PDH Academy

AN edcetera CO

BIOMIMICRY AND REGENERATIVE DESIGN

Course # AIAPDH275
4 LU | HSW Hours

BIOMIMICRY AND REGENERATIVE DESIGN

FINAL EXAM (25 QUESTIONS)

1. **What is Biophilic Design?**
   A. Design that focuses on ignoring human well-being by incorporating toxic elements that harm the natural environment.
   B. Design that focuses on improving human well-being by incorporating natural elements into the built environment.
   C. Design that focuses on decreasing human well-being by incorporating unnatural elements into the built environment.
   D. Design that focuses on the psychological destruction of human well-being by incorporating deadly elements into the built environment.

2. **What is Biomimicry?**
   A. Using systems found in nature to design more efficient and sustainably built environments.
   B. Using systems found in nature to design more inefficient and unsustainable built environments.
   C. Using systems found in space to design inefficient and unsustainable built environments.
   D. Using systems found in the earth's core to design more inefficient and toxic built environments.

3. **Which is an example of implementing Biophilic Design?**
   A. Designing an interior space with no windows.
   B. Incorporating indoor plants and natural wood into a main lobby.
   C. Designing an interior one-story lobby with artificial daylighting only.
   D. Incorporating a faux skylight in an interior lobby with no daylight.

4. **Which is an example of Biomimicry?**
   A. Designing a building with design elements modeled after a pinecone or termite mound.
   B. Designing a standard HVAC system.
   C. Incorporating indoor plants and natural wood into a main lobby.
   D. Incorporating earth color toned finishes into the design.

5. **What is the 3rd step of the 4-Step Biomimicry Thinking Flowchart that AEC professionals can use?**
   Step 1: Define the Challenge
   Step 2: Emulate Nature's Strategies
   Step 3: ____________________
   Step 4: Evaluate and Refine
   A. Contact a Biomimicry specialist
   B. Apply the Strategy
   C. Repeat Steps 1 & 2
   D. There is no Step 3

6. **What is the 4th principle of the 6 Biomimicry Life's Principles?**
   1) Evolve to Survive 2) Adapt to Changing Conditions 3) Be locally attuned and Responsive 4) __________ 5) Be Resource Efficient 6) Integrate Development with Growth
   A. Use toxic chemicals sparingly
   B. Use life-friendly chemistry
   C. Destroy all natural life
   D. Development supersedes natural habitats

7. **What are the Biomimicry Life's Principles?**
   A. There are 6 principles
   B. Design lessons from nature
   C. Design lessons from Brutalism inspired architecture
   D. Design principles that focus on the earth tone colors

8. **How many Biomimicry Life Principles were there originally?**
   A. 15
   B. 11
   C. 9
   D. 300

9. **Who are the co-founders of Biomimicry?**
   A. Oprah Winfrey and Henrietta Lacks
   B. Alma Levant Hayden and Beth A. Brown
   C. Janine Benyus and Dr. Dayna Baumeister
   D. Patrick Mahomes and Travis Kelce

10. **What is available to AEC firms and practitioners to show a deeper understanding of Biomimicry?**
    A. Nothing exists to date
    B. Toxic Chemical Use certification
    C. Certified Biomimicry Professional Program
    D. International Housefire Code

11. **What is Wolff's Law?**
    A. The idea that natural healthy bones will not adapt and not change to adapt to the stress that it is subjected to.
    B. The idea that natural healthy skin will adapt and change to adapt to the stress that it is subjected to.
    C. The idea that natural healthy bones will adapt and change to adapt to the stress that it is subjected to.
    D. The idea that when the body breaks down old bone faster than it can create new bone.

12. **What are diatoms used in?**
    A. Batt insulation
    B. Ultra-high-performance concrete (UHPC)
    C. Treated 2x wood
    D. Spray foam

13. **Where was the first UHPC bridge located?**
    A. USA
    B. Africa
    C. Canada
    D. South America

14. **What do Frank Lloyd Wright's columns in the Johnson Wax Building resemble?**
    A. Tree Trunks and Branches
    B. Ripples of the Water
    C. Rays of the Sun
    D. Grains of Sand

15. **Where was the world's first 3D-printed stainless-steel bridge located?**
    A. USA
    B. South Korea
    C. The Netherlands
    D. Namibia

16. **Which is NOT the AEC Translations(s) for a Lotus Leaf and its ability to remain spotless?**
    A. Self-Cleaning Facades
    B. Water-Repellant Membranes
    C. Windshield Wipers on a Car
    D. Self-Cleaning Roofs

17. **Regarding Mangrove trees, what principle(s) do they embody?**
    A. Quality sound absorption
    B. Filtration of saltwater through specialized root structures
    C. Colorful root system
    D. Low Reverberation

18. **Which fruit possesses principle(s) that would work well in a dry-arid climate?**
    A. Pineapple
    B. Apple
    C. Plum
    D. Kiwi

19. **What animal produces silk that showcases the principle(s) of tensile strength?**
    A. Moth
    B. Spider
    C. Black Panther
    D. Cheetah

20. **Which existing building condenses atmospheric moisture similar to the Namib Desert Bettle for storage and distribution to rural areas?**
    A. Tuskegee University Chapel
    B. Terminal One at LAX
    C. Warka Water Towers
    D. Unity Funeral Home

21. **What is a Mashrabiya screen?**
    A. Proprietary guardrail
    B. Intricate, latticed wooden screens common in African architecture
    C. Intricate, latticed wooden screens common in European architecture
    D. Intricate handrail system

22. **What makes Khoo Teck Puat Hospital unique from a Biomimicry standpoint?**
    A. Designed to be locally attuned and responsive to its surrounding environment
    B. Built in Singapore
    C. Branding logo
    D. Designed to be shaped like an acorn

23. **What natural model did Eastgate Centre follow?**
    A. Shark Fins
    B. Termite Mounds
    C. Mollusk Shells
    D. Octopus

24. **The Harbin Opera House insulation system mimics what animal or natural model?**
    A. Penguin Feathers
    B. Turkey Legs
    C. The eye of a newt
    D. Grasshopper

25. **What would the AEC Translations(s) be for an Abalone shell?**
    A. Blast-resistant panels
    B. Plate Glass
    C. EIFS/Stucco
    D. Washi Tape

END OF FINAL EXAM

BIOMIMICRY AND REGENERATIVE DESIGN

Course Summary

This 4-hour LU/HSW course introduces AEC professionals to biomimicry as a nature-inspired design methodology, using real-world examples to show how natural strategies can be applied to create regenerative, high-performance buildings that enhance sustainability, resilience, and overall occupant well-being.

Learning Objectives

1. **Differentiate** the human-centric goals of Biophilic Design from the technical process of Biomimicry and Apply the Biomimicry Thinking methodology to multiple AEC-related exercises.
2. **Identify** existing natural systems that are being developed into advanced solutions for structural optimization and passive climate control.
3. **Identify** existing natural systems that are being developed into advanced solutions for water management and material surface science.
4. **Identify** and Understand buildings with integrated biomimetic strategy and regenerative performance.

