A Biology-Architecture Collaboration: Integrating Biological Concepts with a Bio-Inspired Design Process

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ABSTRACT: This paper explores a collaboration between architecture and biology educators to integrate core concepts of biology with a bio-inspired architectural design process. Bio-inspired design looks to biology for inspiration to expand design thinking, methods, and strategies. Given today's ever-increasing ecological challenges, designers can benefit from the expertise of biologists and the biological lessons of other species. In this paper, a six-step design process adapted from engineering (Fayemi et al. 2017) is integrated with core concepts of biology, including the ideas of function, biodiversity, and evolution. This integrated process explores how the concept of function serves as a bridge between human challenges and different areas of biology, while simultaneously helping to overcome the limits of simply copying biological traits. Tools are offered to explore biodiversity and the tree of life for biological models that can inform design ideas, stressing the importance of sampling different parts of the tree, as diverse organisms often solve a given problem in different ways. Bio-inspired design shifts the perception of architecture being an object toward exploring architecture as an action. This concept is described in this paper as "biologizing" (Baumeister et al. 2014; Brownell and Swackhamer 2015). The integration of the biological concepts with the adapted six-step design process is illustrated through an example conceptual design of a cold-climate, south-facing building envelope. The findings of the study illustrate biological and design lessons for educators and practitioners, as well as the next steps for bio-inspired design research and education.

KEYWORDS: Architectural Education, Bio-Inspired Design, Biomimetic Design, Sustainable Design
PAPER SESSION TRACK: Pedagogy

INTRODUCTION

This paper investigates a design-research collaboration between evolutionary biology, curriculum instruction, and architectural design at the University of Minnesota to enhance and test a six-step bio-inspired design process integrated with core concepts of evolutionary biology. It brings evolutionary biologists' expertise into the architectural design process to increase the range and depth of biological knowledge and to ground designers in accurate biological concepts and methods to translate into architectural design. Given today's ever-increasing ecological challenges, designers can benefit from the expertise of biologists and the biological lessons of other species. A significant body of research has been developed on bio-inspired and biomimetic design processes encompassing diverse disciplines, such as robotics, product design, biology, and architecture (Fayemi et al. 2016, 2017; Graeff et al. 2019; Cruz et al. 2020; Dixit and Stefanska 2023). This research builds on the analogy-based approach to design with biological systems as a source of inspiration (e.g., Fu et al. 2014). The research discussed in this paper investigates: 1) Why and how core biological concepts (e.g., function, biodiversity, and evolution) can enhance a bio-inspired design process, 2) How a six-step design process could integrate with the core biological concepts, and 3) How biological models can be abstracted and translated into architectural design. The paper discusses the process and outcomes of testing the integrated concepts with the six-step bio-inspired process for the conceptual design of a cold-climate south-facing building envelope.

1.0 FRAMING THE PROBLEM: BIOLOGY - ARCHITECTURE INTERFACE

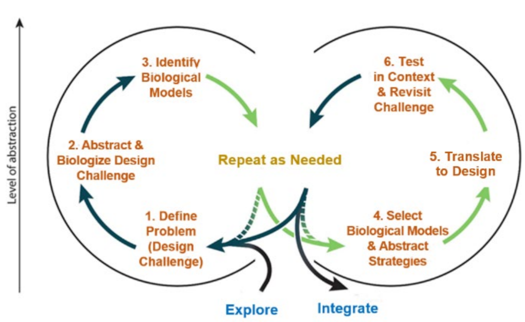


Figure 1: Six-step bio-inspired design process. Adapted from Fayemi et al, 2017. Source: (Authors 2022)

Bio-inspired design frameworks – such as biomimetic, biomorphic, biophilic, bioclimatic, and others – look to biological models, processes, and systems for strategies to expand design thinking in response to the ecological challenges of our day (Bhushan 2009; Fayemi et al. 2016, 2017; Snell-Rood and Smirnoff 2023, in review). While biologically based design frameworks have sought inspiration from biology, they often rely on approaches from design processes more than on concepts from biology. In contrast, the approach discussed in this paper integrates three core biological concepts with a six-step *Bio-Inspired Design Process* that was adapted from a *Biomimetic Process* developed by engineers Pierre Emanual Fayemi et al. (2017). The design process has been reframed from "biomimetic" (mimicking biology) to "bio-inspired" (drawing design inspiration from biology) to provide greater flexibility to designers in translating biological frameworks beyond biomimetic design (Fish and Beneski 2013) - a concept described here as "biologizing" (Baumeister et al. 2014; Brownell and Swackhamer 2015). The six-step process represents a sequence of iterative design explorations that guide a practitioner as they integrate the human design space and the biological space (Figure 1). The core concepts from biology include biological function, biodiversity across the tree of life, and evolution. The integrated concepts and six-step design process enable designers to translate the design challenge more accurately into biological terms, deepen the biological accuracy, and structure the translation of biological strategies into design concepts.

