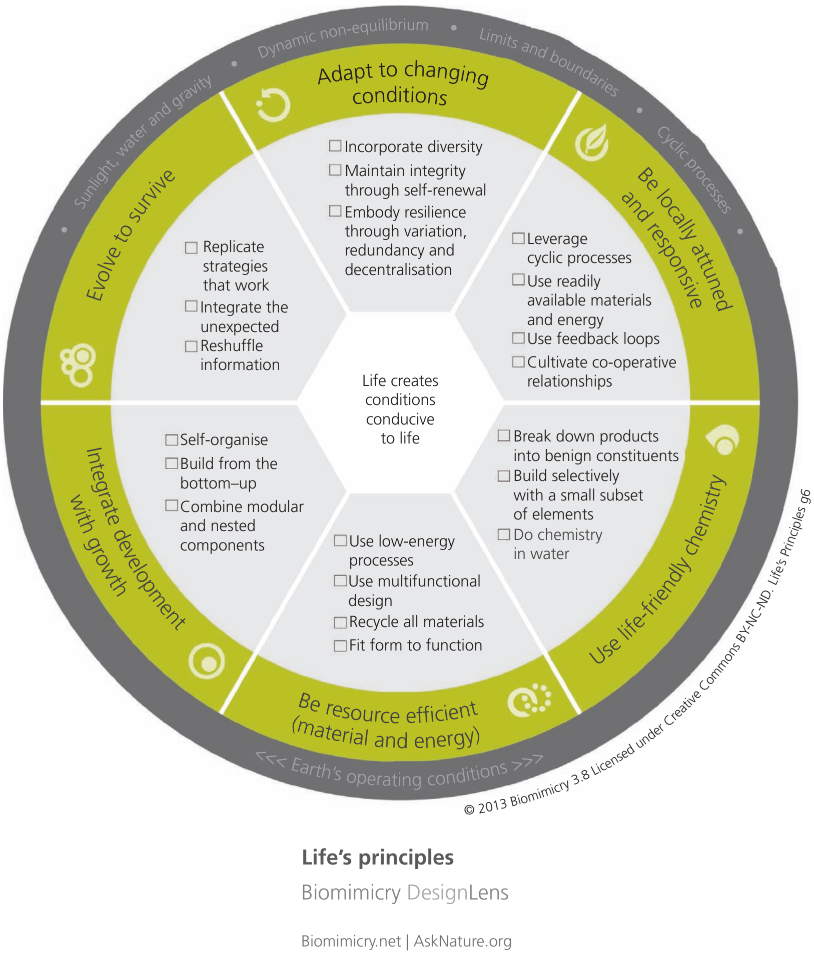

Figure 2. Six main biomimicry life's principles and their subprinciples. © 2013 Biomimicry 3.8. CC BY-SA

design statement listing the specific function that a potential solution must fulfil, (*d*) a vision statement for the desired outcome and impact in the described context and (*e*) life's principles most relevant to the specific type of design challenge. The desired function and most relevant life's principles form the beginning of the design criteria set to be used in subsequent phases.

Activities typical for the scoping phase include collaborative system mapping to explore fully the context and system boundaries in which the design would need to perform. Depending on the nature of the project, the scoping phase might also involve extensive user-focused contextual research to further investigate the problem state. Hundreds of methods for this type of research can be found in Kumar's[26] *101 Design Methods* and in Martin and Hanington's[27] *Universal Methods of Design*.

In terms of function, for instance, for the innovation of a new elevator system, a design statement might be phrased as *moving people and things vertically in the most efficient way*. For the development of a strategy to motivate change of unsustainable behaviour in a coastal area with a coral reef offshore (hence, out of sight for the people living in the area), an approach might be to develop a communication strategy that *connects the local community to the reef*. It is important to note that the function must be described in the form of a verb (what the design is supposed to *do*). This focus on action (expressed in a function verb) may steer developers away from premature solution thinking (as in thinking about a specific concept or object to be designed). By not front-loading the work with final concepts or objects to be designed, and instead front-loading it with a desired action that the design should perform as an outcome, developers may stay more open for discovering innovative design options in nature.

