NATURAL SYSTEMS AND THE SYSTEMS ENGINEERING PROCESS: A PRIMER

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Natural Systems and the Systems Engineering Process: A Primer

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Natural Systems Working Group of INCOSE

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This Primer on natural systems expands on the material in the INCOSE 5E handbook and suggests further detail. It was developed for the larger systems engineering (SE) profession as well as project managers to introduce and integrate natural systems work into systems engineering. Designed as a calling card, this Primer is a technical product for use by engineers, managers and the larger project community as necessary.

Within the following pages readers will learn:

1. What natural systems are and the benefits of using them for inspiration
2. Where natural systems knowledge and tools can be used in systems engineering
3. How to use natural systems knowledge and tools.

Further questions or requests to join the WG can be directed to: natural-systems@incose.net

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What Are Natural Systems?

Long before humans began designing systems, nature was adapting and evolving in a manner that helped all organisms thrive (Benyus, Hoagland). The result is that nature provides a wealth of solutions that can inspire engineers to create better designs. What man has learned about Nature - its vastness, elegance, beauty, complexity, efficiency – have intrigued and inspired man for many centuries, perhaps the most important of which was learning how to light a fire! Living and Non-living systems in Nature have provided and will provide inspiration for a wealth of solutions to system engineering challenges across the entire life-cycle phases. Natural systems include both living systems and non-living physical systems of the air, earth, water and space. Examples include biological, geological, atmospheric systems and physical systems on earth and in space. Appreciation for and knowledge of natural systems and their properties expand a systems engineer's consideration of solutions and alternatives.

One way living systems show advantages is that, by being closely integrated with their environment, they don't need concentrated energy or high temperature to operate or create their structures Decomposition of a natural system results in usable resources for other systems (He, Layton) thereby transforming waste and creating a cycle (Biomimicry Institute, Hoagland and Dobson).

Studying how natural systems utilize local energy and materials increases SE awareness of how a system of interest interacts, affects and is affected by the environment. Natural systems are embedded in their local environment for their complete lifecycle, and have evolved to benefit it. Our designs can do the same.

Both non-living and living systems are interactive and must be fully understood before proceeding with implementation of actions to influence either. Non-living systems can inspire system engineers in that a majority of the forces and physical systems are constant and predictable, and therefore more easily understood and modeled than living systems, once adequate data is obtained about them.

For example, if astronauts are to live on Mars, the environment there must be modeled and validated so that the team can envision and create systems that will enable them to survive. The sand dunes in the photo below are the result of natural systems interaction. They may be part of the solution, such as acting as a shield from radiation. Someday knowing more about the Mars sand dunes may result in an "Ah Ha" moment that leads to creating something beneficial for a mission.

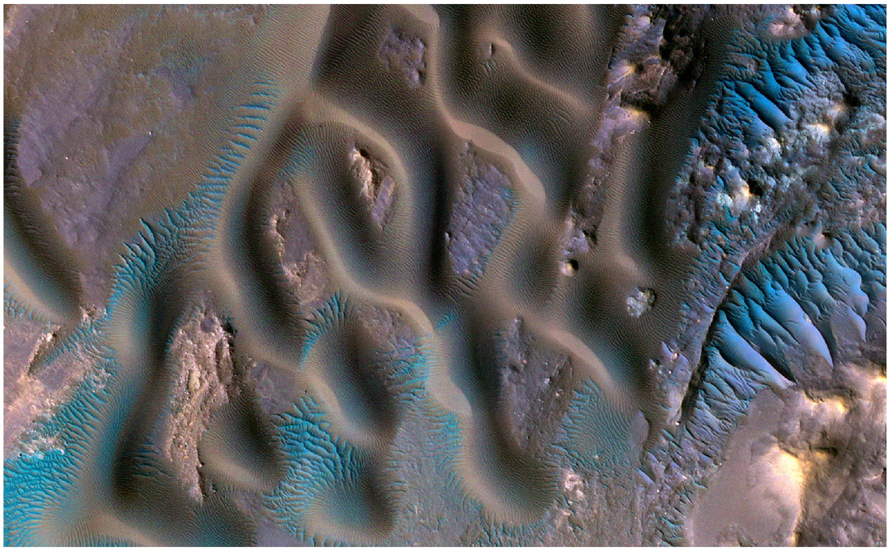


Fig 1:
Sand Dunes on Mars are an example of of natural systems interaction

The image is an enhanced color cutout

https://www.jpl.nasa.gov/images/pia25450-piles-of-sand-with-different-sizes-and-colors

Using Natural Systems in Systems Engineering

Natural systems (NS) engineering is the practice of using inspiration from nature to improve designs, processes, practices, and/or to generate alternatives. This is accomplished through understanding the system well and appreciating nature's elegant forms, structures, behaviors and processes, adaptations, interactions, and functions. Traditional engineering can be more of a "brute force" method of putting something into practice, while nature most often does a similar thing in a more elegant and efficient manner.

There are many advantages to using inspiration from NS, such as:

- Enhancing efficiency in systems and operations, thought to be unachievable in the past
- Improving system engineering agility in both practice and process
- Growing organizational culture and abilities
- Increasing opportunities for employee collaboration via a multi-discipline team
- Developing a better understanding of and reducing impacts on the environment
- Increasing system resilience and adaptability
- Expanding the ability to adapt to environmental, social, and governmental requirements (Peterdy)
- Understanding ways to use resources and raw materials more efficiently and effectively.

A systems engineer often may not be the expert in the natural sciences. However she must appreciate both the engineering challenges and the potential for applying solutions mirroring those in nature well enough to attempt cooperation and even partnerships with scientists and technology developers in order to establish what concepts may be fruitful to pursue. With a deeper appreciation for the elegant simplicity as well as the many times complex solutions are found in nature, the systems engineer may recognize parallels in her system and begin a search for answers to the way nature addresses similar challenges. The systems engineer needs to define problems and opportunities to communicate effectively with natural systems scientists to help her make the connection. Biologists, geologists, and other scientists may already be addressing the modeling, biomimicry, and derived functions that form the basis for realistic expectations of application.

Natural systems inspired engineering is often used as a method for ideation, or coming up with new design concepts. This may be performed during system architecture definition, module or component design, and/or interface design. The enormous number of example systems in nature provide opportunities to explore different designs, configurations, and processes.

Searching for inspiration from nature yields many opportunities for design improvements. As one example, natural systems are evolved to adapt to their context. Studying this can yield ideas on how a new design can be integrated into existing systems. For example, the manner in which living systems deal with waste may provide inspiration for improvements to a long-established wastewater processing facility.

Materials inspired by natural systems often have lower environmental impacts than technological materials. Spider silk is created from protein and is stronger than steel on a weight for weight basis. Social insect nests and hives are built with local materials using a simple set of signals and operations. These examples illustrate how even organisms without much heft can provide weighty and environmentally friendly solutions.

The systems engineer should also be aware that nature's lessons can be applied to any point in the systems engineering process. An SE process is typically well controlled, which can reduce variation. This is very useful, as it constrains development cycles, and often results in products delivered in less time and with less effort. Inspiration from nature can both enhance SE processes and allow increased performance and reduced impact. For instance, developing, testing and improving prototypes (the natural selection process) can be far more efficient than the time and expense of spending man-years on requirements development (Chi).

Opening up a process to NS inspiration will reveal a wider range of design, operations and process alternatives. Selecting the best of these solutions can yield better performance in the areas of costs, schedule, quality, operations and sustaining activities (Interface).

How to increase awareness of nature's potential:

Finding inspiration from natural systems, individually or as a team, is enhanced by:

- Spending time in nature, and feeling a connection to its unique strategies
  - This will prime your subconscious mind.
- Actively consider the elegance of nature
- Having things from nature in the workspace, and sharing nature observations
- Routinely exploring natural system scientific research and specific examples of where modeling and technology development have resulted in successful biomimicry and / or bio-inspiration.
- Increasing awareness of alternatives and how natural systems can improve SE process
- Incorporating natural systems search tools into standard process flows (e.g. PeTaL, Goel, AskNature, BioMole)
- Translating engineering problems into biological terminology (e.g. E2BMO, BioTRIZ)
- Collaborating directly with natural systems experts (e.g. B3.8, Biomimicry hubs)
- Gaining training and mentoring in natural systems (e.g. Biomimicry Institute)

- Considering adjacent and higher-level systems (e.g. Biomimicry Toolbox)
- Practicing metaphor, analogy, and abduction (e.g. Gentner).
- Studying the general properties of natural systems (e.g. Troncale, Bejan, Vogel)
- Nature has strategies to improve performance in all these areas, including circular approaches to materials and energy.

What Knowledge and Solutions Exist In Natural Systems?

The range of solutions available in natural systems exceeds that of human designed systems. These can be utilized over a range of engineering activities and design realizations.

Past solutions have included: identifying an application area for a new technology inspired by nature (Velcro, artificial muscle), improvements in design process (Agile), solving a design constraint (tensegrity robot), and creating a better user design experience (display screen color adjustments).

Natural systems inspiration is often applied in the design of components, structures, and interfaces / materials. However, it can also be applied to systems architecture, concept of operations, and the requirements at functional, logical, and physical levels. For example, the tensegrity robot is inspired by tendon and muscle in bodies; and Encycle uses algorithms derived from ants and bees for communication among heating and air conditioning units.

Robotic systems are often implemented by directly duplicating the natural physical and even computational functions found in nature.

A standard systems engineering process is a dynamic or even 'living' system. It proceeds in a sequence of steps that are dependent on human involvement. At times, the process senses the environment, makes decisions, and takes actions. When the process is complete, it provides an output that is embedded in a variety of external systems that include socio-cultural aspects.