2.0 THREE CORE BIOLOGICAL CONCEPTS FOR THE BIO-INSPIRED DESIGN PROCESS

2.1 Overview of Core Biological Concepts

The six-step design process is enhanced by the integration of core concepts from biology to enable designers to use biological strategies, processes, or systems more effectively. The concept of function serves as a bridge between human challenges and different areas of biology (Vincent and Mann 2022; Baumeister et al. 2014; Roth-Nebelsick 2022). Tools are used to explore the tree of life for models that can inform design ideas, stressing the importance of sampling different parts of the tree as diverse organisms often solve a given problem in different ways (Penick et al 2022). Finally, we illustrate how a problem can be distilled to key environmental challenges that allow exploration of different geographic regions for ideas. We argue that the diverse challenges of a bio-inspired design process can be overcome by incorporating more biology – and collaborations with biologists – into the design process (Graeff et al. 2019). Here, we start by introducing core concepts from evolutionary biology and ecology as a first step (Snell-Rood and Smirnoff 2023, in review). We do not suggest that architects become biologists, but rather focus on key concepts that bridge biology and architecture, while acknowledging the limits of this process.

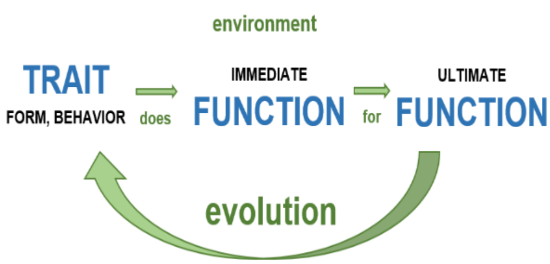


Figure 2: Schematic of core concepts in evolutionary biology that inform a bio-inspired design process in architecture. Source: (Authors 2022).

Biology provides a staggering range of traits and behaviors that we can draw on for inspiration. Traits are physical parts of an organism that contribute to how they perform in their environment, such as a bright feather attracting a mate, or a sharp spine defending against a predator. Behavior considers how an organism's traits are put into action to deal with their environment, for instance a beak cracking a seed, or a sweat gland releasing perspiration. Over time, traits and behaviors evolve in response to interactions with the environment.

With over 1.5 million described species among a likely 10 million species on earth, we have many traits to look at for inspiration. Through evolution by natural selection, biological systems adapt to their environments as trait variants that do well are amplified, while those traits that perform poorly tend to disappear. How do we search the millions of biological traits on earth for inspiration? The concept of function provides an essential connection between biology and architecture. Function in biology can refer to what a trait is immediately doing for an organism. However, function can also refer to the contribution of that trait to the organism's survival and reproduction – a beak is cracking a seed to obtain nutrients to grow and reproduce (Wouters 2005). This ultimate or longer-term function explains how that trait came into existence over evolutionary time and can contrast with the trait's immediate function, which is often what we are trying to "analogize" and translate in bio-inspired design (Figure 2).

While evolutionary processes can produce a wide array of adaptations that solve environmental challenges in creative ways, these processes are limited by available variation. In other words, "what comes before" may bias "what comes after". This means that traits are not necessarily optimized and are generally only incrementally better than what came just before, as we see in the larger concept of evolution by natural selection (Fish and Beneski 2014). Fortunately, as designers, architects are not limited by the same processes: biology can be a source for creative ideas, but designers can pick and choose across systems, species, and traits for design concepts. The most effective way to increase this pool of inspiration is to sample for ideas widely across the tree of life and the globe. Doing so increases the chances of finding organisms that accomplish the same function, but in different ways, some of which may be appropriate for the desired application (Penick et al. 2022). As discussed below, we encourage designers to consider biodiversity in terms of species that represent different branches of the tree of life, and that represent different geographic areas across the globe. Evolution has been moving along independently in separate branches and separate locations, increasing the chances that the designer will end up with a diversity of ideas (Hund et al. 2023).

2.2 Translating Core Biological Concepts to Architectural Concepts

We can draw parallels from core concepts of biology to make analogies with design challenges in architecture. In a design process, we might focus on an object or process that is analogous to a biological trait. We can consider the immediate function of this object or trait - what is being performed by an organism's trait that solves a challenge the organism faces in navigating its environment. This biological concept encourages designers to shift from focusing on the "object" (a shading device, for example) to the function of what the object is "doing" (mediating heat or light). Immediate function can be viewed through different lenses, including the *function* of the physical form and shape (building massing, section, details), a *process* (generate electricity, provide ventilation, harvest sunlight for heat); a *material attribute* (absorb heat, reflect light, insulate); or *behavior* (foster an occupant's seasonal interaction with the building, respond to changing luminous conditions, connect to nature). After considering the immediate function of a trait or design element, we might consider its ultimate function (Wouters 2005) – the purpose of a design feature or element in relation to physical, social, cultural, and environmental contexts – such as the building users, program, structure, or systems. This is analogous to thinking about the ultimate function of a biological trait in terms of how it contributes to survival, reproduction or fitness, and thus its long-term persistence (e.g., architectural shelter, protection from the elements, life safety, etc.).