In order to work towards systemic sustainability, it is important to determine the level of the system at which the solution should perform and various system leverage points for entering the system need to be investigated so that the proper entry point can be determined where the potential solution would have the desired impact. An excellent tool for this determination is Meadows'[28] set of *leverage points*. A simple tool for determining various layers of the problem state, and eventually, yielding its root cause is the five-why-question series of the biomimicry process.[10]

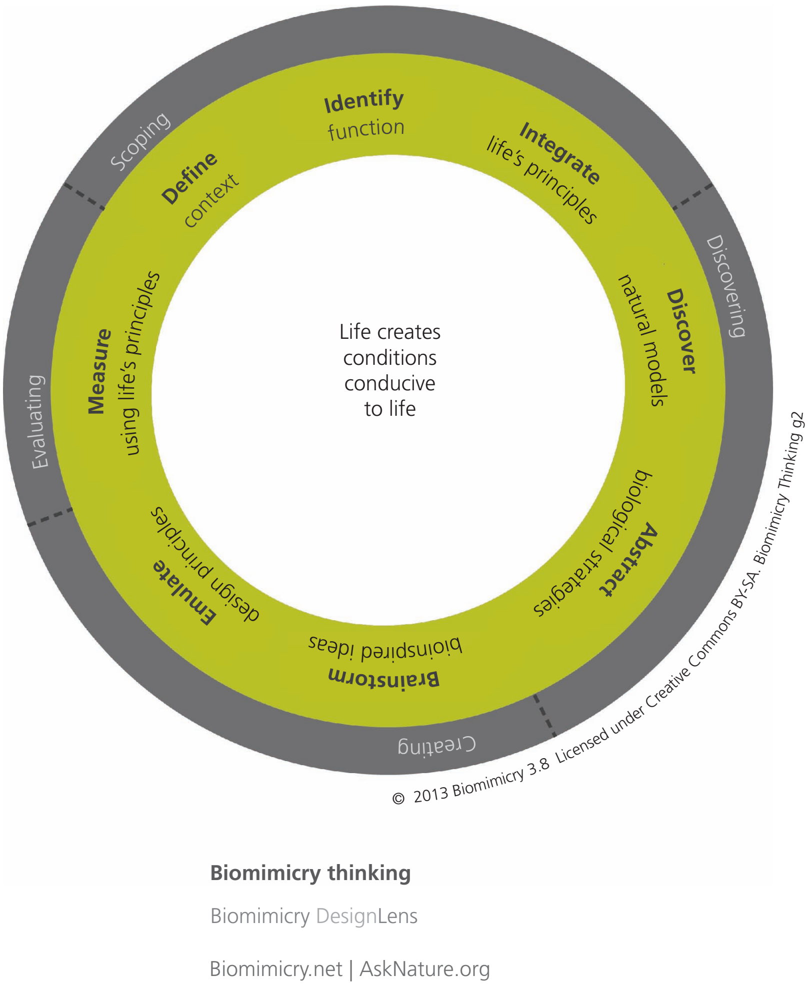

Figure 3. Biomimicry thinking design phases. © 2013 Biomimicry 3.8. CC BY-SA

The scoping phase is successfully completed when the dynamics of the design challenge are fully understood in its context (systems perspective) – when the various system levels have been discovered and a certain entry point to the system has been determined; when the design challenge has been crystallised into a function-based design statement, aligned with the vision of the desired outcome and impact in the chosen layer of the system; and when the desired outcome is clearly communicated in a (beginning) set of design criteria that include the life's principles directly relevant to the challenge and the desired function a potential solution should fulfil. It is in the task of looking to nature as a model in the next (discovering) phase that aligns biomimicry with the other forms of analogy-based biomimetic approaches.

2.3.2 Step 2: discovering phase

The discovering phase yields the final design brief, which includes the same items as defined in the scoping phase with the addition of (*a*) biologised research question/s, (*b*) a set of function cards and (*c*) the final list of design criteria, including the basic function defined during the scoping phase, abstracted design principles that emerged during the discovering phase and the already-defined life's principles most relevant to the design challenge in question.

The discovering phase begins with biologising the function-based design statement into a biology-based research question. By using the same examples for function-based design statements described in the scoping phase above, the research questions might be rephrased to 'how does nature move organisms vertically (elevator design challenge)?' Or 'how does nature, in particular a reef ecosystem, recruit (communication strategy design challenge)?' A very useful tool for biologising the research question is the Biomimicry Taxonomy, as it helps especially non-biologists find the right language to research specific functions in the scientific literature.

Researchers may conduct fieldwork and observe nature directly to experience and see what they can learn from its dynamic processes; they may also consult with experts or review scientific literature and other secondary research sources. The data are then