When the traditional systems engineering process includes inspiration from natural systems, the process itself comes 'alive'. A NS-inspired engineer uses creative examples from strategies found in nature to come up with a more elegant solution for what is "required." In a rigid "how to" approach, products are often created in a mechanical / requirements-driven way. Consider the success of the Prandtl flying wing – a design the aviation industry ignored that greatly simplified the control systems required to fly without a vertical tail (see Appendix C). Since the 1930's there had not been a scientist – engineer that "didn't know that it couldn't be done," so he did it!! The inspiration came from pondering the question "birds fly without a vertical tail, so why can't we?"

As the team searches for the best solution to a challenge, function or requirement, it is beneficial to consider a broad range of possibilities. A good place to start is to become familiar with existing natural system applications which can be reviewed by searching resources such as AskNature.org. These include machine learning, safety, materials, energy, manufacturing, green chemistry and more.

There are a range of architectural configurations in natural systems. Examples include:

- Slime molds exhibit different levels of aggregation, environmental sensing, navigation, and emergent behaviors to support a complete lifecycle
- Birds and fish flock, migrate, and feed as groups when the need arises
- A forest incorporates multiple species, interconnected together to produce complex and resilient responses
- Grasslands are adaptive to changing conditions and sequester carbon.

As the architecture is explored, requirements are noted, elaborated and mapped to potential functions. This process is enhanced when the team considers a wide range of system aspects. It is important to model both the living and non-living aspects of the natural system or functions being explored, these are often intertwined and may limit the practical aspect of the application.

The following aspects or views on natural systems inspiration have been identified (Biomimicry Institute, Nagel):

- Form
- Process
- System
- Surface
- Material
- Function

Each of these can be used as a 'lens' as to view both nature and the system of interest. They provide different entry points into the search, and different perspectives on how to accomplish the system design. In real life, they overlap and are intertwined. Completely understanding how they work together may or may not be important to the potential application in systems engineering.

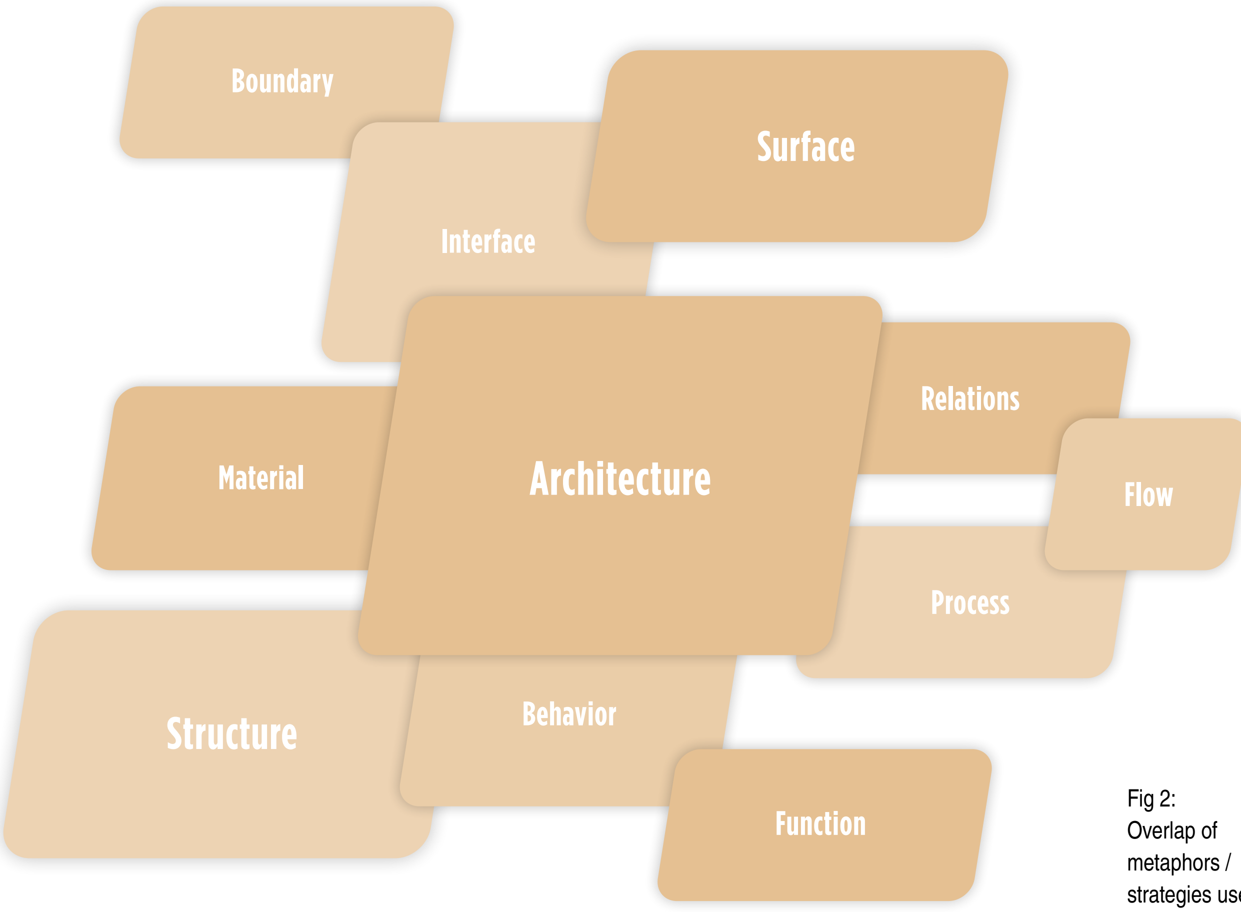


Fig 2:
Overlap of metaphors / strategies used for natural

As you can see, considering the architecture will bring several of these views or aspects to mind. This figure shows one view of how various approaches to natural systems inspiration are related. It is natural for the systems engineer to range over possible modules and arrangements as the architecture is explored. This visual reminder can aid in exploring how various aspects are related.

The figure also reminds us that nature has functional overlaps and is often multi-functional. For example, the material used in a structure can provide more than one function. An architecture goes beyond the arrangement of components to the properties and interfaces with external systems.

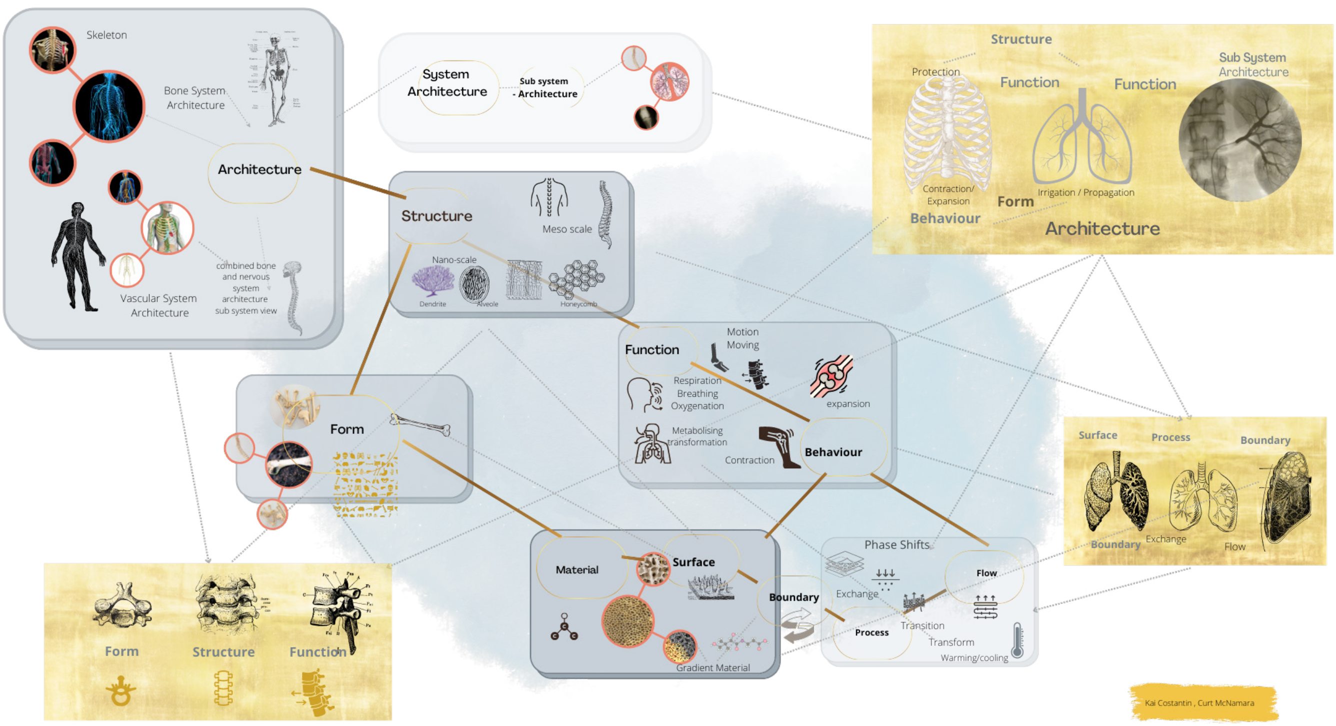


Fig 3:
A view of how natural systems properties overlap and interconnect between systems: the human bone/the human lung…

In this figure depicting the human bone (and other anatomical systems added for visual clarity) we can see a more concrete exploration of the overlaps between architecture, form, structure, material, function/behavior. Compare this to Figure 6 about SBF modeling of bone.