There are also parallels between the concepts of environment, evolution, and diversity in biology and in architecture. Many of the same biotic and abiotic forces that influence how organisms perform in their environment also apply to buildings, with such performance being highly dependent on variations over space and time. Such variations in the environment create diverse selections for different versions of a trait or feature, leading to the emergence of different architectural traits or design elements over time. Diversity in biology captures the millions of species on earth, their patterns of relatedness, and a consideration of how their forms and behaviors have evolved in response to their environments. Diversity in architecture includes variation in building elements and structures to deal with local environmental challenges, including selection pressures based on human and cultural preferences in what is considered aesthetically pleasing, novel, or trendy. From an architectural approach, evolution could focus on a progressive generative process relying on feedback within a system to select a "best fit solution" stemming from intentional or accidental means. It could also consider the chronological and spatial interconnections between humans and other species and living systems. Such evolutionary design will engage with dynamic environmental, social, and cultural conditions, leading to design solutions for adaptation, flexibility, and transformation at any scale (site, envelope, rooms, details); as well as addressing the needs of various users and spatial configurations in time.

3.0 A BIO-INSPIRED DESIGN PROCESS FOR CONCEPTUAL DESIGN

The integrated concepts and bio-inspired design processes discussed above were tested on the conceptual design of a cold-climate, south-facing building envelope. The envelope example explored how biological lessons might inform design responses to the dynamic and changing thermal conditions for seasonal heating (seasonal cooling to be considered in the future). Example conceptual envelope design outcomes are included to illustrate the biologically-integrated design process and will be further developed and tested with explicit design and sustainability performance criteria in subsequent studies.

3.1 Step 1: Define the Problem (Design Challenge) - Function

The first step in the *Bio-Inspired Process* is to clarify the problem and design challenge. It is useful to develop a variety of possible design questions and to subdivide the exploration into a series of related investigations targeting different issues and scales. This step identifies the challenge(s), scale(s) of inquiry, and building or construction functional issue(s) the design is going to address. An exploration of function is essential in determining the scope of this step.

Figure 3: Step 1 Example: Design challenge for cold climate design: extreme seasonal temperatures, humidity, precipitation, wind, solar radiation, daylight. Source: (D. Banker, Research Assistant 2022)

In the example, for the design of a cold-climate, south-facing building envelope in Minneapolis, the identified design challenge focused on how the envelope could respond to the dynamic and dramatically changing seasons and environmental forces (extreme seasonal temperature change, humidity, solar radiation, moisture, precipitation, winds, etc.) (Figure 3). Although the environmental conditions are dynamic, it is common that cold-climate envelopes in Minnesota are predominantly static (with non-operable windows in most commercial and institutional buildings). We asked specifically: How might the envelope design mediate between the dynamic exterior forces and dynamic interior conditions for specific envelope functions (seasonal change for heating, cooling, ventilation, lighting, views, privacy, connection to site, etc.) and performance metrics (energy, carbon, comfort, program activities, etc.)? The following steps were used to define the design challenge:

Step 1 Example: Define the Design Challenge for a Cold-Climate South-Facing Building Envelope

- *Identify the problem:* What are the design challenges of a cold-climate building envelope?
  How does the envelope respond to extreme environmental conditions?
- *Explore parallel questions (broad and narrow):* The broader questions can be narrowed into more targeted questions: How does the envelope regulate temperatures (heat, cold, humidity, light, dynamic conditions, etc.)?

3.2 Step 2: Abstract and Biologize the Design Challenge - Function

In the next step of the bio-inspired design process, we take aspects of the problem analysis and "biologize" the design challenge (Baumeister et al., 2014), seeking analogies from the discipline of biology. For instance, if we are interested in exploring lighting options, we might want to investigate how a light bulb might translate to biology. To facilitate this, we select verbs associated with how light moves through the environment (such as illuminate, reflect, absorb, or refract) to facilitate the search process for biological analogies. As another example, if we are interested in how to design a building envelope to deal with mold, we might think of verbs such as: inhibit growth, repel moisture, or kill microbes. Biologizing the problem is the first step in using function as a bridge between design and biology. It's helpful to expand this list of biologized verbs into as many different functional search terms as possible. These search terms can then be used to identify potential biological models for design. Questions related to function are essential to consider during the abstraction and biologizing process. For the building envelope example, we narrowed the focus to how the envelope "regulates temperature" during the winter months.

Step 2 Example: Abstract & Biologize the Envelope Question

- *Select one question to narrow the design focus:* How does the envelope regulate temperature in winter?
- *Identify "functional priorities" and abstract the design challenge:* What does an envelope need to do in winter? Translate envelope elements to the function they perform (shift from nouns to verbs: cladding=shelters; vapor barriers=block, shading=filters, glazing=admits, insulation=resists, etc.; Figure 4).