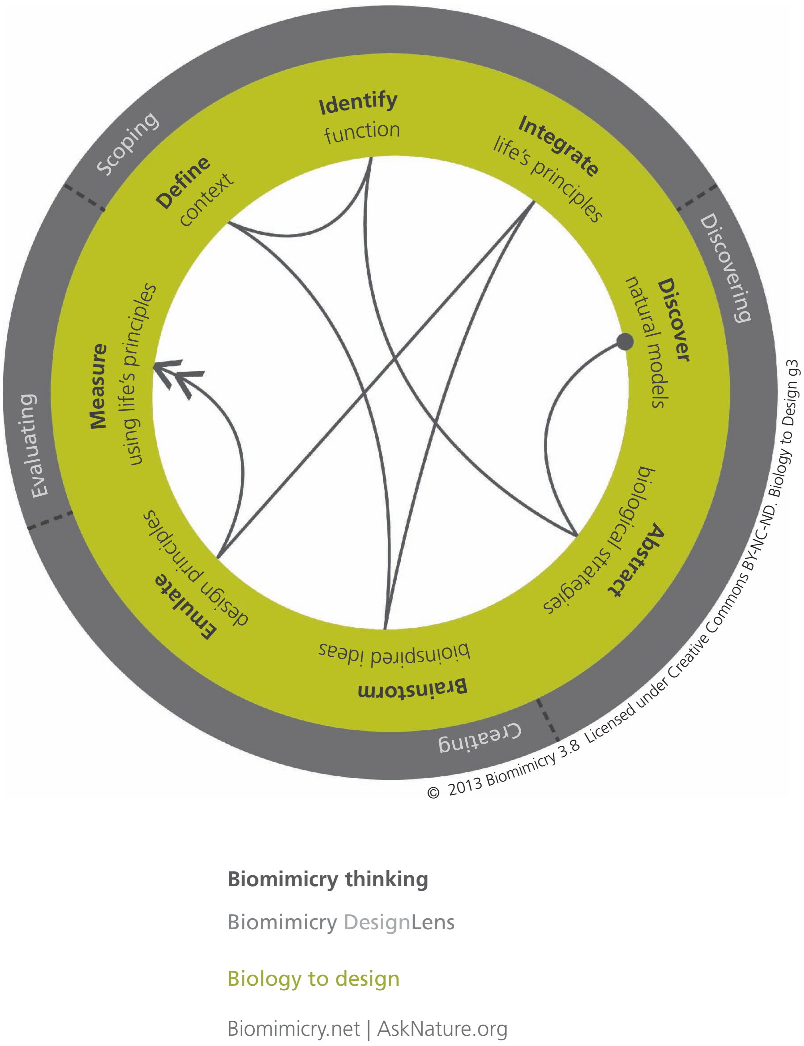

Figure 4. Biomimicry biology-to-design process © 2013 Biomimicry 3.8. CC BY-SA

sorted into (function) categories, and the relevant information from each model is recorded in the particular format of a function card, listing (*a*) the common and Latin names of the organism and/or system, (*b*) the particular function investigated (this may be a subfunction of the overall function of the design challenge), (*c*) the strategy with which the organism and/or system fulfils this function and (*d*) the mechanism for this strategy from which (*e*) design principles are then abstracted. This abstraction is a form of unbiologising the instructions again so that all kinds of participants can understand the design instructions and participate at the design table during the creating phase.

It is highly recommended to engage a biologist, ecologist or naturalist who can teach researchers and/or biomimicry workshop participants about organisms, processes and systems[29] – in biomimicry, scientists-at-the-design table. Not only can they guide participants in exploring nature in real time, where they quickly learn about patterns, similarities and differences in various local ecosystems, altitudes and climates, but scientists-at-the-design table also help developers with their research by pointing them to specific information sources, organisms or environmental conditions relevant to the research question that a non-biologist would not even know to ask. Another aid comes to the researchers with the AskNature[30] resource, where many functions in nature are listed and summarised for non-biologists, including information about the specific organisms fulfilling those functions. The most recent addition to the set of research tools from the Biomimicry 3.8 team is a commercially offered Web-based support system, called *Synapse.bio*, 'providing curated, sector-specific biomimicry content and access to world-leading biomimicry experts'.[31]

In summary, the discovering phase is successfully completed when champion organisms or ecological relationships have been found that address the function-based research question adequately, when function cards have been developed for these models pointing to the relevant design principles. At the end of the discovering phase,