Natural Systems Search

The following section further details a description of a typical natural systems inspiration search process: abstract the function required for the system, and then search using biological terms that correspond to the abstraction. Tools such as AskNature.org and PeTaL include taxonomies of natural systems inspiration and are often organized by functional challenge.

Natural systems have been categorized according to how they achieve functions or tasks (Asknature, PeTaL). They also provide functions in a multiplicity of ways that differ from human designed systems (Vogel). These functions are produced through strategies deployed as a result of one or more system aspects such as structure, materials, behaviors, and processes:

- Structure. There are a wide range of system architectures and structural types in natural systems that can complement traditional systems design (SEBoK System Architecture). Examples of system architecture inspired by nature include bio-inspired robots, natural inspiration for computing (Brownlee), fractal structures (Gouyet), and buckminsterfullerenes (Baggott). System structural properties include form, dimension, density, material properties, thermal/electrical coefficients, modularity and color.

- Materials. Biological materials are more structurally complex than technological materials, leading to properties such as toughness combined with hardness that is hard to duplicate in man-made materials (Vincent).

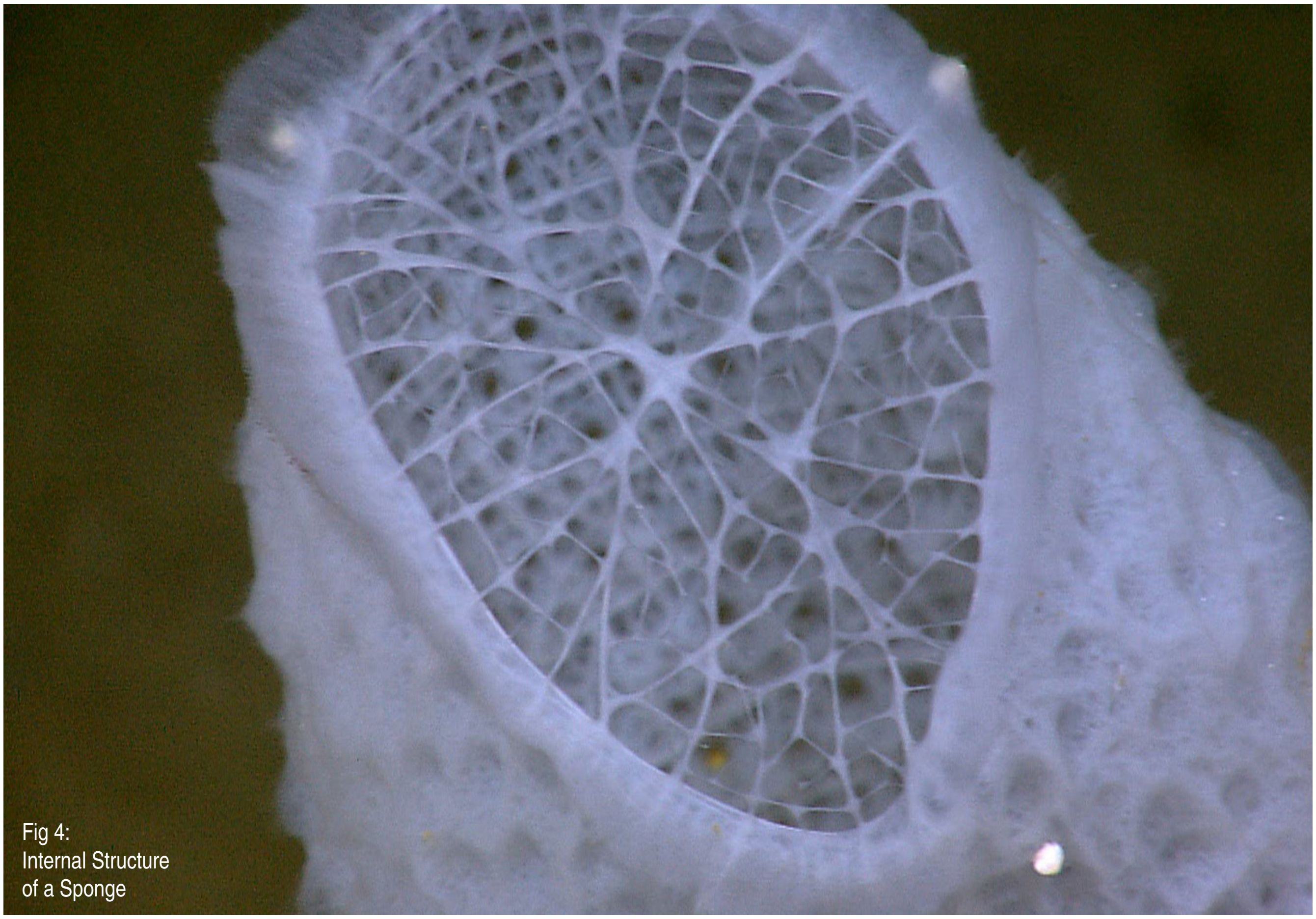


Fig 4:
Internal Structure
of a Sponge

- Behaviors. System behavior is the response (output) of a system to stimuli (inputs). Engineered systems may be designed to work within close tolerances while biological systems are typically more tolerant to input variability which can lead to greater adaptability and fault tolerance.
  - The leaves of some trees can fold in high winds to avoid damage.
  - Birds migrate to optimize their living conditions during winter and during the time they raise their young. They use a variety of signals to proceed only as far as necessary and on schedule.
  - Human social systems can learn from collective behaviors in nature

- Processes. Living system characteristics are modified over time as the result of environmental variations, mutations and natural selection. These "experimenting and testing" modifications are based on changes in the external environment and result in natural systems that have been selected for success in their environment. In a similar way, a system engineering process creates a system that fits the "ecosystem" of users, constraints and overall context. Increasing awareness of variation and selection in natural systems can increase a designer's ability to fine-tune a design or engineering process to match local conditions (i.e. where the design team, customer, requirements, constraints and solution are found).
  - A list of natural system processes includes growth, decay, reproduction, adaptation, control, sensing, and end of life (Troncale). Many of these have parallels in technological systems.

- Lifecycle. Living systems exist in, and are connected to systems (ecosystems or a system-of-systems) at multiple levels and in complex ways. This is similar to human designed systems that utilize services from higher, lower, and similar levels of organization.
  - Living systems have adapted to variations in their environments via variation of response and selection for fitness, over time and generations. The variations that are selected have increased resilience
  - System designers are investigating natural systems as inspiration for increasing resilience and robustness, as human designed systems respond to increasing levels of environmental and economic variation. (Taleb)

- Patterns. Nature's core patterns provide solutions. For example, branching is used for structure in trees and to manage flow in veins and arteries. A bone's density differs at its endpoints and middle. This was used as inspiration for airplane wings (Wolf).

Merging System Engineering and Natural Systems Activities for Solutions

Nature-Inspired SE can be thought of as either an opportunity-based or needs-based path, either of which must result in a solution that meets the system requirements. Of course, it is an advantage to establish the “hard” requirements as soon as practical. The two approaches can be thought of in the following ways:

- The team becomes aware of and is inspired by a feature in a natural system which has the potential to be used in a design or operation. This approach can be described as opportunity driven.
- A challenge, function or other needed attributes for a system are identified. Then a dedicated search/research effort is solicited/conducted to understand what relevant attributes may be found in various natural systems. This approach could be described as needs driven.

Either starting point requires a requirements-driven evaluation of alternatives by the systems engineer, the scientist experts in the field, and the technology developer that is employed to put the attribute into practical use (e.g. analysis, model-based SE, biomimicry).

Remember that scientists/experts on living and non-living aspects of nature may not be collecting data that the technology developer or the systems engineer needs. To select an appropriate natural system to meet the need, the measurements must be made by the science community (solicited/contracted out) and, if a biomimetic device or model becomes available, on the prototype devices as well.

It has been said that systems engineers sometimes do systems archeology rather than systems architecture! In other words, we often choose the architecture based on what has worked in the past. By looking to nature, we can choose from a multitude of candidate architectures. Knowledge of these through various processes and recently developed tools can enhance the SE project.

There are a variety of aspects to consider when defining an architecture:

- Functional characteristics such as support, modularity, adaptability, and resilience
- Static vs dynamic characteristics
- Focus on a form or on a structure
- Support for the behaviors and functions that are required
- In general, using an NS perspective increases the team’s ability to visualize super-system and ecosystem aspects of the project.