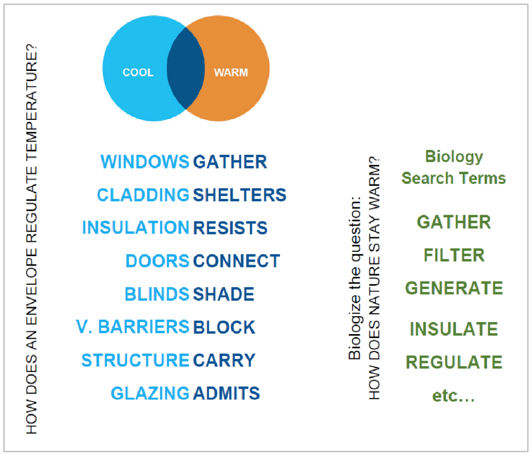


Figure 4: Step 2 Example: Abstracting and biologizing the envelope question. Source: (Authors 2022)

- *Biologize the Question:* How do organisms stay warm?
- *Generate related biology "search terms" (verbs) using the Biomimicry Taxonomy* (Biomimicry Institute 2008).
  - *Abstract the design issue:* Develop phrases that distill the biological lesson for the design process to prompt new thinking. The "abstracted design principle" should: 1) contain the most essential information, 2) be biologically accurate, and 3) use terminology that is relevant and recognizable for an architect (Baumeister et al. 2014).
  - *Consider different biological lenses to generate functional search terms*: 1) Form: How do organisms in nature absorb, gather, or reflect heat? 2) Process: How do organisms in produce or regulate heat? 3) System: How do organisms in nature manage heat at a system or ecological scale? and 4) Material: What materials are used to gather, generate, regulate heat?
- *Organize the Biological Search Terms for the next step:*
  - *Question*: How do organisms stay warm in nature?
  - *Search Terms*: How do organisms in nature manage, respond to, produce, capture, filter, absorb heat, etc.?

3.3 Step 3: Identify Potential Biological Models - Function & Biodiversity

Once we have a list of biological functions, we can start to move into the biological space, finding organisms that do analogous things in their own environment. There are a few ways to start exploring biological models. First, we can make use of existing bio-inspired design databases, like *AskNature*, which have a curated database of *biological traits*, classified by *functional terminology* useful for design (Figure 5) (Biomimicry Institute 2022). We can branch out further by delving into the biology literature, using databases such as *Web of Science* or *Google Scholar.* Here, search terms that include typical jargon of the field can be useful. For instance, the term "beak morphology" will yield more hits than "beak shape". This is where collaborations with biologists can be a great benefit, as they can help identify the types of systems, traits, environments, and appropriate terminology to search for biological ideas.

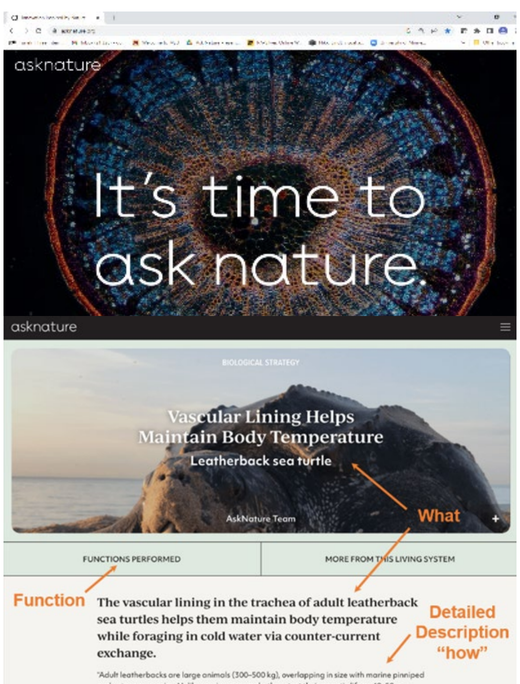


Figure 5: Step 3 Example: *AskNature*: How leatherback sea turtles say warm. Source: (Biomimicry Institute 2022)

At this step in the process, it is beneficial to identify a wide range of biological models to increase the chance of finding a good match to the design challenge. First, look at how diverse organisms accomplish the same function. If unrelated organisms have evolved the same function, but followed different evolutionary paths, there is a good chance that how they accomplish this function – the underlying mechanism – varies in some way, which can provide diverse ideas for design.

Consider that an apparent function might fulfill a different ultimate function (see Figure 2; Snell-Rood and Smirnoff 2023, in review). For instance, temperature regulation is a secondary function for butterfly wings, which have evolved scales that absorb sunlight, but do so to release pheromones more than to warm the organism (Krishna et al 2020). An architectural parallel might be how temperature, solar radiation, and light are interrelated.

To increase the biological diversity of possible design models, search across the tree of life as broadly as possible (Figure 6). The further apart a pair of species on the tree of life, the more likely that a given function is met through different mechanisms, which will provide the designer with the broadest possible set of biological traits that might be translated to the design. *Wikipedia* has a handy bar on the right-hand side of organism entries that shows current classification and *iNaturalist* is another valuable resource.

Finally, consider the environmental context, or ecology, of the desired functions – what abiotic and biotic variables are relevant to the design challenge and what other geographic areas or ecosystems experience such conditions? For instance, in dealing with cold temperatures, consider not only Arctic environments, but also alpine environments, or night-time temperature swings in deserts. Within each type of biome or ecosystem, there are independent replicates across the globe with distinct biological communities that can provide lessons for design (for notes on process in the classroom, see Hund et al. 2023, Snell-Rood and Smirnoff 2023, in review).