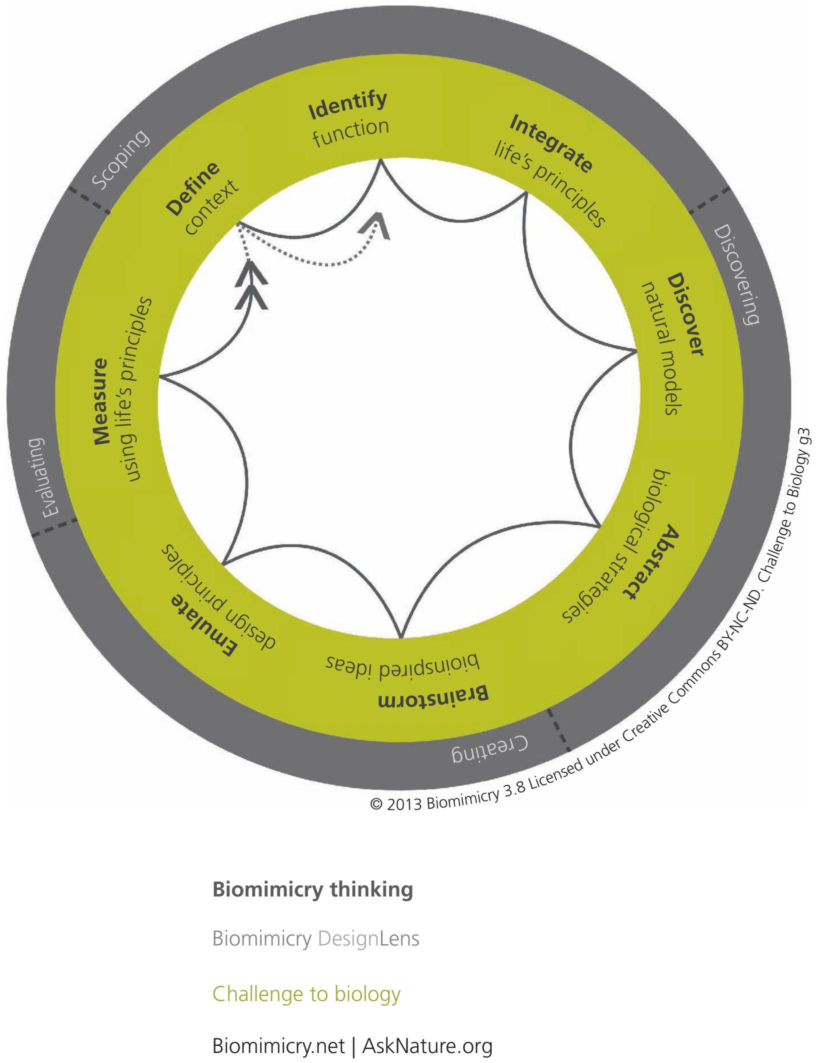

Figure 5. Biomimicry challenge-to-biology process. © 2013 Biomimicry 3.8. CC BY-SA

the Function Bridge tool is used to demonstrate the successful translation of biological strategies back to the human design world where they are to address the original design challenge. The function bridge demonstrates graphically *the walk across the function bridge* outlining how the design challenge was (*a*) properly contextualised and embedded in a function question during the scoping phase and (*b*) how this function question was accurately biologised and scientifically investigated during the discovering phase, yielding (*c*) champion models in nature from which to emulate, and (*d*) how nature's strategies were accurately translated back into the human system as instructions for designers.

The takeaway from the completion of the first two phases (scoping, discovering) is a detailed and complete design brief that directs the next two phases (creating, evaluating). The final design brief is composed of (*a*) the description of the design challenge; (*b*) the description of the context (in which the challenge arises as a problem and its potential solution must perform); (*c*) the design statement (the specific function a potential solution must fulfil); (*d*) the vision statement (desired outcome and impact in the described context); (*e*) the biologised research question/s; (*f*) the function cards of the champion organisms and/or chosen relationships in ecosystem, including the functions investigated, strategies for these functions and mechanism of these strategies described, from which abstracted design principles emerged; and (*g*) the final set of design criteria (basic function/s, abstracted design principles, life's principles). With these instructions for innovation, anyone can participate in the next step, the creating phase, including guests-at-the-design table who may not have partaken in the scoping or research efforts.

2.3.3 Step 3: creating phase

This phase is best started with a dynamic design charrette that involves additional guest participants from a variety of disciplines to bring a diversity of fresh perspectives to the design table.[29] The design charrette is front-loaded with a thorough review of the design brief elements. Once the group is fully informed, the fun begins with collaborative transdisciplinary brainstorming and design activities, such as decomposition matrices, kinaesthetic modelling and storyboarding that lead to initial design concepts. Many such methods for designing and evaluating concepts can be found in the already-mentioned studies by Kumar[26] and Martin and Hanington.[27] For instance, small teams might combine and criss-cross various brainstormed options, and create three-dimensional (3D) models of potential solutions through intuitive thinking by building collaborative structures in silence. The teams learn about the nature of their own constructions and that of other teams' through a specific form of debriefing their kinaesthetic models (teasing the meaning to the surface) and rotating through the various structures to optimise the mixing of ideas and then storyboarding potential concepts. The charrette is usually a marathon event that may last for 1, 2 or 3 d. It ends when the teams have developed initial concepts in 2D and 3D renderings and can communicate how their proposed designs would operate in the defined context. It should be mentioned that many other techniques and tools have been developed that can, of course, also guide the creating phase;[10] it is up to the user to decide which tools fit best.

Concepts developed during the charrette are further elaborated, refined and tested until viable prototypes emerge. Prototyping also includes testing (often and quickly) the emerging designs in form or concept, in process or as a system, in real time and with actual stakeholders so that the developers can learn from the feedback. There is a lot of backtracking during this phase; developers often need to return to scientific research tasks to improve the design, sometimes even reinvestigating the context originally defined in the scoping phase to see if they may have missed important aspects. The prototyping process includes assessing the emerging prototypes, multiple times, against all 26 life's principles and components listed on the design brief, in order to avoid surprises during the final evaluation phase that may cause unnecessary delays in the innovation process.