Course Structure

- ✓ **PART 1 –** The Foundations: From Biophilic Goals to Biomimicry and its History
- ✓ **PART 2 –** Biomimicry in Structure and Thermal Systems
- ✓ **PART 3 –** Biomimicry in Water Management and Material Surface Science
- ✓ **PART 4 –** Real World Examples of Integrated Biomimetic Strategy and Regenerative Performance in the Built Environment

BIOMIMICRY AND REGENERATIVE DESIGN COURSE

PART 1 – THE FOUNDATIONS: FROM BIOPHILIC GOALS TO BIOMIMICRY AND ITS HISTORY

Learning Objective No. 1: Differentiate the human-centric goals of Biophilic Design from the technical process of Biomimicry and *Apply the Biomimicry Thinking methodology to multiple AEC-related exercises.*

Before we get started let's differentiate between biophilic design and biomimicry.

Biophilic design *improves the building for the occupants*

and

Biomimicry improves the performance of the building in relation to the environment and indirectly also for the occupants. Let's investigate both in more detail and specificity.

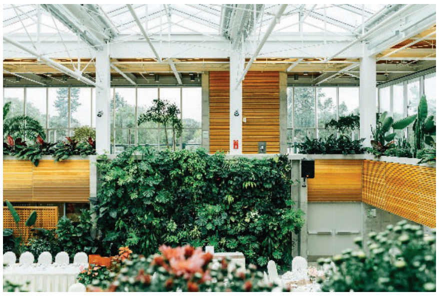

Figure 1.1. – Example of Biophilic Design. © Scott Webb, Pexels.com

Biophilic Design:

Biophilic Design focuses on improving human well-being by incorporating natural elements, patterns, and experiences into the built environment.

Biomimicry:

Biomimicry uses nature's systems, structures, and strategies as technical models to design more efficient, sustainable, and high-performing solutions for the built environment.

Figure 1.2. – Example of Biomimicry. © Rick Otten, Pexels.com

The differences between both can be found below:

Differences between Biophilic Design and Biomimicry

BIOPHILIC DESIGN	BIOMIMICRY
Human-centric approach focused on improving occupant (human or animal) health, well-being, and emotional connection to nature.	Technical, problem-solving approach focused on copying or mimicking nature's strategies to improve performance, efficiency, or structure typically within the built environment.
Enhances comfort, mood, productivity, and stress reduction through natural elements.	Enhances function, performance, durability, and sustainability of buildings, et. cetera by emulating biological systems.
Uses nature for an experience (sunlight, plants, natural materials, views, water).	Uses nature for solutions (structural forms, materials, energy systems, airflow patterns).
Aims to create spaces where humans feel at peace and function better.	Aims to create products, buildings, or systems that work better by mimicking nature's mechanisms that have withstood the test of time.
Focuses on sensory and psychological benefits — color, texture, pattern, smell, touch, views, sounds.	Focuses on mechanical, structural, and environmental optimization, strength, self-cleaning, cooling, efficiency.
Involves design choices like incorporating natural light, greenery, organic shapes, and natural materials into a space.	Involves studying nature and applying scientific principles, like termite mounds for ventilation or lotus leaves for self-cleaning surfaces.
Concerned with how people feel inside a space. Mental health.	Concerned with how a building or system performs or behaves.
Mainly used by architects, interior designers, and planners.	Used by architects, engineers, product designers, and material scientists.
Goal: Human wellness + emotional connection to nature.	Goal: Technical innovation + efficiency inspired and then guided by nature.
Example: Adding indoor plants, natural wood wall paneling or flooring, water features, and daylighting.	Example: Designing a façade modeled after a pinecone, or an HVAC system modeled after termite mound cooling.

Biophilic Design:

Biophilic design focuses on creating environments that connect building occupants with nature, promoting well-being, healthy surroundings, creativity, serenity, and productivity.

Figure 1.3. – Biophilic design promotes peace. © Yan Krukau, Pexels.com

It's centered on improving the *quality of life* for occupants through natural elements and patterns. Through the lens of architecture, this means your end-user feeling at peace and calm in a very high pressure and high stress environment or at the very least having a space to retreat to, to re-center their thoughts.

Key Biophilic Design Goals:

1. **Psychological Well-being:** Improve the mental and emotional health of building occupants through nature-inspired designs, which lends itself to a reduction in stress.
2. **Connection to Nature:** Foster a sense of direct or indirect connection to natural elements (i.e. plants, water features, natural light, wind). Through the lenses of architecture this can be achieved by incorporating interior gardens, ivy on exterior walls, fountains, access to an abundance of natural light, et. cetera into the design.
3. **Enhanced Productivity:** Design environments that improve cognitive function, nurture and increase creativity, and reduce stress and increase mindfulness.
4. **Aesthetic Engagement:** Integrate natural forms (*think Zaha Hadid and the use of curves, as there are no truly straight lines in nature*), colors, and textures to create visually stimulating and calming spaces.
5. **Biodiversity:** Encourage a seamless and harmonious relationship between natural and built environments, enhancing ecosystem services. A really great example of this is SoFi stadium in California.

> **"...When it came to academic results, the students in the biophilic classroom experienced 3.3x the average test score gain compared to the control students. At the end of the seven-month study, 7.2% more students in the biophilic classroom tested at grade level than control students..."** – **Spaces4Learning**

THE HISTORY OF BIOMIMICRY

Timeline

- **1997 –** The origin of Biomimicry and its life's principles was the culmination of twenty plus years of work by biologists, biomimics, and designers.
- **1998 –** Janine Benyus and Dr. Dayna Baumeister co-founded the Biomimicry Guild as an innovation consultancy.
- **2006 –** Janine Benyus co-founded The Biomimicry Institute with Dr. Dayna Baumeister and Bryony Schwan
- **2008 –** Biomimicry Institute launched AskNature.org, "an encyclopedia of nature's solutions to common design problems"
- **2010 –** Biomimicry 3.8 is formed and offers consultancy, professional training, development for educators, and "inspirational speaking"

Co-Founders of the Biomimicry Movement

Janine Benyus

Authored *Biomimicry: Innovation Inspired by Nature (1997)*, which developed the following thesis that human beings should consciously emulate nature's genius in their designs. She encourages people to ask, ***"What would Nature do?"*** and to look at natural forms, processes, and ecosystems in nature to see what works and what lasts

- Coined the term "Biomimicry" to describe intentional problem-solving design inspired by nature
- President of Living Education, a nonprofit dedicated to place-based living and learning

Figure 1.3.1. – Janine Benyus © Heinzawards.org

"After 3.8 billion years of research and development, failures are fossils, and what surrounds us is the secret to our survival."
– Janine M. Benyus

Dr. Dayna Baumeister

- Designed (and continues to teach) the world's first Certified Biomimicry Professional Program, an in-person, 2-year master level course that trains, certifies, and connects biomimicry professionals with practitioners world-wide
- Co-designed the Biomimicry Specialist Program
- Senior editor of Biomimicry Resource Handbook: A Seed Bank of Knowledge and Best Practices (2014)

Figure 1.3.2. – Dr. Dayna Baumeister © sustainabilityleadersnetwork.org

Originally there were 9 principles, which were described in "*Biomimicry: Innovation Inspired by Nature*".