Figure 6: Tree of life showing relationships of animals that have adapted to cold environments, or not. In the "bird branch," some ducks and penguins thrive in cold environments. In the insect branch, some Icelandic midges, and high-altitude bees can fly in freezing conditions. In the plant branch, species survive winter by going dormant, or reducing activity. Source: (Vivera Design, Adapted by Authors 2022)

For the envelope example, we used a variety of temperature-related search words related to "how nature stays warm", including: How does nature regulate temperature, gather heat, generate heat, capture heat, absorb heat, etc. (Figure 5). The biologists helped in selecting a range of potentially relevant models to consider in subsequent steps:

Step 3 Example: Identify Biological Models Related to Envelope Functions and Biodiversity

- *Carry forward the biologized question:* How do organisms stay warm in nature?
- *Use AskNature and "biological search terms" to find biological models:* Explore biological models for the identified functional search terms (e.g., gather, reflect, generate heat, etc.). Explore the search for different functions and traits across the tree of life (evolutionary time) and for different biomes (evolutionary space).
- *Document many biological models:* Organize select biological models using screen captures images, words, etc.

3.4 Step 4: Select Biological Models & Abstract Biological Strategies - Function, Biodiversity & Evolution

After generating a list of possible biological systems to consider with respect to the design challenge, the next step is to move from the list of design criteria and identified biological models to the ones that are most appropriate for more detailed study and application (Figure 7). The first step is to consider whether any are a better match to the challenge. This may be a question of scale, materials, or the fit of the analogy. For instance, physical properties often play out differently at nano scales versus macro scales and moving from one scale to another is not possible – in which case a different biological system that matches the scale of the application (e.g., nano to nano or macro to macro). In other cases, the physical properties of the materials need to match, for instance, when filtering air in an application, some aspects of water filtration may apply, but looking at air filtration may be more relevant to the design inquiry.

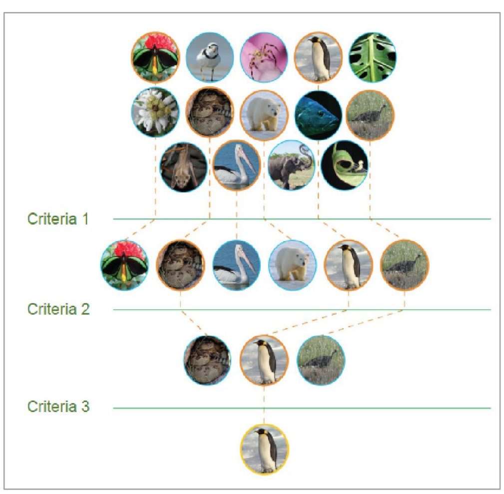


Figure 7: Step 4 Example: Selection of biological models and narrowing of models based on design criteria (how nature regulates temperature to stay warm). Source: (D. Banker, Research Assistant 2022)

The next step is to consider the range of functions that apply to a biological system and determine how these may relate to tradeoffs associated with the traits that support the functions. Most biological traits do more than one thing for the organism. A butterfly wing may absorb light and heat to rapidly waft pheromones to attract a mate, but it also repels water and permits flying. In some cases, evolutionary selection in one context may constrain how selection in another context operates and the trait may not be "optimized" for the function a designer is most interested in. For instance, the heat-absorbing function of the butterfly wing would presumably be of more interest to the designer than would the dispersion of pheromones (Snell-Rood and Smirnoff 2023, in review).

Once the biological systems being studied for inspiration have been narrowed, the next step is to delve deeper into the biological literature. In many of the biological sciences, researchers work to generate a mechanistic model, or working hypothesis, that relates "trait form to function". In other words – can we draw a diagram of how the trait works (Table 1)? In many cases, we understand how a biological trait works, and it's just a matter of finding it in the literature. For instance, the basic model for a bird beak crushing a seed is a lever system imposed on a bird skull. Other adaptations in terms of internal beak structure or skull shape are often layered on top of this basic understanding. Here, the designer might draw a diagram of a lever system that is moderated by other adaptations in the system and use this as the abstraction for the biological strategy. In some cases, it may be obvious that a trait is related to some function of interest, but as we learn more, we realize that it is not completely understood just how that trait works. In this case, the abstraction of the biological strategy may currently be a "best guess" or simply in need of more study, in which case the designer may opt to move on to a new system, or perhaps partner with a biologist to study the trait in more detail.