The creating phase is successfully completed when viable prototypes have emerged, have been refined through multiple rounds of testing, have been assessed for sustainability and fulfilment of the design brief and have been chosen for final evaluation. It is the creative engagement of participants and the iterative steps from concept to final prototype that align the biomimicry thinking-creating phase with any analogy-based design and innovation process. The distinction from other design processes is in the type of bioinspired research that informs and directs the creating phase in biomimicry and other BID approaches. While conventional design processes might be human-centred (learning from previous man-made solutions), biomimicry and other biomimetic innovation processes focus on nature's strategies (learning from the survival strategies of organisms or relationship dynamics of ecosystems). It is the inclusion of other than technology-focused applications and the strong sustainability mandate that distinguish biomimicry from other BID approaches.

2.3.4 Step 4: evaluating phase

During the final evaluation phase, the final prototype is formally assessed, again and on a much deeper level, against the 26 biomimicry life's principles and goes through a series of other sustainability-related assessments, such as addressing what nature would do or not do in this scenario, how specifically the solution is sustainable and what might be missing or left to investigate. Each life's principle is addressed separately and thoroughly, and the team discusses and confirms how well each principle is embodied in the proposed solution and what would need to be improved in the final prototype to achieve better alignment with nature's patterns. The tools used for this phase are (*a*) the design brief developed by the scooping and discovering team/s and (*b*) the Life's Principles sheet offered as part of the *DesignLens* materials[32] available to the public under a Creative Commons licence.

In the end, the design team may not be able to satisfy all design criteria due to lack of knowledge and/or skills, and issues may remain open for further investigation. In these cases, specific experts may need to advise or join the design team. Sometimes, there are no solutions available at the time for the identified dilemmas, and the prototype may then be considered an interim solution to be improved over time as more insights, resources and developments become available.

The classic biomimicry thinking design process ends with the successful completion of the evaluation phase. Success is possible even if not all design criteria or life's principles have been met; rather, the requirement for success lies in the design team having fully addressed all remaining questions, so that the next steps are clearly identified.

After the final prototype has been refined and all open issues have been solved, further steps in the innovation process may involve the development of implementation and business plans and strategies for bringing the invention to the market. In terms of design management, this last part is a critical step in the innovation process, but it is not a mandated step for the biomimicry thinking design process.

3. Case studies

Case studies exist to validate the biomimicry approach, and several companies are listed with their innovations in the 2010 Fermanian Business and Economic Institute report,[33] such as Biolytix – for developing an ecologically friendly sewage treatment process and equipment; Biomatrica – for developing ways to preserve biological samples; Brinker Technology – for discovering a marketable platelet technology for the water- and oil-piping industries; InterfaceFlor – for developing tile flooring modelled after nature; Joinlox – for developing a technology to connect and/or join a variety of objects, including boxes, pipes, walls and bridges; Pax Scientific – for developing devices that are either more efficient, have reduced drag, use less materials or are cheaper to produce; Qualcomm Mems Technologies – for being inspired by the way colours are created in butterflies; and STO Corporation – for developing Lotusan coating, which was inspired by the way the lotus leaf is structured, forcing water to bead and attract dirt and other particles. More case studies are described on the Biomimicry 3.8[34] and the Biomimicry Institute websites.[34,35]

4. Challenges

It must be acknowledged that there are significant challenges when applying nature's strategies to human systems. Listed in the following sections are only a few of these challenges; more have been identified, researched and paired with potential mitigations as offered by Helms *et al.*,[2] Yen *et al.*[36] and Linsey and Viswanathan.[37]

4.1 Additional methods and tools needed for upfront research tasks and design processes

During scoping, it is important to come to a comprehensive understanding of the dynamics of the design challenge in its context, and this investigation may need to include user-based research methods. While a multitude of such methods has been made available to the public,[26,27] it would be useful to include and continually update a plethora of such methods and tools in the materials describing the biomimicry thinking design process. The same goes for the creating phase, where a variety of methods and tools is needed for developing a prototype, only a few of which are listed in the biomimicry materials.

4.2 Enthusiasm challenged by detailed scientific research and evaluation

During the function-based research, conducted during the discovering phase and potentially reengaged during other phases, analogies for the desired functions of the design challenge need to be found in biological systems. Finding these analogies and identifying the exact mechanisms for the strategies used by organisms to fulfil those functions requires a knowledge base that is usually not easily accessible to non-biologists as the research is very specific and often requires expertise even within the various biology- or ecology-oriented disciplines.