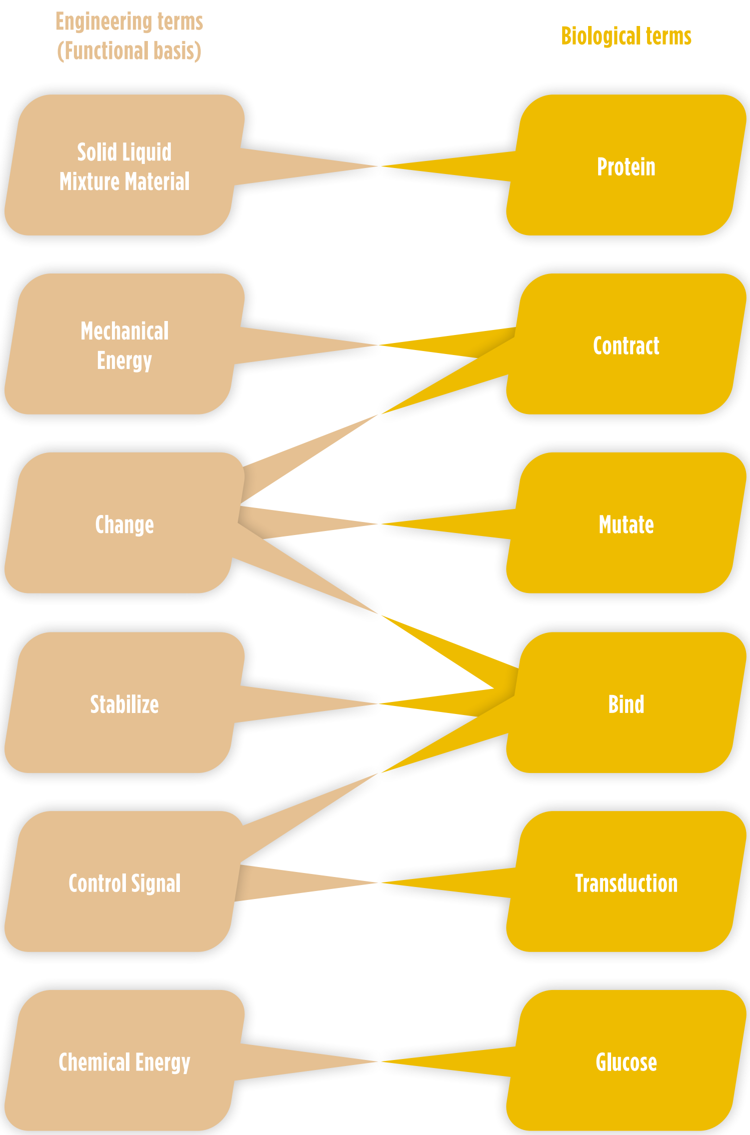


Fig 5:
The Engineering to Biology Thesaurus
Note that there are many other mappings! For example, solid / liquid / mixture equates to more terms than protein.

The standard process follows this sequence:

- Create an abstracted systems view of the design situation. Use a framing that corresponds to the design challenge such as interface, process, structure, or substance (Helms). Look at alternate framings (Fig 2 and 3) to help identify other approaches to the challenge. Model based systems engineering can aid this process.
- Consider using a structure / behavior / function (SBF) model for the feature of interest. A function is an outcome of a behavior, and behaviors are properties of structures (Goel, Fig 6).
- Establish technical performance measures, success criteria, and measure of effectiveness
- Recommended: map the lifecycle of the system of interest. This can increase awareness of opportunities and impacts.
- Identify and describe the design challenge as a function.
- Abstract the function in general terms
- Translate the terms for the abstracted function into natural systems concepts. You can use the engineering to biology thesaurus (see Fig 5) to find related terms in biology. These will aid in searching for natural systems inspiration.
- Search for natural systems examples using that description.
- Identify multiple candidate natural systems
- Select the top candidates based on potential performance

For each:

- Investigate the mechanism (or strategy) nature uses to accomplish the function.
- Draw or diagram the features found in nature to explore the strategy and mechanism.
- Use metaphor and analogy based on the natural systems example to create a strategy and mechanism in design
- Apply what you learned to generate potential solutions;

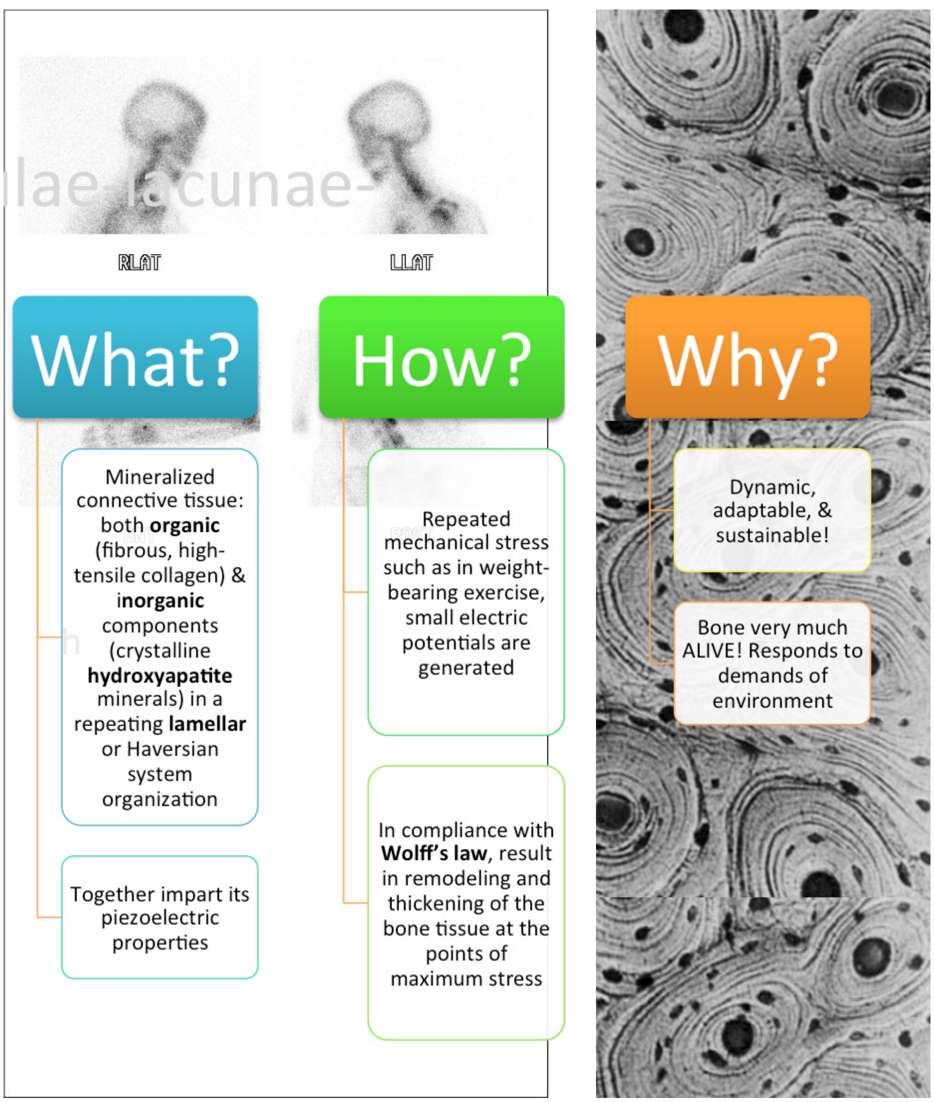


Fig 6:
Illustration of SBF modeling using bone
Note how structure (What) enables behavior (How) to provide function and (Why)

- Prototype the abstracted strategy
- Establish baseline measurements of the new approach
- In the cases where an inspiration from nature is found without a specific system design application:
  - » Identify a niche for the material or approach
  - » Work to establish an infrastructure from science to engineering to manufacturing.

Activities in a natural system inspired systems design may also include:

- Reviewing the design and development process to identify areas where consideration of natural systems could lead to an improvement in performance, schedule, and resilience; or standard solutions have potential for risk
- Ensuring that the team has access to resources and training in natural systems

At each process step, ask:

» How would a nature-inspired solution benefit economic, environmental and social arenas?

» Do we truly understand all the options in nature so that we can pick what could work best for our situation?

At reviews

» Search for areas where a nature inspired solution could satisfy a system requirement, improve a process, create a novel solution, inspire an improved architecture, or lower/healthier environmental, social and governmental impacts.

» Consider both natural and use environments as early as possible, including potential interruptions and variations in infrastructure, supply, and climate.

» Potential techniques include robust design, resilience studies, sensitivity analysis, and life cycle analysis.

» Evaluate the environmental impact of the system and its components during construction, operation, reuse (circular design) and end of life.

Systems Engineering vee diagram with Natural Systems inspiration process connections V2

Note: Assuming that both processes start with an understanding of the problem.

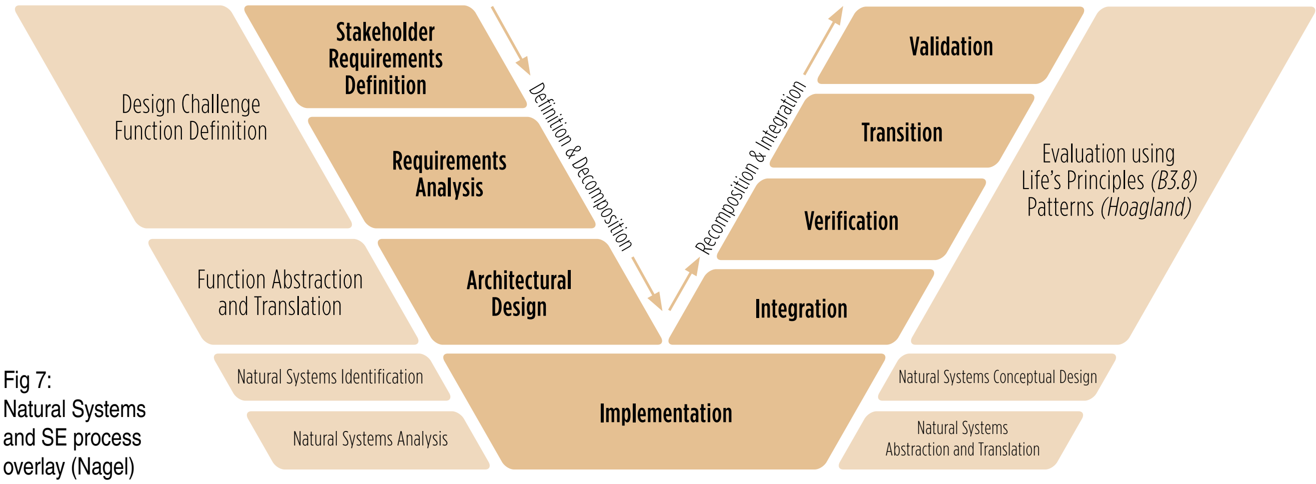


Fig 7: Natural Systems and SE process overlay (Nagel)

These approaches complement, extend and augment traditional design realization methodologies. Consider tailoring SE processes (http://sebokwiki.org/wiki/Tailoring_(glossary)) to fit the situation.