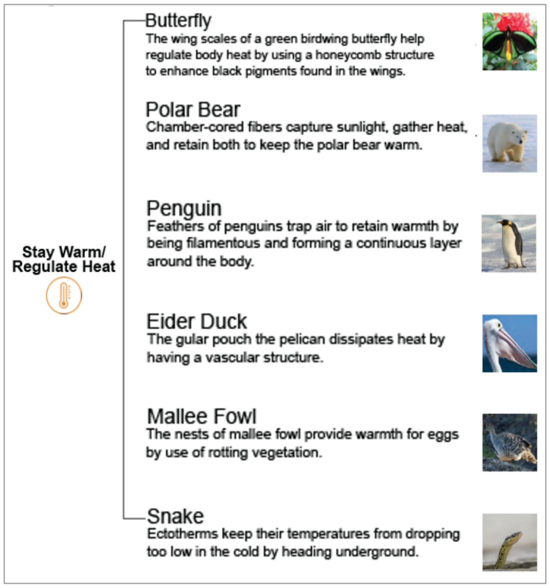


Figure 8: Step 4 Example: Six biological models to study in detail based on design criteria. Source: (D. Banker, Research Assistant 2022)

In the envelope example, Figures 7 and 8 illustrate the process of moving from "many to one" for the biological model. The biological traits and mechanisms used to stay warm were studied for six species and eventually narrowed to one species (the emperor penguin). The biologists selected the top six models and recommended the emperor penguin because the problem (dealing with cold) and the scale (macro versus nano) match the design challenge. In addition, multiple adaptations in the penguin to an extremely cold climate are well understood and studied sufficiently to provide the detail necessary to abstract biological traits of the penguin into design strategies.

The biological mechanisms and traits that provided warmth were further researched. In addition to function and biodiversity, evolution was considered in how the biological traits respond to varying environmental and behavioral conditions. A detailed investigation of the feathers and wings of the emperor penguin was developed and translated into conceptual design ideas. Table 1 provides an example of the process used to clarify the functions, traits, and mechanisms used by the emperor penguin's feathers and wings to stay warm. Based on these strategies, envelope design concepts were developed. The steps below describe the process used to curate and abstract the biological strategies for design.

Step 4 Example: Curate and Abstract the Biological Strategies to Inform Design

- *Evaluate the strategies of select biological models based on design criteria and function, biodiversity, and evolution:* Evaluate the biological models from Step 4 based on the identified design challenge and problem (staying warm). Identify the biological traits and mechanisms to achieve the function (staying warm). Consider functions across different species in the tree of life (evolutionary time) and different biomes (evolutionary space).
- *Select and organize biological models for design:* Select the most relevant biological models from Step 4 and translate into the design process (example Table 1). Consider different biological lenses (form, process, system, and materials). Use diagrams, sketches, narrative texts, or other means to identify and organize the biological strategies to inform and translate into conceptual design scenarios in the next step (Figure 9).

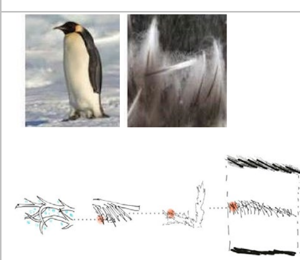
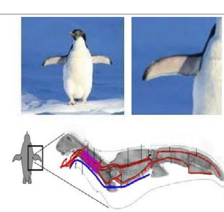
Biological Model	Biological Mechanism: How the trait works to accomplish the function	Diagrams	Envelope Design Translation
EMPEROR PENGUIN TRAIT: FEATHERS **FUNCTION: Protect from temperature**	AskNature: https://asknature.org/strategy/feathers-trap-air-to-provide-warmth/ ● Dynamic feathers: regains loft after compression. Short stiff feathers evenly packed across surface. ● Outer "pennaceous" (vane region) and "downy" inner 'after-feather. ● Moveable: muscle attached to compress under water or make feathers erect on land. ● Overlapping vanes (like overlapping tiles) ● Deeper insulating layer: "barbules" with "cilia"; attachment to neighboring barbules – move in one direction; mechanisms interact; "still air space". "After feathers" trap air.	 https://asknature.org/strategy/feathers-trap-air-to-provide-warmth/	**Cold Climate Envelope Concepts** Winter (stay warm) ● Key ideas: adjustability; compression-expansion (cellular layers that change for different functions for light, temperature, heat-cool, etc.); interlocking layers, tiles, air; dynamic movement of "cladding". ● Layers outside and inside envelope; seasonal tuning.
EMPEROR PENGUIN TRAIT: WINGS vascular system – heat exchange **FUNCTION: Protect from temperature**	AskNature: https://asknature.org/strategy/wings-reduce-heat-loss/ ● Flipper: humeral arterial plexus, vascular countercurrent heat exchanger (CCHE). ● Water below core body temperature; hypothermia threat; avoid by flow of heat along the wing. ● Brachial artery splits into two arteries. Each humeral artery is associate with two or more veins to form a countercurrent heat exchanger (CCHE). https://royalsocietypublishing.org/doi/10.1098/rsbl.2010.0993	 https://fossilpenguins.wordpress.com/2010/12/01/penguins-	**Cold Climate Envelope Concepts** Winter (stay warm) ● Key ideas: heat-cold heat exchange (passive or active; air and/or hydronic system) ● Passive: double envelope (gather expel heat). ● Active: Hydronic systems; integrate heating and cooling.