Methods and tools for aiding this specific research process have been offered by the biomimicry community, who may have learned them from other bioinspired researchers and educators, as listed by Yen *et al*.[36] The already described biomimicry taxonomy sheet and the AskNature feature, the biomimicry function card creation steps and the function bridge walk diagram, as well as the newest offer Synapse.bio, are resources for helping developers complete the specific research tasks.

While these resources are being used extensively during the biomimicry thinking design process, and while much can be learned, even by non-biologists, from simply observing the natural world directly, participants, in particular the creative types, often get discouraged by and frustrated with the specific research process. They might run out of energy right before a breakthrough. The same challenges emerge when it comes to evaluating the prototype against life's principles and other sustainability benchmarks.

Motivation to stay true to the accurate scientific information is tremendously increased when a scientist-at-the-design table is part of the team, such as an enthusiastic generalist from the disciplines of biology and/or ecology. Even a naturalist or nature enthusiast can be very helpful. These experts not only help the developers with finding and understanding relevant biological scientific information during the discovering and evaluation phases, but may also help translate the biology or ecology back into the disciplines working at the design table during the creating phase.

4.3 Premature solution focus

During all phases, developers (creative professionals and engineers alike) quickly leap to (preconceived) solutions – what the design should *be* (object and/or concept to be validated). Maybe due to prior (solution-focused) training, it is very hard for them to empty their minds of premature ideas, which most of the time lead to redesigns or improvements of already existing man-made (often unsustainable) solutions. Once such ideas have entered their minds, the possibilities for innovation are limited and keep developers from seeking alternative options still to be discovered in nature; instead, they look for validation of their preconceived solutions. Even after completing the research phase successfully, developers may get hooked on one of these premature ideas during the creating phase and then find ways to retrofit their designs by returning to the research to find the strategies they are looking for, rather than working with the action-oriented function already defined in the scoping face and letting the function question drive the discovery of analogous strategies. A skilled biomimicry-trained facilitator can pay attention and return developers to the discovery-focused approach initially intended; however, this behaviour pattern needs attention throughout all the phases, and it may be useful to design checkpoints into the biomimicry thinking design process where this issue is addressed repeatedly as part of the routine.

4.4 Difficulty with emulating natural systems into psychosocial systems

The application of the biomimicry thinking design process is an easier sell when the design challenge is of a tangible nature. Applying the same process to intangible designs, such as innovating a social system or generating sociofacts (behaviour change), developers have to bridge the strategies for survival in nature (for instance, learning from the behaviour of bees or the strategies for adaptation in insect colonies) through metaphorical social constructions that involve people's personal and cultural beliefs and individual and collective value systems and morals – none of which exist in the rest of the natural world. If the concept of moral obligation, for instance, were to exist in nature, then it would probably be about securing the survival of the whole by any means necessary, and individual and/or group sacrifices might be necessary actions for the system to stay alive, and the system, per se, would not care about these sacrifices. However, in the human world, such orientations would lead to significant moral dilemmas. Impasses may happen when, for instance, the morals held by individuals or groups are challenged, when participants lack the imagination or courage to move through paradoxical conflicts or when resistance emerges in the group that stalls the process. On the other hand, there is the danger that participants happily design away, going down the wrong path by deviating from nature too far in their metaphorical interpretations. Similar issues emerge when applying biomimicry to any other of the *soft* sciences, such as economic or social sciences.

There is room for the biomimicry community to gain more experience in applying the biomimicry practice to the softer sciences and to deliver more viable case studies for designing, implementing and assessing, for instance, bioinspired psychosocial systems or approaches to business ventures that are modelled after nature. Such models or approaches have certainly been developed and solutions have been applied, for instance, for the world of investing[38] or the world of organisational systems,[39] but there is little information about the actual implementation or assessment of the desired impact these approaches might yield.

4.5 The need to adjust expectations

While the opportunities for nature-inspired design are, literally, endless, the steps from the prototype to the diffusion of the innovation may be difficult to accomplish and represent another potential for stalling the process that may lead to short-lived bioinspired efforts. The necessary changes in production methods may not be feasible or economical, the creation of the needed supply chains may be too slow or non-existing, the willingness or capacity to change behaviour may not be present in the system or the design might simply be too utopic for investors to support more development or to move into production at the given time. Even the best idea may need the building of significant infrastructures before the invention can be diffused. Changing the ways of thinking and operating requires investment of resources with few or no guarantees that the gain may outweigh the associated risks. Having an array of successful biomimicry solutions to showcase and preparing those involved in the innovation process for the long haul may mitigate these concerns so that momentum can be sustained. These case studies exist, but more are needed that also deliver hard data concerning the fulfilment of the value proposition over the long haul.

5. Conclusion

All species living and breathing on this planet have gone through billions of years of evolution to be here today, each of them having developed and mastered successful strategies to live within the operating conditions on the planet. Methods and tools are available for exploring these strategies, and the biomimicry thinking design process is one way that guarantees a thorough investigation into the patterns and strategies of nature, holding the promise for successful emulation into human systems.