In either path, SE practices will be used to manage the design process. The solution from natural systems may require new materials or construction techniques. Lifecycle analysis may be indicated in addition to prototyping, testing, and trade studies.

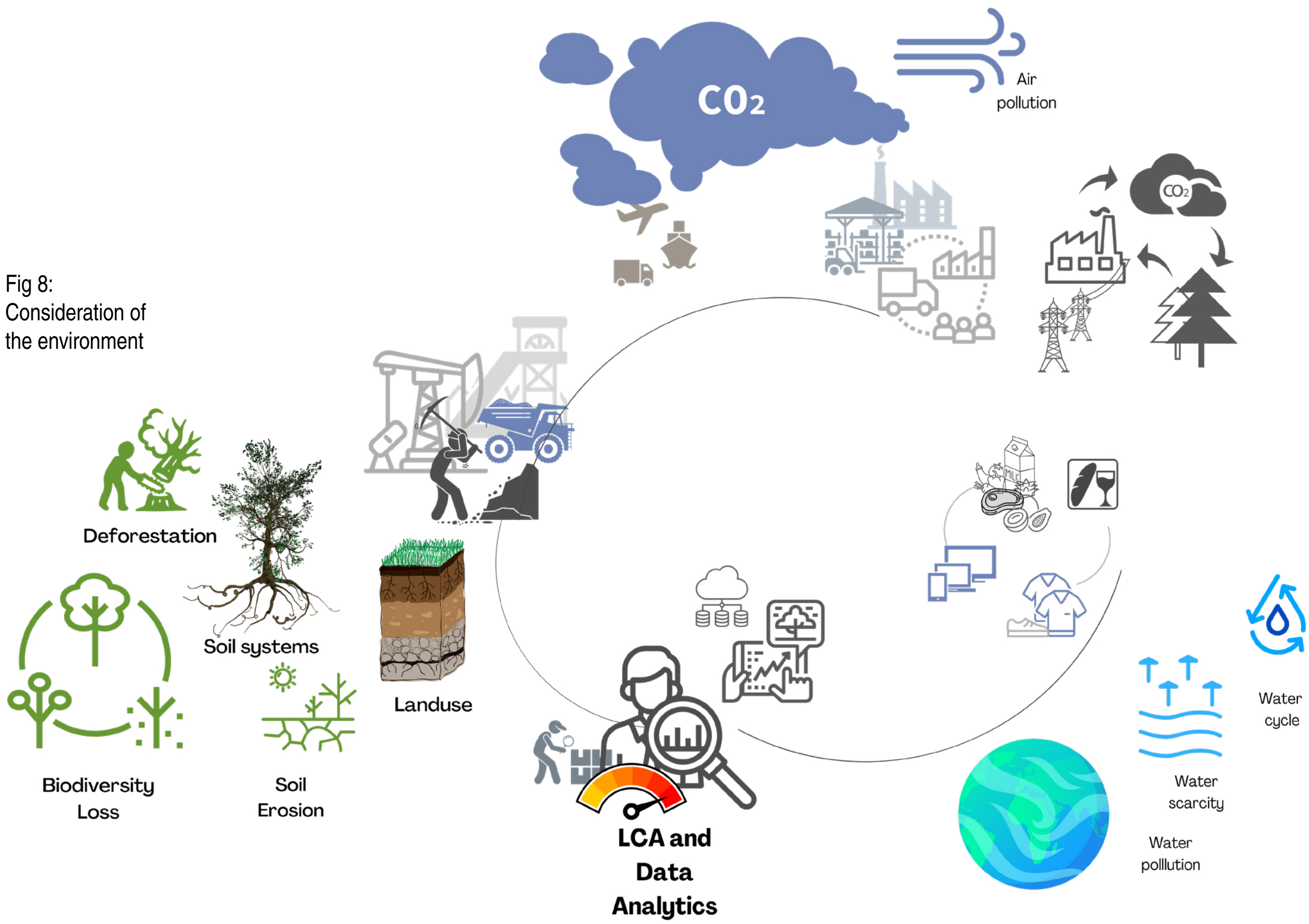


Fig 8:
Consideration of
the environment

Related Work

Consideration of natural systems as a basis for design has a rich history. Leonardo da Vinci based many designs on nature, Buckminster Fuller developed a theory of systems based on nature inspired geometry, Otto Schmidt coined the term biomimetics, and Janine Benyus used the term biomimicry to characterize work across many domains. Some key references are included in the reference section. A working group within INCOSE for Natural Systems published a special edition of Insight with a variety of topics (INCOSE NSWG).

Recommendations

- Consider alternate design processes based on natural systems. Examine algorithms that model a design or process and environment. Consider modifying design artifact parameters, evaluating the results, and iterating (NASA LADEE Antenna App C).
- Include a variety of disciplines in the design team, including natural systems expertise.
- Create a glossary of terms agreed to by the design team members. Anticipate and address challenges in communication between systems engineers and natural scientists.
- Consider all phases of the lifecycle and concept of operations when reviewing design alternatives.
- Routinely consider natural systems as
  - sources of design inspiration
  - logical extensions of current systems engineering processes
  - an approach to environmental, social, and governmental concerns (Peterby) For example, NS strategies can be used for material or energy use reduction, as a way to address risk reduction, and as a way to reduce the use of potentially toxic or non-circular materials.
- Establish mechanisms to access natural systems expertise.
- Work towards local adaptation and symbiosis of engineered systems into cyclical and regionally embedded circular material systems.

Appendix A

Why Should Systems Engineers Care about Natural Systems?

Substantial opportunities exist for SE's to increase their knowledge of Natural Systems and its application to material, product, and service system design. The natural world may be considered a vast library for learning and its variety and complexity daunting; careers are spent and made in pursuit of the knowledge to be found on earth and in the universe. Yet inquiry into natural structure, function, behavior, interfaces, and systems is manageable.

Natural systems exhibit extraordinary diversity and a range of attributes applicable to systems engineering: optimized size-weight-power-function, sensing, predictive response, problem-solving, sustainable growth, anti-fragility, complexity, autonomy, and more.

Emerging communities of practice offer accessible and useful research and learning opportunities for systems engineers. Evidence of this is found in (1) growth in the knowledge of natural systems (Vogel), (2) ability to share the knowledge (Biomimicry Institute), (3) ability to mimic nature (AskNature), and/or (4) the number of success stories where nature directly and indirectly contributed to innovative solutions (NSWG, Terrapin).

More broadly, integration of technical and social systems with natural systems entails 'circular' approaches and economic benefits for enterprise (Raworth).

Areas of notable opportunity:

- Integrating technical systems to help curtail or reverse earth system degradation.
- Optimizing for a complex environment rather than a few highly rationalized parameters.
- Using information and structure instead of energy to integrate functions (Vincent).
- Aligning to ambient conditions: contextual materials, energy, and by-product processing.
- Exploring complex problem-solution spaces and strategy selection.
- Expanding the 'envelope': environmental extremes, resilient operations, flexible performance.

Personal motivations for SE's to consider NS could include:

Curiosity - enjoy exploring an intriguing finding
Interest - develop knowledge in an area where the SE wishes to establish a reputation
Skills and Capabilities - practice and advance the art and science of engineering
Legacy - learn as much as possible from near-extinct species or disappearing ecosystems.

Motivations for organized groups to become involved could extend to:

Education - transfer valuable NS skills and knowledge to enhance the SE learning journey
Enterprise - developing SE innovations for markets attuned to and based in natural systems
Leadership - advancing use of NS knowledge throughout SE processes.

In sum, current engineering approaches may be challenged by, benefit from, and even require natural systems considerations. Informed attribute analysis and application may contribute to:

- strategic design and project processes
- reducing environmental, social, and economic harms and amplifying benefits
- technical improvements in cost, schedule, quality, operations, or sustaining activities (Reed).

Quick Reference Guide:

Elevating Natural Systems Knowledge in System Architecture Practice

While it is not possible to cover a vast field of inquiry in a brief primer, here are some key ideas to make the process more approachable. The following tips may be useful towards understanding how you can contribute to engineering agility and performance while balancing demands of applied research, diverse system architectures, and multiple projects. Consider starting or joining a community of practice to extend your learning and tailor a body of knowledge for your specific situation and interests.

- Review the design and development process to identify areas where consideration of natural systems could lead to an improvement in performance, schedule, and resilience; or where standard solutions exhibit potential risk.

- Engage multi-disciplinary views and representations to enlarge the range of design characteristics, enablers, and affordances. View natural systems data and solutions as expansions of your repertoire of functional concepts for engineering enterprise products and processes.

- Use a function based approach to capture system requirements, and use these functions in the search for natural systems structures, behaviors, and metaphors (AskNature, Nagel). This may be aided by: defining a structure / behavior / function (SBF) model for the feature of interest (Goel); describe the feature as a pattern; create two (parallel) system models for the design situation and the natural system.

- Identify a challenge or function in a system to be designed, and find relevant attributes in a natural system via a search process. A large number of example systems means that nature provides a great opportunity to explore different inspirations. A useful review yields many potential strategies. Making sense of this can be involved, so using tested toolkits for this process could be highly beneficial. Seek a comfortable pace for absorbing new information effectively and efficiently and selectively prioritize 'failing fast' and building on knowledge gained with agility. Prototype and use low-risk refining loops in developing selected strategies.

- Evaluate the environmental impact and opportunities of the system design and its components during sourcing, assembly, operation, repair/reuse, and repurposing (total life cycle).