The original 9 principles are listed below:

Original 9 Principles

1. Nature runs on sunlight
2. Nature uses only the energy it needs
3. Nature fits form to function
4. Nature recycles everything
5. Nature rewards cooperation
6. Nature banks on diversity
7. Nature demands local expertise
8. Nature curbs excesses from within
9. Nature taps the power of limits

Figure 1.3.3. – "When the sun rises, the sunflower follows it loyally. Learn from the sunflower how to be true to your path."
– Lakota Proverb © Vitaliy Bratkov , Pexels.com

Current 27 Principles

The current Biomimicry Life's Principles are a set of 27 strategies that all organisms and ecosystems on Earth use for creating conditions conducive to life. The strategies are also beneficial to any organization or design.

1. Evolve To Survive A. Replicate Strategies that Work B. Integrate the Unexpected C. Reshuffle Information	4. Adapt To Changing Conditions A. Incorporate Diversity B. Maintain Integrity through Self-Renewal C. Embody Resilience
2. Be Locally Attuned and Responsive A. Leverage Cyclic Processes B. Use Readily Available Materials and Energy C. Use Feedback Loops D. Cultivate Cooperative Relationships	5. Integrate Development with Growth A. Self Organize B. Build from the Bottom Up C. Combine Modular and Nested Components
3. Be Resourceful with Material and Energy A. Use Low Energy Processes B. Use Multi-Functional Design C. Recycle All Materials D. Fit Form to Function	6. Use Life-friendly Chemistry A. Employ Elegant Processes B. Use a Small Subset of Elements C. Do Chemistry in and with Water D. Break Down Products into Benign and Useful Constituents

The 6 Overarching Biomimicry Life's Principles

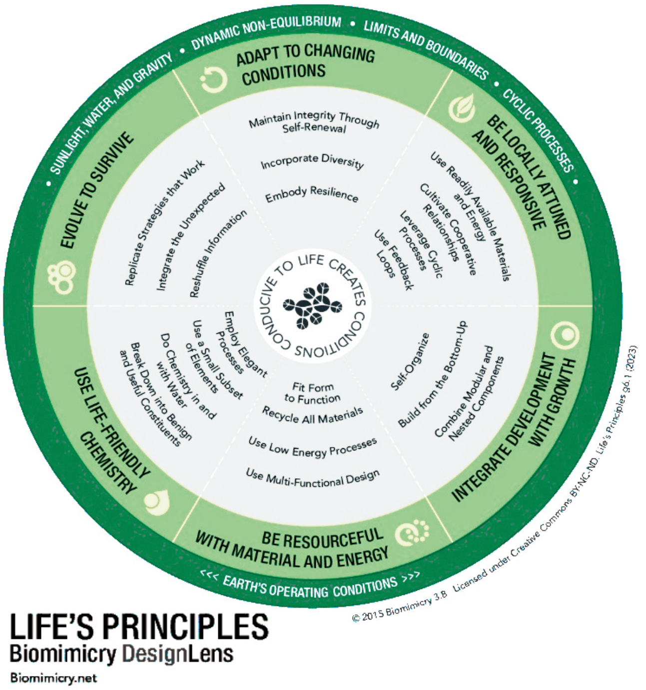

Figure 1.3.4. – 6 Life's Principles © biomimicry.net

1. **Evolve to Survive**
2. **Adapt to Changing Conditions**
3. **Be locally attuned and Responsive**
4. **Use Life-friendly Chemistry**
5. **Be Resourceful with Material and Energy**
6. **Integrate Development with Growth**

Biomimicry Methods:

Biomimicry borrows its inspiration and direction from nature's patterns, processes, and strategies in order to solve human design and built environment challenges. Biomimicry looks to nature for innovative, time-tested and lasting solutions to enhance efficiency, sustainability, and resilience in the built environment. The irony is not lost on us that we create the built environment to mimic nature when we could just exist within nature and not create a built environment – problem solved without ever creating the problem.

Key Biomimicry Methods:

1. **Learning from Nature's Designs**: Identifying natural systems and processes that can be applied to human challenges (i.e. self-healing materials inspired by biological cells).
2. **Circular or Closed-Loop Systems**: Designing circular or closed-loop systems, paralleling nature's ability to recycle waste, reduce energy consumption, and use materials efficiently.
3. **Adaptation and Resilience**: Studying how organisms adapt to their environments and using those same or similar methods to improve the built environment, for example building resilient buildings in response to climate change.
4. **Energy Efficiency**: Paralleling nature's strategies for energy exchange, such as passive cooling or solar energy capture methods, which can be applied in buildings.
5. **Efficient Use of Resources**: Using minimal resources to create highly efficient systems, akin to how certain plants or animals use minimal energy for maximum output.

> "Jellyfish may be the most energy-efficient animals in the world"
> – Gizmodo

BIOMIMICRY 4 STEP PROCESS THROUGH THE LENS OF AEC

Figure 1.3.5. – Bahia, Brasil, South America © Priscila Almeida, Pexels.com

The following 4 step process is designed to smoothly transition or convert any building design challenge into a nature-based solution. The following process has been geared towards AEC professionals:

Step 1: Define the Challenge

- **Goal**: Clearly articulate the design or operational challenge. Consider the site, local materials, and the macro and microclimates.
- **Example**: How can we design a building in the semi-arid tropical climate ("BSh" per the Köppen Climate Classification System) of Caatinga, Rafael Jambeiro Municipality, Bahia (BA), Brasil, South America that reduces energy consumption and improves indoor air quality (IAQ)?

Key Question To Ask Yourself/Team: What specific problem are we solving? (i.e. energy inefficiency, poor indoor air quality, et. cetera)

Step 2: Emulate Nature's Strategies

- **Goal**: Search locally within the microclimate and then expand to the macroclimate first to learn how native elements of nature, animals, etc. survive and thrive in the climate of that local area and region. Then identify natural models, processes, or behaviors that address the design or operational challenge.
- **Example**: Look at termite mounds for natural ventilation, study how fish use hydrodynamics for energy-efficient movement in water, or how cactus adapt to arid environments for water conservation.

Key Question: Locally, what natural systems, organisms, or processes can provide inspiration? How does nature solve similar problems, more specifically the design challenge?