Table 1: Step 4 Example: Curation and abstraction of the mechanisms of the emperor penguin's feathers and wings. Source (Authors 2022)

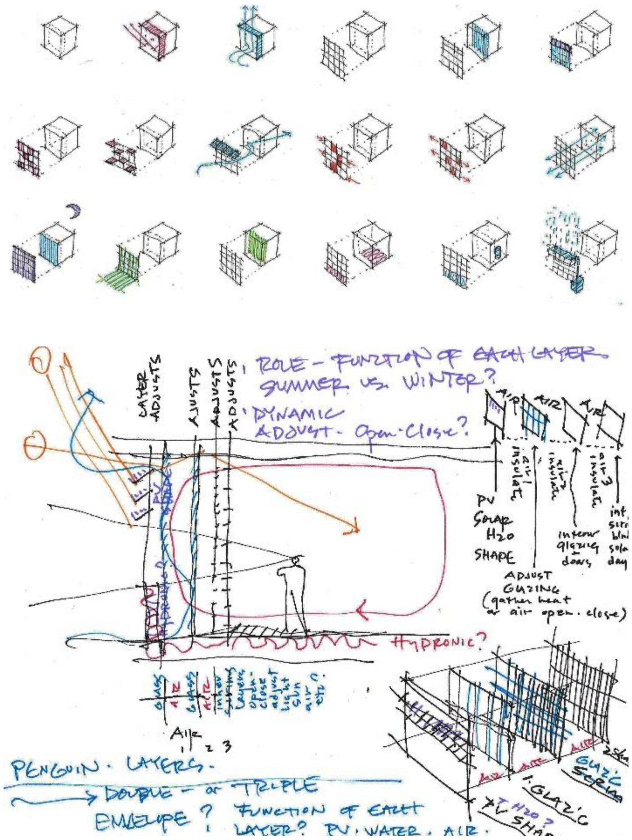


Figure 9: Step 5 Example: Translating conceptual design ideas from the emperor penguin's feather and wing attributes to a cold-climate south-facing building envelope. . Source: (Authors 2022)

1) Exterior adjustable screen: Structural grid to accommodate a selection of seasonally adaptable layers (photovoltaics, light shelves, active solar hydronic, solar hot water, shading, etc.).

2) Double envelope: Operable exterior and interior glazing to seasonally admit or block daylight, solar radiation, natural ventilation with adjustable screen inside the envelope to absorb or reflect light, heat, air.

3) Interior adjustable screen: Comprised of select materials to fine tune daylight, thermal, privacy, views, etc. Seasonally modify the amount of light, solar gains, and air. Hydronic heating and cooling.

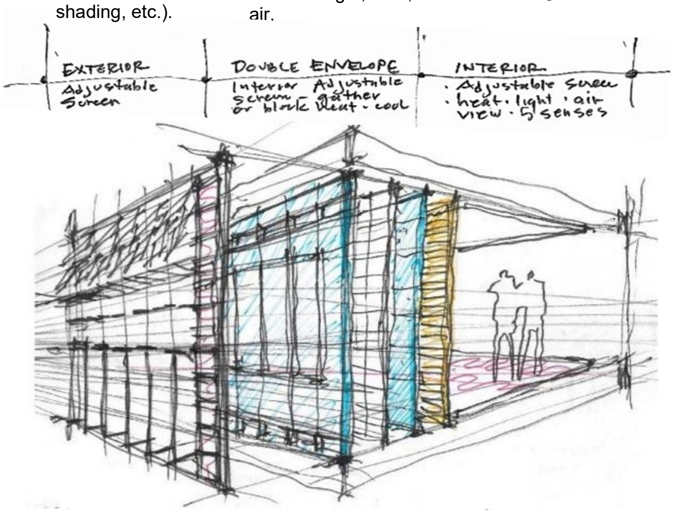


Figure 10: Step 6 Example: Conceptual design for a cold-climate south-facing building envelope based on the emperor penguin feathers (three adjustable grids) and wings (heat exchange with passive double envelope and active hydronic system). Three layers are described above. Source: (Authors 2022)

3.5 Step 5: Translate to Design - Function, Biodiversity & Evolution

Working from the understanding developed in the exploration of biological models, the next step is to develop conceptual design diagrams that address the design challenge. The design solutions will vary based on the types of traits selected while moving from biology to design application. It is necessary to consider the translation of biological traits related to form, process, system, and material from a variety of perspectives, asking the question: How are these traits architectural? For example, a form-based trait will influence the design configuration and massing. A system-based trait will consider the larger context defined by relationships amongst the components. A material-based trait will inform the physical matter such as structure and details.

In the cold-climate, south-facing envelope example, the penguin feathers informed exploration of multi-functional adjustable louvers (feathers) combined with a double envelope integrated with passive and active heating and cooling systems (wing heat exchanger) (Figure 9). Concepts of iterative change (evolution), time, seasons, and dynamic response to environmental conditions were considered for passive solar heating and daylighting performance and comfort in winter. The steps below describe the biology-architecture translation process.