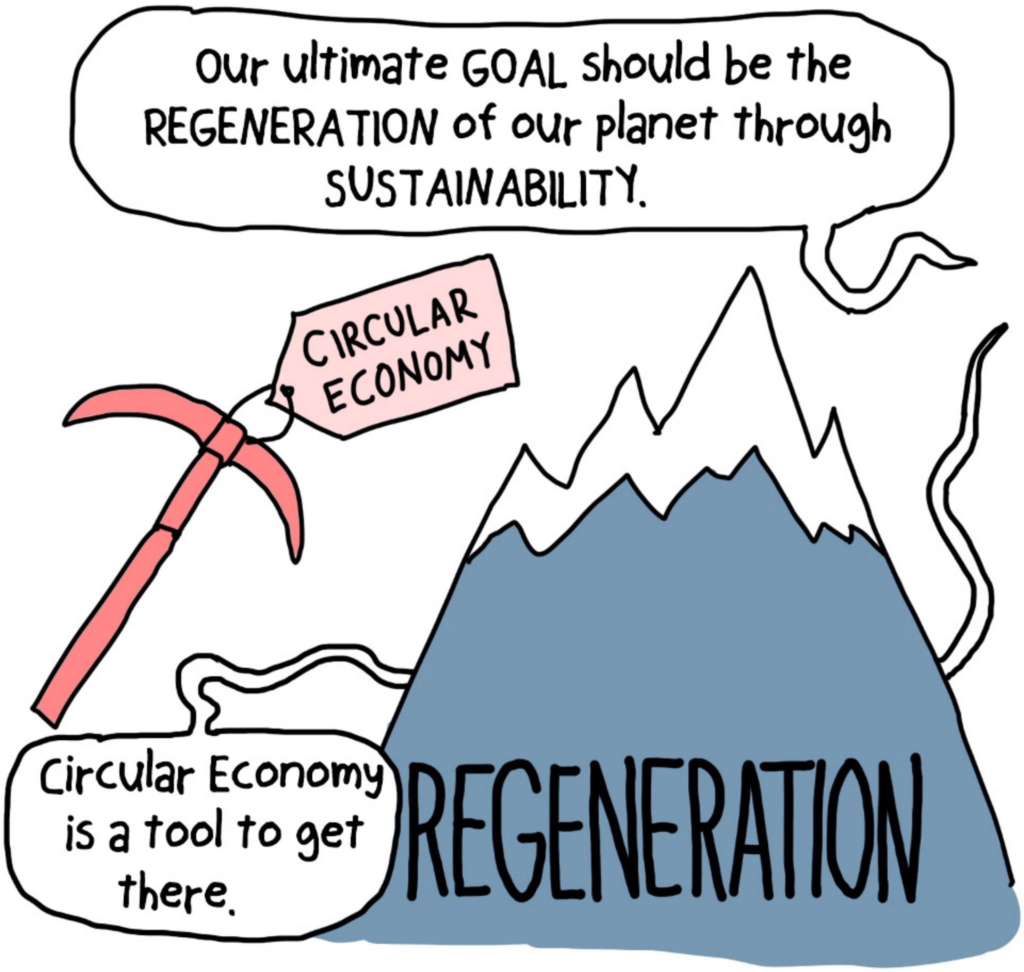
- Consider both natural, use, and out-of-use environments at multiple levels (physical, chemical, cognitive, cultural, ecological, planetary) as early as possible, including potential interruptions and variations in infrastructure, supply chains, and climate.

- In the System Architecture activity (http://sebokwiki.org/wiki/System_Architecture), consider alternative architectures based on natural system morphology. The best solutions may be modular, nested in environmental conditions, or arranged as a network.

- At architectural reviews, search for areas where a nature inspired solution could satisfy a system requirement, improve a process, create a novel solution, or inspire an improved architecture.

- The study of natural systems includes their forms and structures, behaviors and processes, pathologies, and 'laws' that govern how they interact - as abstractions more or less immediately useful for engineering. Consider that both designed and natural systems exhibit function, have interfaces (boundaries), are composed of modules, may capture or store energy, could sense and filter inputs, protect themselves, and obey commands (such as move and stay put). Develop language around such areas of common concern and analytical procedures that may be familiar to engineers with little or no biological sciences background.

- Generic techniques include robust design, resilience studies, sensitivity analysis, and life cycle analysis. Less familiar techniques might include evolutionary or circular approaches to materials and energy. Consider how these techniques compete and collaborate to create diverse value in thriving, nested, and dynamic engineering co-systems.



Bosschaert, T. 2022

Appendix B

Circular Economy

Nature inspired engineering is a key component of Circular Economy (CE) strategies. CE is increasingly being used both to innovate and lower impacts. The concepts of CE have been around since the 1980's. The term "closed loop" was coined in 1967 by W. Stahel and "more specific ideas on CE have been argued to date back to the metaphor of Spaceship Earth (Boulding, 1966)".

One can differentiate 3 major phases:

In the early phase of circular economy thinking, economists, industrialist and engineers were inspired by how ecosystems function which can be seen in the rise of industrial ecology as a discipline for instance but also a growing search for 'bioinspired process', in engineering and innovation (biomimetics - Otto Schimdst 1950/Biomimicry - Jenine Benyus 1997). For industry and economists this interest is illustrated in the "Bioeconomy" concept, a term coined in 1971 by Nicholas Gorgescu in his book "The Entropy Law and the Economic Process" but also with its uptake and Herman Daly and his "Biological Economy". This ongoing trend has translated into the largest global attempt at integrating ecosystem functions with economic thought and action, and to date, Circular Economy efforts form one of the largest and most globally impactful efforts at Biomimicry.

Since then CE evolved: During the 19-70-1990's CE was essentially seen as "Waste Management - a reactive action rather than re-design and prevention. The second phase , roughly from 1990 to 2010 can be seen as CE defining itself as eco-efficiency; here a move towards a more systemic approach viewing outputs and inputs and efforts at prevention characterize the time. Keywords are: Reverse logistics, Industrial Ecology and Clean products concepts focus on actions within business.
Today in its 3rd phase, emphasis on 'regeneration' and "biomass" grow in importance. But more essential, the 3rd phase focuses on 'business model innovation' hence emphasizing the need to transform organization more deeply. This in turn pushes for a more systematic approach to bio inspired innovation, biomimetic design and a nascent circular bioeconomy.

The 3rd phase of CE - denotes a systemic shift beyond stocks and flows towards preventive measures, with an understanding that circularity goes beyond the technical and needs to be realized on an organizational level. This moves CE beyond the - the narrow loops of Industrial ecology or Clean product concepts focusing it on business models and supply chain, - towards closed loops for greater geographies, effectively enlarging the stakeholder landscape.

The short definition of CE in its 3rd phase is: design out waste, keep products and materials in use at their highest level, and regenerate natural systems.

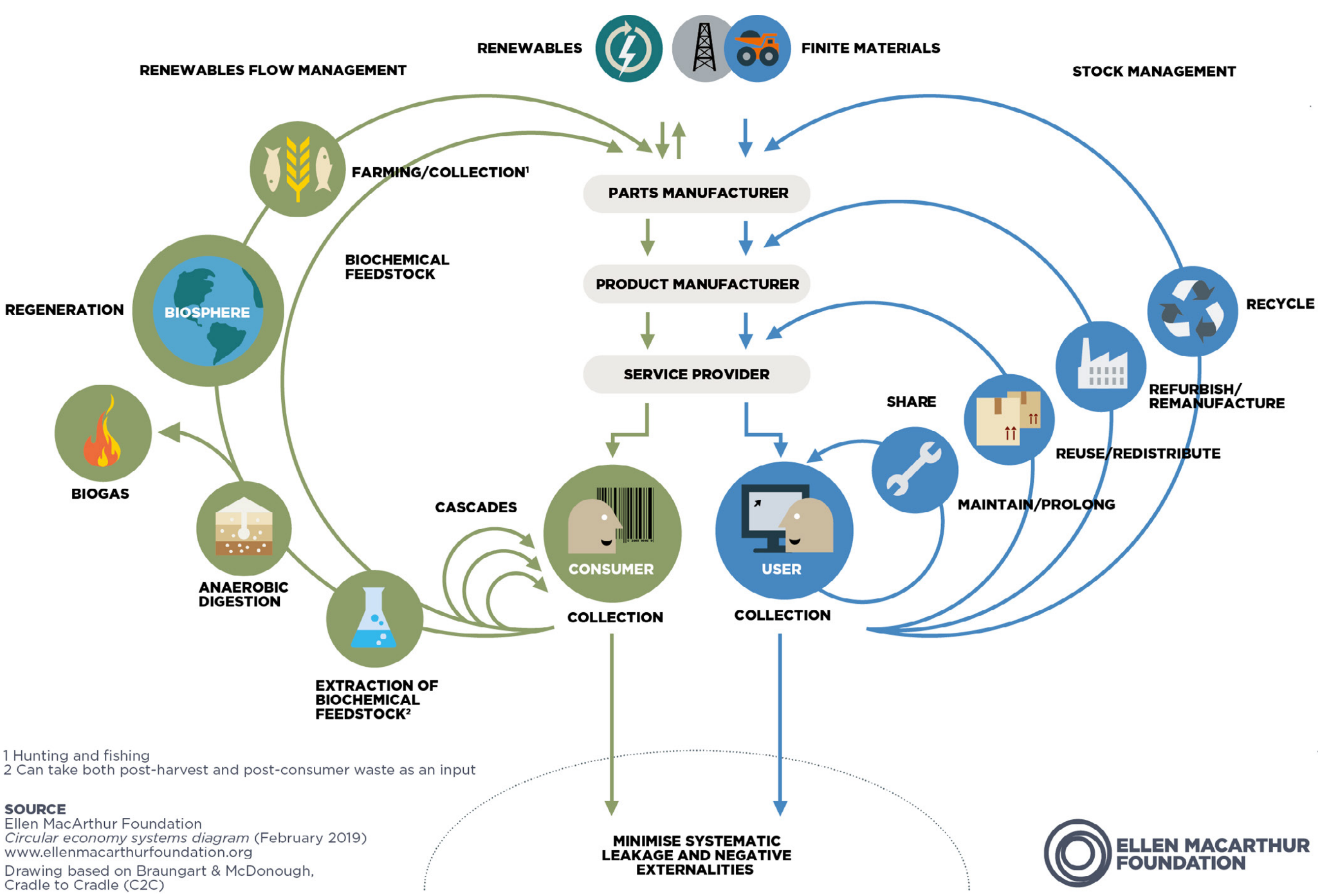
The SE Handbook chapter on Natural system integration states:
"Consider both natural and use environments as early as possible, including potential interruptions and variations in infrastructure, supply, and climate. Techniques include robust design, resilience studies, sensitivity analysis, life cycle analysis and circularity frameworks" (INCOSE 5E Handbook)"