The general interest in BID approaches to innovation is just beginning to emerge, and the genre attracts aspiring practitioners. The steps for the biomimicry thinking design process are not difficult to learn, and they can be merged with other existing sustainability-oriented innovation approaches. The instructions for the steps are available in the public domain; facilitating the process, however, requires training and experience with the process over time.

The enthusiasm for learning from nature is easily sparked across generations, ultimately leading to sensing optimism, abundance and opportunity – important ingredients in orienting humanity towards sustainable futures where life continues to flourish[40] – and humanity continues to co-evolve. For some people, it makes a lot of sense to emulate nature; others come to biomimicry with more scepticism for a variety of reasons. With all BID approaches, it is important to remember that nature is neutral – void of the potentially limited or limiting perspectives people hold (determined by the cultures to which they subscribe), void of any spiritual aspirations individuals may have for living lives worth living, void of the moral obligations that guide the human world. Seen from these human-oriented vanishing points, life remains a mystery to a large extent, and not all of nature is considered good (moral), true (confirmed in objective reality) or even beautiful (aesthetic), and therefore, not all of nature is worth emulating into human systems as society understands them today. Nonetheless, all of nature's strategies for survival might be worth exploring for people to create conditions conducive to life.

Acknowledgements

Special gratitude is extended to the Biomimicry 3.8 organisation, the Biomimicry Institute and their teams for sharing resources and educating the public on biomimicry as a framework and a practice towards sustainable futures. Immense appreciation goes to nature for offering models, processes and systems to learn from.

REFERENCES

1. Benyus JM (1997) *Biomimicry – Innovation Inspired by Nature*. HarperCollins Publishing, New York, NY, USA.
2. Helms M, Vattam SS and Goel AK (2009) Biologically inspired design: process and products. *Design Studies* **30(5)**: 606–622.
3. ISO (International Organization for Standardization) TC266 (2015) ISO 18458:2015: Biomimetics – terminology, concepts and methodology. Beuth Verlag, Berlin, Germany.
4. Lepora NF, Verschure P and Prescott TJ (2013) The state of the art in biomimetics. *Bioinspiration and Biomimetics* **8(1)**: 5633.
5. Taylor G and Thomas A (2014) *Evolutionary Biomechanics*. Oxford University Press, New York, NY, USA.
6. Fish FE and Beneski JT (2014) Evolution and bio-inspired design: natural limitations in bioinspired design and analogy. In *Biologically Inspired Design* (Goel AK, McAdams DA and Stone RB (eds)). Springer Verlag, London, UK, pp. 287–312.
7. Russel MJ (2013) *Thrivability*. Triarchy Press, Devon, UK.
8. Biomimicry Institute (2016) *What is Biomimicry?* Biomimicry Institute. Missoula, MT, USA. See https://biomimicry.org/what-is-biomimicry/ (accessed 23/01/2017).