Figure 1.4. – Nature has all the answers.
© Chevanon Photography, Pexels.com

Step 3: Apply the Strategy

- **Goal**: Translate nature's strategy into a usable, practical design solution for the built environment.
- **Example**: Use biomimetic principles to create a passive cooling system based on termite mound ventilation, apply bio-inspired shading devices to reduce solar heat gain, or develop a water harvesting system based on cactus-like structures.

Key Question: How can we adapt this biological principle or system for use in our built environment? How does it integrate with existing and upcoming construction technologies?

Step 4: Evaluate and Refine

- **Goal**: Evaluate the impact and effectiveness of the biomimetic solution.
- **Step 4 Example**: Test how the proposed solution (i.e., natural ventilation, energy-saving design) performs in a real-world setting and refine it based on feedback, environmental conditions, and performance metrics. The findings can be used to improve the next similar building design challenge.

Key Question: Does the solution achieve the desired outcomes in terms of sustainability, performance, and user experience? What improvements can be made for the project or future projects?

BIOMIMICRY FLOWCHART (NATURE TO BUILT ENVIRONMENT)

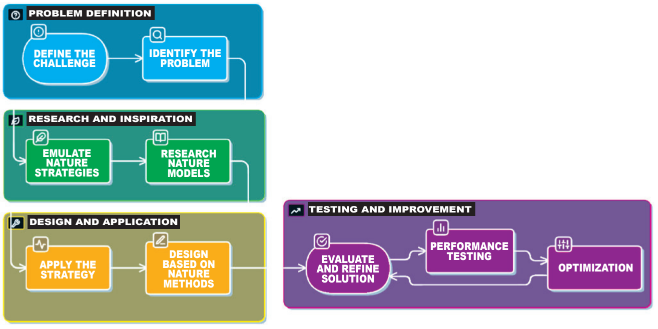

Figure 1.5. – Visual of the Biomimicry Flowchart
(Nature to Built Environment)

Key Benefits for AEC Professionals:

1. **Sustainability**: Using nature's inherent efficiency to reduce waste, energy consumption, and material usage.
2. **Resilience**: Designing with nature's proven strategies *(remember the co-founder of Biomimicry's quote above)* to increase the durability and adaptability of buildings.
3. **Innovation**: Stimulating new ideas for problem-solving by looking beyond conventional solutions to nature's time-tested systems.
4. **Cost-Effectiveness**: Reducing long-term operational costs through efficient energy use, water management, and waste reduction.

Great resources when searching for Nature-Based Solutions:

WEBSITES	DESCRIPTION
https://biomimicry.org/	**Biomimicry Institute** The Biomimicry Institute is a leader in biomimicry research. Within is a wealth of resources on how nature can inspire innovative design solutions. The Biomimicry 3.8 program offers case studies, design tools, and educational materials to help individuals and organizations learn about nature-inspired innovation.
https://asknature.org/	**AskNature** An interactive database for biomimetic innovations that gives access to thousands of nature-inspired design solutions across various industries like architecture, energy, and materials.
https://www.learnbiomimicry.com/	**Biomimicry** They work with biomimicry practitioners, influential educators, and accomplished professionals to bring forth Nature's winning strategies.

APPLYING BIOMIMICRY THINKING TO COMMON PROBLEMS OR CHALLENGES IN THE AEC INDUSTRY

Common Problem Exercise 1: Overheating of the Western façade of a structure

1. Define the Challenge (What is the problem?)

Challenge: The overheating of the western façade of a building.

Desired Outcome: The western façade must reduce heat gain, block harsh low angle afternoon sun, and maintain daylight without relying heavily on active or mechanical cooling systems.

2. Emulate Nature's Strategies (How does nature solve this?)

Research and search for organisms and elements of nature that face a similar situation (intense afternoon heat) and have strategies for rejecting, reflecting, shading, or dispersing said heat. Refer to the following examples:

- **Pinecones** that open/close depending on environmental conditions.
- **Saguaro cactus ribs** that cast self-shade throughout the day.
- **Termite mounds** that regulate internal temperature with passive ventilation.
- **Desert beetles** with reflective shell surfaces that reduce solar absorption.
- **Leaf canopies** that create layered shading without blocking wind or light.

Figure 1.6. – Nature teaches if you listen. © Nathalie De Boever, Pexels.com

3. Apply the Strategy i.e. Biology to Design (Translating biological strategies into building concepts)

Based on the organisms above, generate design solutions inspired by the mechanisms listed in Step 2:

- **From pinecones:** Design thermal-responsive shading panels that open/close based on heat or sun intensity.
- **From cactus ribs:** Design vertical or faceted fins that create self-shading on the west façade as the sun moves.
- **From desert beetle shells:** Use reflective or high-albedo façade surfaces that reject a significant portion of solar radiation.
- **From termite mound ventilation:** Incorporate passive ventilation channels or stack cooling cavities behind the façade to dissipate heat.
- **From leaf canopies:** Create layered shading screens (perforated metal, louvers, or lattice systems) that reduce direct solar gain but still allow daylight and airflow.

4. Evaluate & Refine (Does the nature-inspired solution work? How does it perform?)

Test concepts through simulations and prototypes:

- Solar studies to measure heat reduction
- Daylighting analysis to avoid over-darkening
- Wind/airflow modeling for passive cooling performance
- Constructability and cost assessments

5. Integration (Scale into a real building solution)

Combine the most effective biological strategies into a cohesive façade system, for example:

A western facing façade with angled cactus-like fins paired with reflective coatings (mimicking the desert-beetle) which creates passive airflow channels, creating a highly efficient biomimetic envelope that cools itself naturally.

In Summary

By studying how nature and its creatures reflect, shade, or ventilate against intense afternoon heat along the Western facade, it is possible to find a solution using the following:

- self-shading through thermal-responsivity (cactus)
- reflectivity (desert beetle)
- and passive ventilation (termites)

all of which dramatically reduces heat gain in the interior space of a structure placed along the Western facade.

Common Problem Exercise 2: Heat Island Effect

Figure 1.7. – Heat Island Effect Can Increase Energy Costs up to 30%.
© Dar ius, Pexels.com

1. Define the Challenge (What is the problem?)

To reduce energy costs and energy consumption along with associated emissions, illness and death due to heat island effect (some areas experience temperature increases of up to 15-20 degrees Fahrenheit versus vegetated areas).

> **"Numerous studies have linked extreme heat with illness and death among vulnerable populations such as older adults, very young children, and people with respiratory illnesses. Extreme heat can also damage essential services such as transportation and energy systems and reduce productivity." – RFF.org**

The goal is to reduce ambient temperatures in urban areas, cool surfaces, increase shade, and improve airflow to make the city more comfortable and energy efficient.