Local embeddedness of design and process engineering - will be ever more closely tied to the local environment / niche / stakeholders / users. A continued move towards more regionalized economies, industrial symbiosis and tighter, narrower material loops increase the demands on product service and systems design, for greater modularity for instance, with design for disassembly and reuse becoming paramount. (see the NSWG white paper on SE process and Natural systems - replication of design modules, closed loop strategies,...).

In the circular economy a circular approach to materials and energy is a given.

Looking to nature to help close the material loops is essential to reduce the number of new or virgin external inputs used in the design of products or services.

The following Butterfly diagram - (see below) is the most widely used introduction to CE and shows the technological and biological cycles of material flows in a circular economy model and its respective loops.



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

SOURCE
Ellen MacArthur Foundation
Circular economy systems diagram (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough, Cradle to Cradle (C2C)

ELLEN MACARTHUR FOUNDATION

In the commonly used 9R Framework - the top 3 levels of the hierarchy - R0-R2 - imply tighter loops which concentrate on the "Refuse" - "Rethink" - "Reduce" - level of the 9R Framework - and translate into lesser external inputs needed to close the loops, which in consequence create a more circular strategy.

		Strategies	
Circular economy	Smarter product use and manu-facture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
		R1 Rethink	Make product use more intensive (e.g. by sharing product)
		R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
	Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
		R4 Repair	Repair and maintenance of defective product so it can be used with its original function
		R5 Refurbish	Restore an old product and bring it up to date
		R6 Remanufacture	Use parts of discarded product in a new product with the same function
		R7 Repurpose	Use discarded product or its parts in a new product with a different function
	Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
Linear economy		R9 Recover	Incineration of material with energy recovery

The 9R Framework for circular systems - for a more detailed and an extended 10R Framework applicable in the SE NS Design process - refer to the NSWG Circularity Whitepaper.

"The tighter the loop (lower R), the fewer external inputs are needed to close it, and the more circular the strategy. The longer the loop (higher R), the less circular it is." The 9R Framework. Source: Adapted from Potting et al. (2017, p.5)

Looking for circular design can easily be inspired by the process for translating biological knowledge from Natural Systems described before and may easily fit into the 4 categories of: Physiology, Morphology, Behaviours and Strategy. (see Primer and Appendix A).

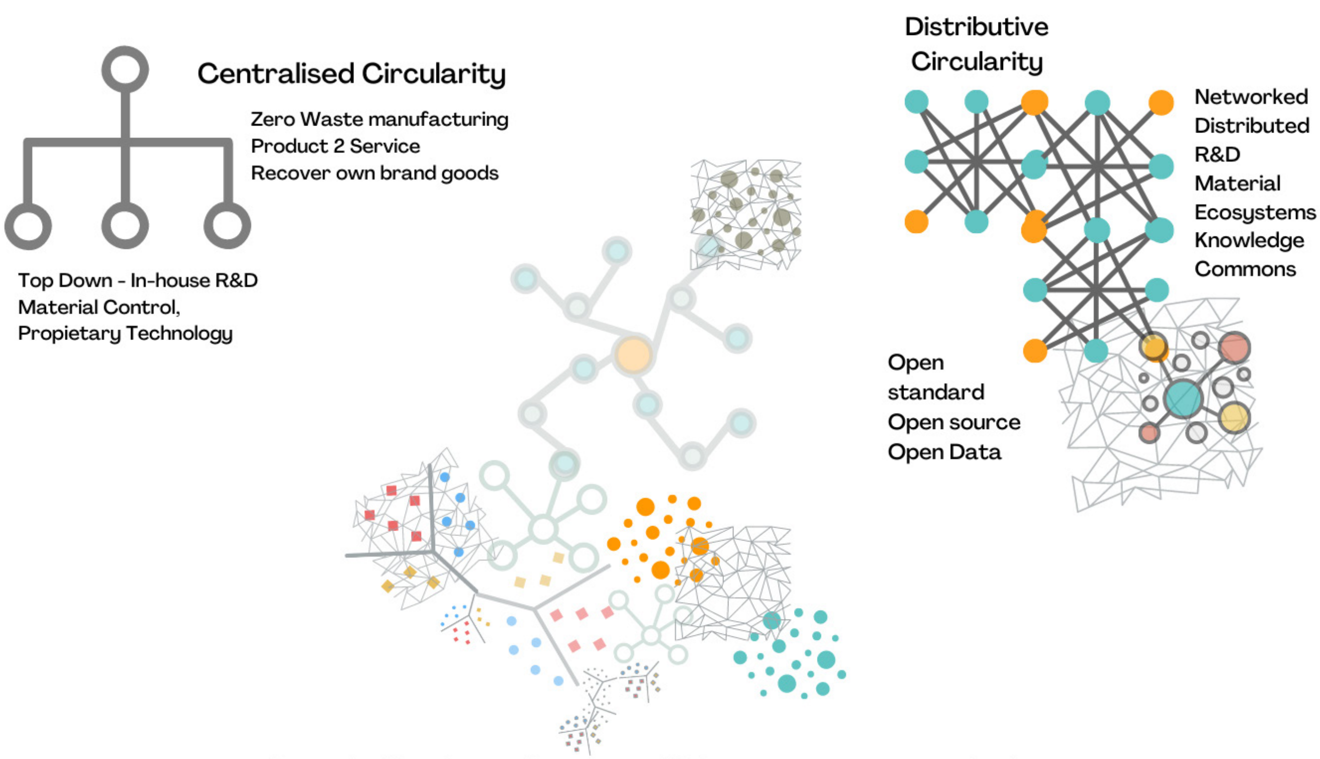
The categories" Behaviour" and "Strategy" (cf. Nagel/page 5) - may warrant special interest for circular systems design given the shortcomings noted in our current attempts at circular product and systems design. (see above).

The circular economy as a new - narrative and a paradigm shift - to enable humanity to live collectively within the planetary boundaries, and to create conditions conducive to all life on the planet- entails a makeover of infrastructures, production systems, design methodologies and supply chains to name just a few.

It also forces us to rethink our human patterns of and for collaboration necessitating large scale overhaul of our leadership training, valuation, thought patterns in education, training and organization of ourselves and our current and future workforces.

CE Living Labs are a widespread practical means to start collaborative approaches and experimentation in real user and multi stakeholder environments. For further details, review the NSWG white paper on NS and CE.

Emergent Circular Economies



Notions of effective rather than efficient systems answer both through iteration of nested systems within enabling conditions

adapted from Kate Raworth : inaugural lecture Exeter centre for Circular Economy 2018

Illustrations/Cartoon Comics: based on chapters and research from upcoming *X Factor* Book

5th *Factor X* publication from the Federal Environment Agency (UBA), *The Impossibilities of the Circular Economy: Separating Aspirations from Reality*. Comic Authors: Christoph Hinske, Harry Lehmann
Comic story and art: Virpi Oinonen

Appendix C

Examples from a few thousand successful NS application examples include:

1. NASA-LADEE Antenna - accelerated antenna design with nature's mutation and selection approach

In 1950, Alan Turing proposed a "learning machine" which would parallel the principles of evolution. The first "evolved antenna" designs appeared in the mid-1990s from the work of Michielssen, Altshuler, Linden, Haupt, and Rahmat-Samii. The process that creates an evolved antenna is actually a computer driven mutation and natural-selection process where both process criteria are actually determined by the engineer. The huge advantage comes in when computer modeling and evaluation of antenna performance greatly decreases the time and effort to optimize antenna design. This was especially valuable accommodating late requirements changes for NASA's ST5 mission (2006) X-band antennas. Gregory S. Hornby http://alglobus.net/NASAwork/papers/Space2006Antenna.pdf

Lunar Atmosphere and Dust Environment Explorer(LADEE) mission (Sep 6, 2013 – Apr 21, 2014) applied this approach successfully to 3 Sband antennas. A post-LADEE mission publication stated the "new designs without flight heritage" were "accepted potential prelaunch risks" that "were unrealized… throughout the entirety of the mission and its modes." SSC14-XII-4 - 28th Annual AIAA/USU Conference on Small Satellites

Today, the www.AWR.com commercial product "AntSyn" is available as an "EM simulation with genetic-based optimization for exploration of design options and achievement of user-defined performance."