Step 5 Example: Translate Biological Models into Conceptual Design Strategies

- *Translate functions, traits, and mechanisms for design based on criteria:* What are the essential biological functions or traits to translate from biology into design? Consider form, process, system, and material translations.
    - What biological attributes need to be translated (essential, accurate, relevant)?
    - Be careful not to limit the design exploration by literal translation or what already exists. Explore new design models.
- *Bio-inspired design charette*: Create iterative concept designs using images, sketches, diagrams, and notes. Revisit essential biological concepts in the scenarios to expand design thinking and translations.

3.6 Step 6: Test in Context, Repeat as Needed, Integrate - Function, Biodiversity & Evolution

The sixth step revisits the original design challenge to clarify the design intentions and to refine design criteria to evaluate conceptual design scenarios. Develop a prototype and use it to refine, through iterations and explorations, the relationships and impacts across scales. Consider how the solutions interact with real world conditions, as well as how the solutions impact other design issues. The iterative design process can be repeated as needed with parallel questions (how nature cools in summer) and other related issues (envelope design for lighting, moisture, energy performance, etc.). Conceptual design scenarios can be further developed through the lens of select design and performance metrics.

In the cold-climate, south-facing envelope example, the attributes of the penguin feathers and the vascular system of the wings informed a layered and integrated passive-active hybrid approach to the conceptual design (see Figure 10 and following discussion).

First, the feathers inspired the concept of three adjustable louvered structures from outside to inside (Figure 10):
1) An exterior adjustable screen (to provide a range of functions that might include integrated shading, solar control, lightshelves, photovoltaics, rainscreen, active solar collectors, rain collection, etc.), 2) A double envelope with operable interior and exterior glazing with an adjustable interior screen (to further modify material attributes seasonally or diurnally to absorb or reject heat, light, air, etc.), and 3) An interior adjustable screen (to fine tune views, sound, sensory experiences, privacy, biophilic connections, etc.).

Second, the penguin wings and vascular system (heat exchanger) informed the conceptual development of a double envelope for seasonal passive heating and cooling integrated with active hydronic solar heating (Figure 10). Developing and testing this concept design requires further exploration of seasonal strategies for staying cool, including the integration of natural ventilation, solar control, and daylighting with passive and active strategies for winter. The designer would then repeat the bio-inspired design process, for instance studying how birds stay cool during the summer in part by holding their feathers in ways to trap less air or incorporating butterfly-wing-inspired structural materials that would absorb more warmth during the winter. The steps below illustrate the conceptual design process.

Step 6 Example: Revisit Design Challenge

- *Evaluate conceptual designs based on design criteria:* Identify most-promising design scenarios based on design criteria. Further develop scenarios based on design and performance criteria across time and seasons.
- *Revisit larger questions (broad vs narrow):* Repeat iterative process for parallel questions and integrate: How does nature stay cool, how does nature illuminate, stay dry, respond to dynamic conditions, etc.?
- *Repeat parallel design iterations:* Determine which design concepts to develop and integrate across seasons and/or other design considerations.
- *Select scenarios for evaluation:* Move forward with select scenarios to evaluate using qualitative and quantitative design criteria, assessment tools, and metrics.

4.0 CONCLUSIONS

This six-step bio-inspired design process, with integrated biological concepts from evolutionary biology and ecology, can inform architectural design thinking in the following ways:

1. *Expand Design Perspective*: The collaboration with biologists, and the integration of biological models from the emperor penguin's feathers and wings opened unexpected ways of thinking about three seasonably adjustable layered screens (multiple functions) and integration with a double envelope (passive and active heat exchange). As architect Jim Lutz, design advisor stated: "I have never thought of design in this way and in what I can learn from other species." The concepts and six-step process are useful in challenging and expanding how to abstract and translate specific biological strategies based on design criteria. The biological concepts connect the design exploration to tangible biological phenomena.
2. *Practice Design Humility*: The Biomimicry Institute's *AskNature* tool and curation of biological models (species selection) with biologists revealed brilliant and awe-inspiring strategies that other species use to stay warm. Exploring biologically diverse models and different biomes illustrates that there are many approaches to the same problem or design challenge. Introduction to and exploration of the tree of life reminds designers that humans are just one of many species.
3. *Employ a Tangible Process*: The six-step process provides an organized structure to move back and forth between the design and the biological realms. As an iterative process, parallel questions need to be investigated and integrated. This bio-inspired design process asks designers to shift from seeing architecture as an "object" to exploring architecture as a "verb" and a "process": what is the design element doing and what is its function (program, performance, experiential, aesthetic, time, seasons, adaptability, etc.).
4. *Next Steps*: The first phase of design research explored collaboration with biologists, integration of select biological principles, and testing with a simplified bio-inspired design process. The next step of the research will include testing the conceptual design process with students in architecture and biology during the coming academic year. Future studies will develop evaluation criteria and processes to assess design scenarios, including: 1) Evaluation of the performance related to the design challenge (regulation of temperature based on bioclimate; diurnal and seasonal thermal comfort; user control, satisfaction, etc.), 2) Criteria and performance metrics for sustainability and resilience (bio-inspired is not necessarily sustainable), and 3) Biological effectiveness (this may be a question of scale, materials, or the fit of the analogy). Finally, does the proposal represent the essential principles and attributes of the biological model?

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