2. Emulate Nature's Strategies (How does nature solve this?)

Research and find in nature, organisms or ecosystems that stay cool in hot environments or manage heat efficiently, such as:

- **Termite mounds** – maintain stable internal temperatures despite extreme heat outside.
- **Mangrove Forests** – reduce surface heat through shade and water evaporation. *(Refer to Figure 1.8 below)*
- **Lotus leaves** – repel heat and water through reflective surfaces.
- **Desert plants (succulents, cacti)** – store water and reduce surface heat through reflective textures and orientation.
- **Urban trees and forest canopies** – provide shade and facilitate evaporative cooling.

3. Apply the Strategy i.e. Biology to Design (Translating biological strategies into building concepts)

From termite mounds:

Incorporate into the design ventilation corridors (learn about Stuttgart's ventilation corridors in Germany), open courtyards, and building layouts to promote airflow and dissipate heat.

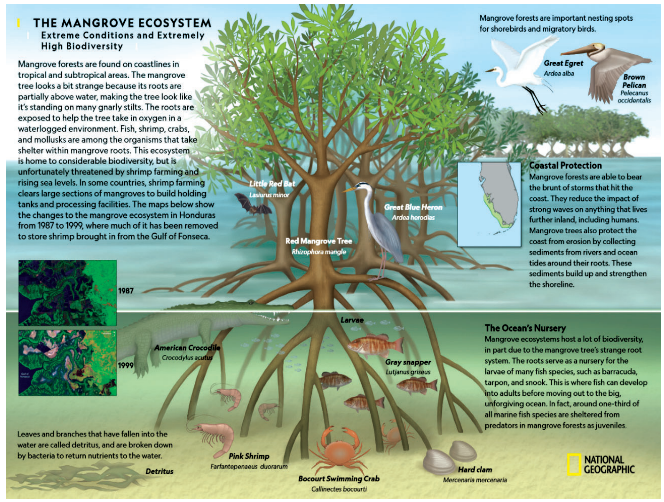

Figure 1.8. – The Mangrove Ecosystem.
© National Geographic, https://education.nationalgeographic.org/resource/the-mangrove-ecosystem/

From mangrove forests:

- Introduce water features such as fountains, and wetlands that cool surrounding areas through evaporation.

From lotus leaves:

- Utilize high-albedo surfaces (i.e. a surface that strongly reflects sunlight and has low absorption), this can be placing reflective materials on roofs, pavements, and facades to reflect solar radiation.

> **"...To determine the ideal implementation of cool pavements in Boston and Phoenix, researchers investigated the life cycle impacts of shifting from conventional asphalt pavements to three cool pavement options: reflective asphalt, concrete, and reflective concrete..." – MIT.edu**

From desert plants:

- Implementation of green roofs, vertical gardens, and shading elements to store less heat and reduce surface temperature.

From urban trees/forests:

- Expand street trees, green corridors, and parks to provide shade and promote evapotranspiration cooling. This contributes to the "ventilation corridors" mentioned above.

4. Evaluate & Prototype (Test the strategies)

- Model urban heat reduction using thermal simulations.
- Measure shade coverage, airflow patterns, and reflective efficiency.
- Test combinations of green infrastructure, reflective materials, and water features for maximum cooling impact.

5. Evaluate & Refine (Does the nature-inspired solution work? How does it perform?)

Combine strategies for a holistic Urban Heat Island (UHI) mitigation approach:

- Tree-lined streets + green roofs + reflective pavements + water features + optimized building orientation. This mimics how nature manages heat while creating healthier, cooler urban environments.

Figure 1.9. – Mangrove forest in its natural habitat.
© Ksu&Eli Studio, Pexels.com

SUMMARY

By mimicking nature's strategies—trees for shade, lotus leaves for reflectivity, mangroves for evaporative cooling, and termite-inspired airflow—cities can reduce the heat island effect and create cooler, more comfortable urban environments.

COMMON PROBLEM EXERCISE 3 (FOR ENGINEERS): OPTIMIZATION OF STRUCTURAL SYSTEMS UNDER EXTREME HEAT LOADS

1. Define the Challenge (What is the problem?)

Structural systems as it pertains to structural stress, increased energy demand and overheating. The desired outcome being to reduce structural stress and maintain durability while minimizing energy demand and overheating in buildings.

2. Emulate Nature's Strategies (How does nature solve this?)

- **Termite mounds:** Maintain stable internal temperatures despite extreme external heat.
- **Cactus ribs:** Shade and self-cool surfaces naturally.
- **Desert lizards:** Use reflective and light-colored skin to reduce heat absorption.

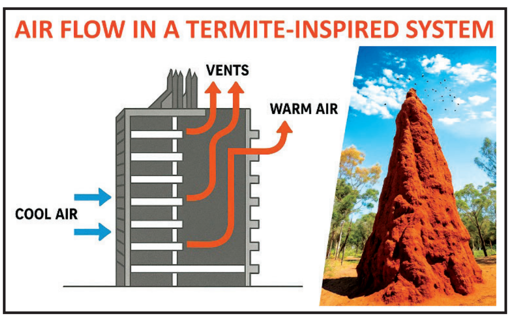

Figure 1.10. – Simplified infographic of airflow in a termite mound.
© sustainabilityglobal.org

3. Apply the Strategy i.e. Biology to Design (Translating biological strategies into building concepts)

- Integrate passive ventilation channels inspired by termite mounds into structural cavities.
- Design facade fins or structural shading elements inspired by cactus ribs.
- Use lightweight, reflective cladding modeled after desert lizard reflective skin.

4. Evaluate & Refine (Does the nature-inspired solution work? How does it perform?)

- Test thermal simulations of facades and structural elements under sun loads.
- Measure internal temperatures and material expansion to validate design.

5. Integrate:

- Implement hybrid passive cooling strategies in structural and envelope design for long-term durability and energy efficiency.

COMMON PROBLEM (FOR INSPECTORS) EXERCISE 4: IDENTIFYING SUBTLE CODE VIOLATIONS IN LOW VISIBILITY AREAS

1. Define the Challenge (What is the problem?)

The challenge is subtle violations being missed due to the lack of technology, poor visibility, distance issues, et. cetera. The desired outcome is to be able to detect hidden code violations quickly and accurately regardless of the location and environment.

2. Emulate Nature's Strategies (How does nature solve this?)

- **Owls:** Exceptional vision in low light and ability to detect subtle motion.
- **Bats:** Echolocation to detect obstacles in darkness.
- **Ants:** Systematically explore and map complex spaces and terrain efficiently.

Figure 1.11. – Owls need only 10 lux to see in an environment.
© mark broadhurst, Pexels.com

> "...Owl is developing thermal-ranging 3D sensors that, the company claims, can detect objects in any light or visibility conditions..." – Mobility Engineering Tech

3. Apply the Strategy i.e. Biology to Design (Translating biological strategies into building concepts)

1. Implement AI-assisted imaging or thermal cameras to identify hidden anomalies. (Owl)
2. Implement sonar or acoustic scanning akin to bat echolocation to detect voids or structural defects. (Bats)
3. Use systematic inspection patterns inspired by ants to ensure no space is overlooked. (Ants).