9. Baumeister D (2013) *Biomimicry Handbook*. Biomimicry 3.8, Missoula, MT, USA.
10. Fayemi PE, Maranzana N, Aoussat A and Bersano G (2015) Assessment of the biomimetic toolset – design spiral methodology analysis. In *ICoRD'15 – Research into Design across Boundaries*. Springer, New Delhi, India, vol. 2, pp. 27–38.
11. Lindemann U and Gramann J (2004) Engineering design using biological principles. *DS 32: Proceedings of the DESIGN 2004 8th International Design Conference, Dubrovnik, Croatia*, pp. 355–360.
12. Chechurin L (ed.) (2016) *Research and Practice on the Theory of Inventive Problem Solving (TRIZ)*. Springer International Publishing, Cham, Switzerland.
13. Bogatyrev NR and Vincent JF (2008) Microfluidic actuation in living organisms: a biomimetic catalogue. *Proceedings of the First European Conference on Microfluidics, Bologna, Italy*, pp. 175–182.
14. Lenau TA (2009) Biomimetics as a design methodology – possibilities and challenges. *DS 58-5: Proceedings of ICED 09: Design Methods and Tools, Palo Alto, CA, USA*, vol. 5, part 1, pp. 121–132.
15. Nagel JK (2014) A thesaurus for bioinspired engineering design. In *Biologically Inspired Design* (Goel A, McAdams D and Stone R (eds)). Springer Verlag, London, UK, pp. 63–94.
16. Fayemi PEI, Maranzana N, Aoussat A, Chekchak T and Bersano G (2015) Modeling biological systems to facilitate their selection during a bio-inspired design process. *DS 80-2: Proceedings of the 20th International Conference on Engineering Design (ICED 15): Design Theory and Research Methodology Design Processes, Milan, Italy*, vol. 2, pp. 225–234.
17. Vandevenne D, Verhaegen PA, Dewulf S and Duflou JR (2011) A scalable approach for the integration of large knowledge repositories in the biologically-inspired design process. *DS 68-6: Proceedings of ICED 11, Impacting Society through Engineering Design: Design Information and Knowledge, Lyngby/Copenhagen, Denmark*, vol. 6, pp. 210–219.
18. Vattam SS, Goel AK, Rugaber S *et al.* (2011) Understanding complex natural systems by articulating structure–behavior–function models. *Educational Technology & Society* **14(1)**: 66–81.
19. Vincent JF (2014) An ontology of biomimetics. In *Biologically Inspired Design* (Goel A, McAdams D and Stone R (eds)). Springer Verlag, London, UK, pp. 269–286.
20. Shu LH and Cheong H (2014) A natural language approach to biomimetic design. In *Biologically Inspired Design* (Goel A, McAdams D and Stone R (eds)). Springer Verlag, London, UK, pp. 29–62.
21. Design Management Institute (2016) *Design Management Definition*. Design Management Institute, Boston, MA, USA. See http://www.dmi.org/?WhatisDMI (accessed 23/01/2017).
22. Kennedy EB and Marting TA (2016) Biomimicry: streamlining the front end of innovation for environmentally sustainable products. *Research-Technology Management* **59(4)**: 40–48.
23. Kolko J (2011) *Exposing the Magic of Design*. Oxford University Press, New York, NY, USA.
24. Biomimicry 3.8 (2016) *General Info*. Biomimicry 3.8, Missoula, MT, USA. See https://biomimicry.net/ (accessed 23/01/2017).
25. Biomimicry Institute (2016) Biomimicry Institute. Missoula, MT, USA. See https://biomimicry.org/ (accessed 23/01/2017).
26. Kumar V (2013) *101 Design Methods*. Wiley, Hoboken, NJ, USA.
27. Martin B and Hanington B (2012) *Universal Methods of Design*. Rockport Publishers, Beverly, MA, USA.
28. Meadows D (1999) *Leverage Points*. The Sustainability Institute, Hartland, VT, USA.
29. Snell-Rood E (2016) Interdisciplinarity: bring biologists into biomimetics. *Nature* **529(7586)**: 277–278.
30. AskNature (2016) Biomimicry Institute. Missoula, MT, USA. See https://asknature.org/ (accessed 23/01/2017).
31. Biomimicry 3.8 (2016) *Synapse.bio*. Biomimicry 3.8, Missoula, MT, USA. See https://synapse.bio/ (accessed 23/01/2017).
32. Biomimicry 3.8 (2016) *DesignLens*. Biomimicry 3.8, Missoula, MT, USA. See https://biomimicry.net/the-buzz/resources/designlens-download-2/ (accessed 23/01/2017).
33. Fermanian Business and Economic Institute (2010) *Global Biomimicry Efforts: an Economic Game Changer*. The San Diego Zoological Society, San Diego, CA, USA. See http://www.pointloma.edu/experience/academics/centers-institutes/fermanian-business-economic-institute/forecasting-and-expert-commentary/economic-reports (accessed 23/01/2017).
34. Biomimicry 3.8 (2016) *Our Effect*. Biomimicry 3.8, Missoula, MT, USA. See https://biomimicry.net/our-effect/ (accessed 23/01/2017).
35. Biomimicry Institute (2016) *Biomimicry Examples*. Biomimicry Institute, Missoula, MT, USA. See https://biomimicry.org/biomimicry-examples/ (accessed 23/01/2017).
36. Yen J, Helms M, Goel A, Tovey C and Weissburg M (2014) Adaptive evolution of teaching practices in biologically inspired design. In *Biologically Inspired Design* (Goel A, McAdams D and Stone R (eds)). Springer Verlag, London, UK, pp. 153–199.
37. Linsey J and Viswanathan VK (2014) Overcoming cognitive challenges. In *Bioinspired Design and Analogy* (Goel AK, McAdams DA and Stone RB (eds)). Springer Verlag, London, UK, pp. 221–244.
38. Collins K (2014) *The Nature of Investing*. Bibliomotion, Brookline, MA, USA.
39. Thomson K (2008) *Bioteams: High Performance Teams Based on Nature's Most Successful Designs*. Meghan-Kiffer Press, Tampa, FL, USA.
40. Ehrenfeld JR and Hoffman AJ (2013) *Flourishing*. Stanford University Press, Stanford, CA, USA.

How can you contribute?

To discuss this paper, please submit up to 500 words to the journal office at journal@ice.org.uk. Your contribution will be forwarded to the author(s) for a reply and, if considered appropriate by the editor-in-chief, it will be published as a discussion in a future issue of the journal.

ICE Science journals rely entirely on contributions from the field of materials science and engineering. Information about how to submit your paper online is available at www.icevirtuallibrary.com/page/authors, where you will also find detailed author guidelines.