2. NASA-Prandtl Aircraft – aircraft that fly with wings of a bird - no vertical tail

In 1933, Ludwig Prandtl published a little-known paper on a superior model of span-load design of birds. But it wasn't until 2015 that Al Bowers, Chief Scientist at NASA Armstrong Flight Research Center, was able to demonstrate and measure Prandtl's theory for superior efficiency and coordinated control in a single solution in what is now known as proverse yaw. This model offers the only solution to three aspects of bird flight: how birds are able to turn and maneuver without a vertical tail; why birds fly in formation with their wingtips overlapped; and why narrow wingtips do not result in wingtip stall.

NASA/TP—2016–219072 https://ntrs.nasa.gov/citations/20160003578

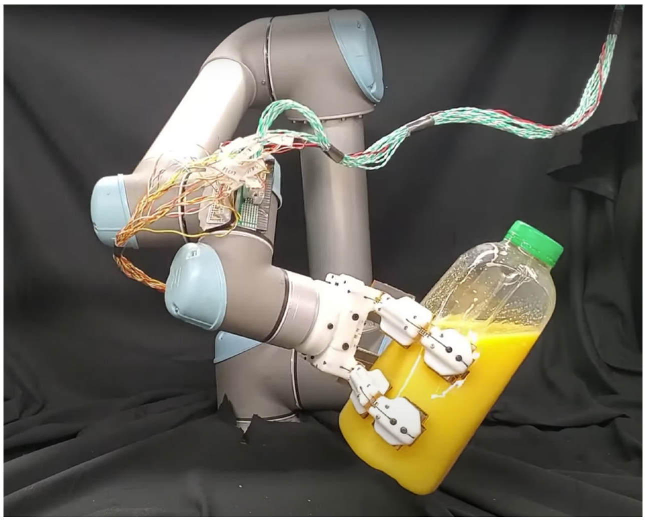
Videos: https://www.amaflightschool.org/PRANDTL

Prandtl -D

Prandtl-M (Mars glider demo)

3. NASA JPL-Stanford Gecko-Grip method for controlled temporary adhesion
By duplicating the tiny hairs and the motion to achieve similar Van der Waals forces of a gecko's foot, the team at JPL and Stanford have demonstrated an attachment mechanism on a free-floating spacecraft inside the International Space Station called Astrobee.

Stanford Dextrous Manipulation Lab:
https://youtu.be/km_M9KyTpsY



Today, OnRobot offers a single pad gecko-gripper
https://onrobot.com/en/case-studies/onrobot-gecko-gripper

4. Advanced Robotics Inspired by Nature:
Boston Dynamics - "Spot" and "Atlas" - Robotics with whole body coordination
https://www.youtube.com/watch?v=7atZfX85nd4

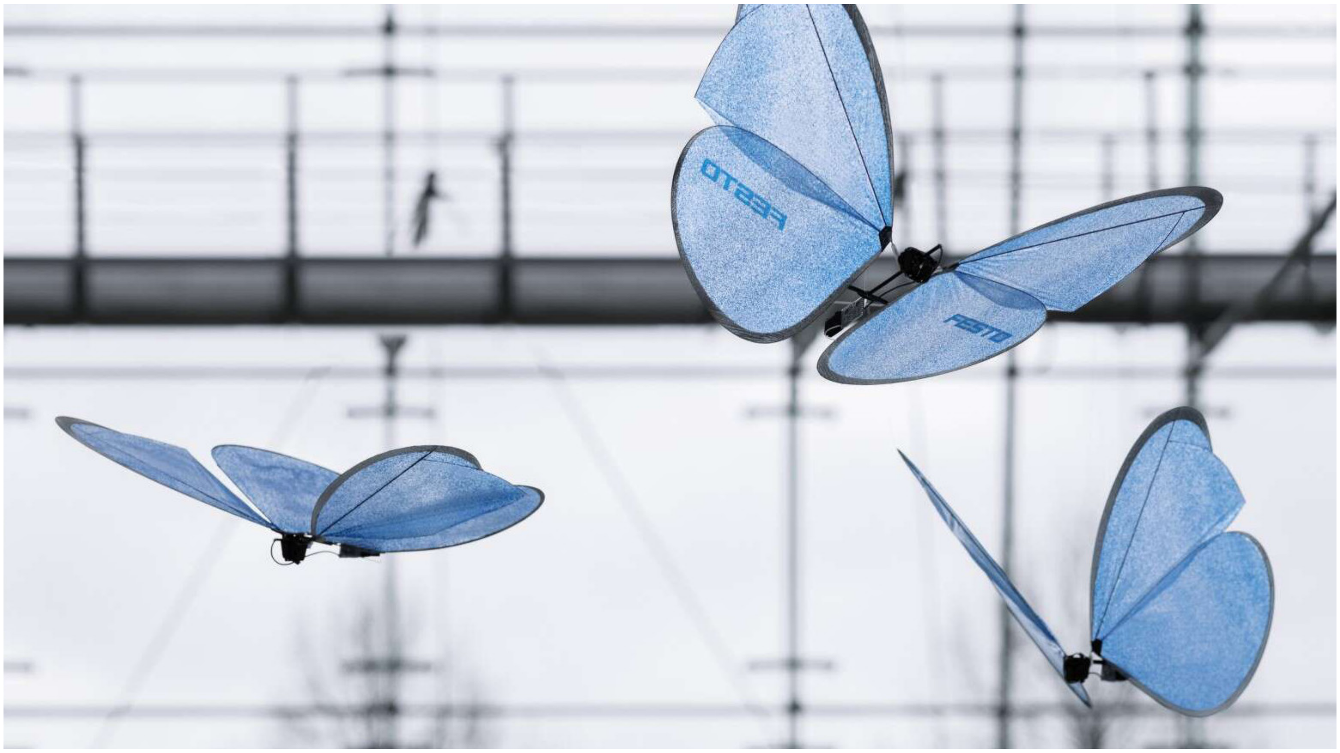
https://www.bostondynamics.com/atlas

("Do You Love Me" dancing robot video)
https://youtu.be/fn3KWM1kuAw

NASA/JSC- "Valkyre" maintainable dexterous robot assistant for space:
https://youtu.be/IE-YBaYjbqY

Equinor – "Eelume" undersea snake robot – (catch it in the movie "the Burning Sea")
https://www.cnn.com/2021/01/20/tech/eelume-undersea-snake-robot-spc-intl/index.html

Festo Robotics:
Bionic Workplace: https://www.festo.com/us/en/e/journal/talking-to-machines-id_45185/
Butterflies: https://www.festo.com/media/video/de/CC/eMotionbutterflies-2015-720p-de.mp4
Dragonfly: https://www.youtube.com/watch?v=4C9LTZCmb8Q



Examples from Zygote Quarterly
Regen/Encycle:
http://issuu.com/eggermont/docs/zq_issue_01final/68
https://issuu.com/eggermont/docs/zq_issue_22_final/108

Shinkansen bullet train http://issuu.com/eggermont/docs/zq_issue_02final/14

PowerCone https://issuu.com/eggermont/docs/zqissue16/88

"Stories from the Trenches" series
https://issuu.com/eggermont/docs/zqissue21_final/38
https://issuu.com/eggermont/docs/zq_issue_22_final/8
https://issuu.com/eggermont/docs/zq_issue_23_final/22

Materials https://issuu.com/eggermont/docs/zq_issue_24/8
Tensegrity https://issuu.com/eggermont/docs/zq_issue_25final01/90
Biomimetic innovations https://issuu.com/eggermont/docs/zq_issue_27/8

References

Key resources
"AskNature - Innovation Inspired by Nature." https://asknature.org/. The world's largest, open access library of design lessons. It contains more than 1700 Biological Strategies used by living things to achieve thousands of different functions. There are also hundreds of Innovations that allow you to see how others have applied lessons from nature.

Natural Systems Working Group. https://www.incose.org/incose-member-resources/working-groups/analytic/natural-systems

PeTaL is a web-based biomimetic discovery tool available at https://petalai.org. It contains over 1300 biomimicry papers organized by function using artificial intelligence and machine learning.

Zygote Quarterly (http://zqjournal.org/) is an open-source, award-winning journal that reports on recent developments in bio-inspired design (BID). It features in-depth case studies, interviews, portfolios, and product, tool, and methodology discussions.

Agile https://www.agilealliance.org/agile101/

https://en.wikipedia.org/wiki/David_Attenborough

B3.8 https://biomimicry.net/work-examples/

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Biomole http://biomole.asknature.org/

Biotriz https: //inventorium.gumroad.com/l/ClgcdR

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Institutions/Actors/Organizations
EMF Ellen Mac Arthur Foundation
GACERE Global Alliance on Circular Economy and Resource Efficiency (GACERE)
Platform for Acceleration of Circular Economy Transition (PACE)
Circle Economy
WCEF
Sitra
African Circular Economy Alliance / CircularAfrica
Coalition for Circular Economy Latin America / Caribbean

High Level Analysis Reports
Circular NorthAmerica Report Ministry for Environment and Climate Change Canada
Circular Gap Report Circle - Dutch CE Think Tank
"Valuing Nature" IPBS report
"The State of Finance for Nature" UNEP

Important Policies - Standards
Eco Design Guide EU
European Circular Action Plan
Extended Producer Reliability

Policy-driven agendas are also focused on the circular economy shift:
- Paris Climate Agreement
- UN Sustainable Development Goals (SDG 12, 11, 9, 13)
- European Green Deal Circular Economy Action Plan
- 2019 African Durban Declaration
- China's 5-Year Circular Economy Plan
- Circular economy strategies across Latin American countries see above

CE ISO Standards
ISO/TC 323 Circular Economy - Learn2improve
ISO TC/323 connects the dots for a circular economy
ISO TC323 – Proposals for Circular Economy Standards | ECD Compliance News

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