These patterns can be streamlined by investing in CMT or Construction Management Technology including defect management software. This uses cameras and drones to inspect large areas quickly and collect images for evaluation. Also executing remote inspections using digital tools like 360 degree cameras, Virtual Reality headsets, laser scanners, and thermal imaging allows for inspecting hard to reach areas or hazardous areas effectively, quickly and safely.

This also means having a process and following it, for example a typical inspection life cycle is as follows below:

1. Planning & Scheduling
2. Stage-Based Inspections
    1. Foundation
    2. Rough-In
    3. Framing/Structural
    4. Final Inspection
3. Documentation and Checklists
4. Enforcement and Follow-Up
5. Record Keeping

4. Evaluate & Refine (Does the nature-inspired solution work? How does it perform?)

- Test the detection systems on sample buildings and hidden spaces.
- Track inspection accuracy and speed compared to traditional methods.

5. Integrate:

- Combine visual, thermal, and acoustic tools with systematic workflows for efficient, thorough inspections.

COMMON PROBLEM (FOR CONTRACTORS) EXERCISE 5: MANAGING ON-SITE HEAT AND MATERIAL PERFORMANCE

1. Define the Challenge (What is the problem?)

Preventing or minimizing worker death and poor material performance in high-heat conditions. The desired outcome being to keep workers safe and alive and to maintain material performance in high-heat conditions.

2. Emulate Nature's Strategies (How does nature solve this?)

- **Camels:** Regulate body temperature to survive in extreme heat.
- **Termite mounds:** Passive cooling and ventilation strategies.
- **Lotus leaves:** Reflect solar heat to stay cool.

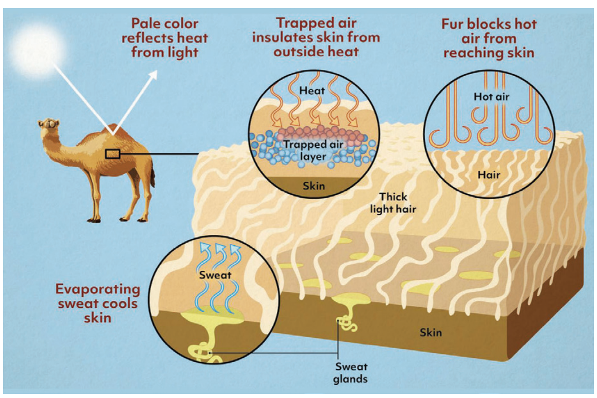

Figure 1.12. – How camels stay cool in extreme heat © Ask Nature, https://asknature.org/strategy/how-a-camels-fur-coat-keeps-it-cool/

3. Apply the Strategy i.e. Biology to Design (Translating biological strategies into building concepts)

- Provide shade structures and reflective temporary coverings inspired by lotus leaves.
- Implement natural ventilation corridors on-site inspired by termite mounds.
- Use heat-adaptive scheduling like camels resting during peak heat, shifting work hours to cooler periods.

4. Evaluate & Refine (Does the nature-inspired solution work? How does it perform?)

- Monitor on-site temperatures, worker comfort, and material quality under different mitigation strategies.

5. Integrate:

- Adopt heat-mitigating site planning, temporary shading, and adaptive scheduling for safer, more efficient construction.

PART 1 – BIOMIMICRY AND REGENERATIVE DESIGN KNOWLEDGE CHECK (5 QUESTIONS)

1. What is the primary goal of Biophilic Design?

A. Improve the performance of buildings in relation to the environment

B. Enhance occupant well-being and emotional connection to nature

C. Mimic nature's strategies for technical innovation

D. Reduce energy consumption through passive cooling

2. Which of the following best describes the goal of Biomimicry?

A. To create spaces that reduce stress and improve mental health

B. To mimic nature's strategies to improve performance and sustainability technical challenges in the built environment.

C. To enhance the aesthetic appeal of buildings through natural elements.

D. To increase biodiversity within urban environments.

3. Which of the following is an example of Biomimicry?

A. Adding indoor plants to an office space

B. Designing a façade inspired by a pinecone's ability to open and close

C. Using natural wood for flooring

D. Incorporating water features into a lobby

4. What is the key difference between Biophilic Design and Biomimicry?

A. Biophilic Design focuses on technical innovation, while Biomimicry focuses on human well-being

B. Biophilic Design uses nature for experiences, while Biomimicry uses nature for solutions

C. Biophilic Design is used by engineers, while Biomimicry is used by architects

D. Biophilic Design is concerned with building performance, while Biomimicry is concerned with aesthetics

5. **Which of the following is NOT one of the six overarching Biomimicry Life's Principles?**
   A. Be Resourceful with Material and Energy
   B. Use Life-friendly Chemistry
   C. Focus on Aesthetic Engagement
   D. Adapt to Changing Conditions

This concludes Part 1 of the course.

Let's continue to Part 2.

PART 2 – BIOMIMICRY IN STRUCTURE AND THERMAL SYSTEMS

Learning Objective No. 2: Identify existing natural systems that are being developed into advanced solutions for structural optimization and passive climate control.

BIOMIMICRY FOR STRUCTURAL EFFICIENCY

OVERVIEW

Take a moment to stop reading and look at your forearm, did you know the bones in your body have relevance to the architecture you see being structurally maintained today? Learn how below.

1. Bone & Trabecular Architecture

Natural Model

- Cortical + trabecular bone demonstrates hierarchical optimization. *(refer to Fig 2.1 below)*

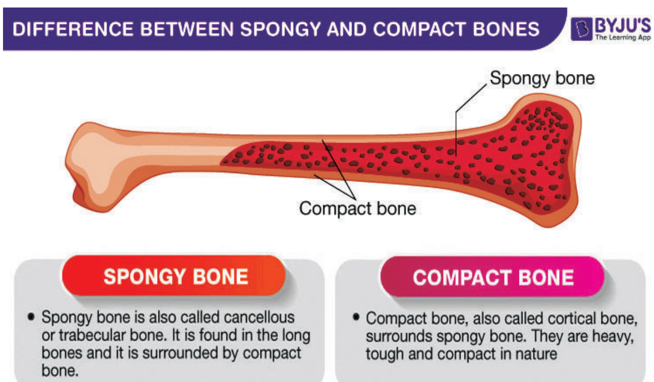

Figure 2.1. – Difference between Spongy and Compact Bones © ByJus

- Trabecular bone distributes material only where needed, following principal stress trajectories (Wolff's Law).
  - *"Wolff's Law is the idea that natural healthy bones will adapt and change to adapt to the stress that it is subjected to. For example, if the bones are subjected to heavier and heavier loads, they will naturally reconstruct themselves to accommodate that weight. This is how bones typically respond to stress." – WebMD*
- Exhibits high strength-to-weight ratio, anisotropy, and void optimization.
  - *Anisotropy* is the property where a material's physical characteristics (like strength, optical properties (think glass), etc.) change depending on the direction they are measured in.
  - *Void optimization in this context means eliminating or removing voids in engineering designs. For example, removing unnecessary materials or ensuring internal voids can be removed. Also referred to as topology optimization.*

Principle(s)

- Topology optimization
- Stress-aligned lattices
- Gradients of density: Denser material where stresses peak; lighter where stresses fall off.

AEC Translation(s)

Lighter Columns

- 3D-printed steel or concrete columns with void patterns aligned with load paths, reducing material while preserving axial capacity.
- Optimized "bone-mimetic" branching at column heads to reduce punching shear; Punching shear is what occurs when a concentrated load is applied to a small area of a slab.

Optimized Slabs

- Voided slabs with stress-mapped cellular voiding patterns (vs. uniform bubble decks).
- Ribbed slabs where rib directions follow principal bending moments.

Diagrid Systems

- Bone's stress-based anisotropy supports angle-optimized diagonals—diagrid density increases near high shear zones (i.e. building corners), decreases elsewhere. (Refer to Figure 2.2)

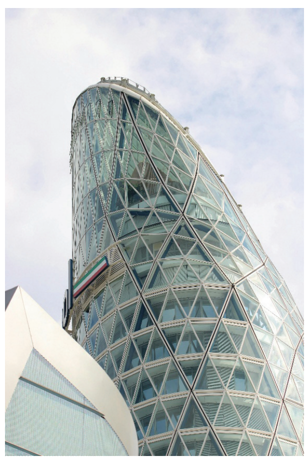

Figure 2.2. – High rise with a Diagrid Structural System located in Milano, Italia © Earth Photart, Pexels.com

Building Example(s)

a. MX3D Bridge, Amsterdam, The Netherlands

- World's first 3D-printed stainless-steel bridge.
- Structural optimization guided by stress trajectories, like trabecular patterns.
- Substantial material savings versus comparable solid steel.

b. One Airport Square, Ghana, Africa

- Diagrid facade structure uses angle optimization (a trabecular principle).
- Reduced steel tonnage + enhanced lateral resistance.

Figure 2.2.1. – Diagrid façade shown of One Airport Square in Ghana, Africa © newofficeafrica.com

Emerging AEC Application

- Topology-optimized column/beam nodes for steel diagrids.
- Biomimetic 3D-printed concrete columns.

2. Diatoms (Silica Micro-Shells)

A diatom is *"a microscopic, single-cell form of marine or fresh-water algae, having siliceous cell walls…"* – *ForensicFiles*

Figure 2.3. – Diatoms produce 20-30% of the air we breathe. © Diatoms.org

Natural Model

- Exoskeletons made of porous silica with:
  - Hexagonal micro-lattices
  - Ribbed frameworks
  - Perforation patterns for lightweighting without losing stiffness.
- Exceptional buckling resistance

Principle(s)

- Porosity-based stiffness optimization
- Perforation fields optimized for bending and shear
- Local reinforcement with minimum material

AEC Translation(s)

Lighter Façade Panels / Slabs

- Ultra-high-performance concrete (UHPC) or metal panels with diatom-inspired perforation fields optimized for bending and shear.
  - Diatoms, specifically diatomaceous earth (DE), are a natural, silica-rich material used in Ultra-High-Performance Concrete (UHPC). It replaces expensive silica fume and acts as a supplementary cementitious material to create a stronger, more durable, and eco-friendly concrete.
    - Diatomaceous earth is primarily composed of amorphous silica which are the fossilized skeletal remains of diatoms.

Figure 2.4. – You're looking at the first UHPC bridge constructed in the United States; Location: Wapello County, Iowa © FHWA DOT

- Thin-shell slab geometries with rib-like stiffeners that mimic diatom frustule ribs.

Column Jackets / Tubular Columns

- Diatom-inspired ribbed tubular forms increase Euler buckling capacity (the Euler Buckling Load formula allows you to predict the buckling load of slender columns) with minimal added mass.

Diagrid Nodes

- 3D-printed node connectors with diatom-like perforated-but-stiff geometry, reducing weight and improving fabrication efficiency.

Building Example(s)

a. Zaha Hadid Architects – "Striatus Bridge"

- Arched masonry footbridge composed of 3D-printed concrete blocks (dry stack with no mortar or reinforcement)
- Masonry blocks arranged in diatom-like compression-only geometry.
  - "Striatus is an unreinforced concrete structure that achieves strength through geometry. In arched and vaulted structures, material can be placed precisely so that forces can travel to the supports in pure compression." – ThePlan It

Figure 2.4.1. – Striatus Bridge by Zaha Hadid Architects © Photograph by Naaro, Zaha Hadid Architects

b. Al Bahar Towers Facade

- Mashrabiya shading screen replicates porous lattice mechanics.
- Reduces solar load/heat gain; Has a lightweight fiberglass structure

c. Emerging AEC Application

- Rib-stiffened Ultra-High Performance Concrete (UHPC) façade panels considerably thinner than conventional Glass Fiber Reinforced Concrete (GFRC).

3. Nacre (Mother of Pearl)

The iridescent, tough inner lining of mollusk shells

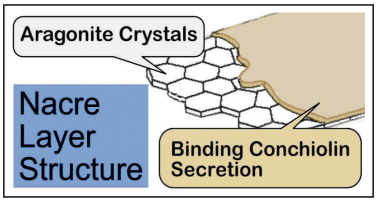

Figure 2.5. – The layer structure of the Mother of Pearl. © HERMJ

Natural Model

Made of microscopic "bricks" of a mineral called aragonite, laced together with a "mortar" made of organic material. This bricks-and-mortar arrangement gives mollusks their strength

> "…the "bricks" are actually multisided tablets only a few hundred nanometers in size. Ordinarily, these tablets remain separate, arranged in layers and cushioned by a thin layer of organic "mortar." But when stress is applied to the shells, the "mortar" squishes aside and the tablets lock together, forming what is essentially a solid surface. When the force is removed, the structure springs back, without losing any strength or resilience.
> This resilience sets nacre apart from even the most advanced human-designed materials. Plastics, for example, can spring back from an impact, but they lose some of their strength each time. Nacre lost none of its resilience in repeated impacts at up to 80% of its yield strength." – News UMich.edu

Principle(s)

- Layered composites with:
  - Hard–soft alternating layers
  - Crack-arresting interfaces
  - Distributed micro-reinforcement
- Low-weight but extremely tough.

AEC Translation(s)

> "This study explores enhancing the mechanical properties of fiber-reinforced polymer composites using a biomimetic approach inspired by nacre… The optimal configuration, with 25mm platelets, showed an 18% increase in impact strength…and a 115% increase in flexural strength…compared to monolithic laminates…"
> – Biomimetic nacre-inspired composites reinforced with glass fibers for enhanced strength

Composite Slabs

- Glass/carbon fiber reinforced polymer (GFRP/CFRP) panels with nacre-inspired layered layups, allowing:
  - Thinner slab sections
  - High damage tolerance during impact (e.g., seismic, blast, etc.)

Column Wrappings

- Nacre-patterned composite wraps that improve confinement while reducing mass compared to purely steel jackets.

Diagrid Joints

- Laminated composite joints that use brick-like micro-tessellation to spread stress and prevent sudden brittle failure.

Building Example(s)

a. HSB Turning Torso (Sweden)

- Laminated composite façade panels use toughened, layered structures to resist wind loads.
- Nacre-inspired digital lamination used in panel design.

Figure 2.6. – HSB Turning Torso by Santiago Calatrava is based on Twisting Torso, a white marble sculpture by Calatrava; Location: Malmö, Sweden

© Amjad Sheikh, Wikipedia

b. Bridge Example: FRP wrapped seismic columns

- Nacre principles used to deflect cracks and increase ductility.
- Results: Increase in energy dissipation.

c. Emerging AEC Application

- Nacre-inspired hybrid composite slabs:
  - Significantly lighter than steel–concrete composite decks
  - Increased impact resistance

4. Trees (Stem-Tapering, Branching, Reaction Wood)

Natural Model

- Trees are optimized towers:
  - Tapering trunks reduce weight while maintaining stability.
  - Branching follows stress paths and distributes loads efficiently.
  - Wood thickens where bending stresses occur.

Principle(s)

- Variable cross-sections
- Stress-adaptive geometry
- Load-path continuity

AEC Translation(s)

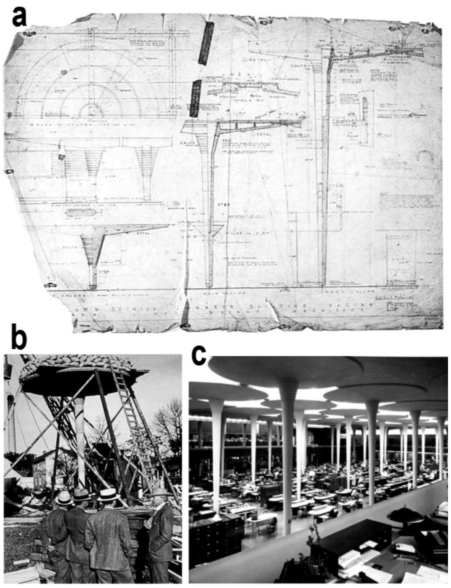

*Figure 2.7. – **(a)** Cross-section of the columns **(b)** Load testing on tubular mushroom column by F.L. Wright in 1938; **(c)** tubular mushroom columns supporting a glass ceiling, Johnson's Wax Building, 1939, by F.L. Wright (Lipman and Wright, 1986). © ScienceDirect*

Lighter Columns

- Tapered concrete or steel columns with diameters calculated from moment and buckling demand, not uniform code minimums. (performance based design)
- Tree-like branching capitals (e.g., Gaudí-inspired forms) decrease shear and allow for thinner slabs.

Diagrid Systems

- Tree-branching logic equates to diagrid density being near the base, thinning upward.
- Continuously curved members reduce stress concentrations at nodes.

"...Wright's mushroom columns, inspired by natural trees structural strength, remain one of the most remarkable structural designs in the 20th century architecture..." – ScienceDirect

Slab–Column Transitions

- Flared column tops inspired by tree trunks merging into branches:
  - Less punching shear
  - Thinner flat slabs
  - Reduced reinforcement congestion

Real World Example(s)

a. Centre Pompidou-Metz (Metz, France)

- Roof is a branching hexagonal timber lattice inspired by tree canopies.
- Material minimization via tapered, curved glulam elements.

b. Basílica de la Sagrada Família Columns (Barcelona, Spain)

- Hyperboloid/tapered columns following catenary (gravity-driven) tree logic.
- Demonstrates nature's branching load paths.

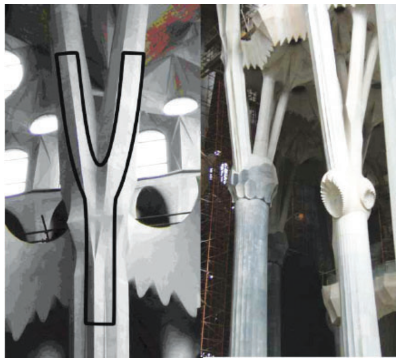

Figure 2.8. – The Columns of La Sagrada Familia in Barcelona, Spain by Antoni Gaudi © Julian Francis Vincent, Research Gate

"Columns in Gaudi ' s Sagrada Familia. Left: a branching column with the outline of a divided tree superimposed. Note the difference in shape of the internal corner. Right: the lumps are probably Gaudi ' s solution to the inevitable stress concentrations which the sharp corners of his design will engender." – Julian Francis Vincent Vincent (ResearchGate)

c. Emerging AEC Application

- High-rise diagrids with variable member density (thick at base → thin upward), mimicking trunk tapering.

5. Fungi Mycelium Networks

Natural Model

Mycelium, the root system of fungi (think mushrooms), forms a highly connected network that acts as a biodegradable building material. This natural material has excellent strength-to-weight ratios and can be used for structural reinforcement while being environmentally friendly.

Figure 2.9. – Fungi Mycelium Networks © mayneconservancy.ca

Principle(s):

- Microfibrous network that forms a strong, lightweight material with high resilience to stress.
- Biodegradability means mycelium-based materials can return to the earth, providing a closed-loop system.

AEC Translation(s):

1. **Mycelium-Based Structural Panels:**
   - Mycelium composites for load-bearing structures, insulation, and wall panels.
2. **Fungus-Inspired Building Bricks:**
   - Biodegradable fungal bricks that can be grown on-site, reducing the carbon footprint.

Real-World Example(s):

a. The Growing Pavilion (Paris, France)

- This pavilion was built using mycelium-based bricks to demonstrate the potential of biodegradable materials for the future of sustainable construction. The mycelium material is both lightweight and resilient, yet biodegradable at the end of its lifecycle.

Figure 2.10. – The Growing Pavilion © TheGrowingPavilion.com

B. Greensulate and MycoComposite™ (USA)

- Greensulate is an insulation that can be grown in place and is created using fungi and agricultural waste.
- MycoComposite™ is a compostable material used for packaging it's created by growing mycelium (mushroom roots) and agricultural matter. A response to the problem of sytrofoam and plastic waste.

> **"Greensulate is an R-3-per-inch rigid insulation material that is made from intertwining mycelium (rootlike filaments of a fungus) that are grown in agricultural waste materials (primarily seed hulls) under controlled conditions. The mycelium forms a foam-like material that insulates reasonably well." – Building Green**

BIOMIMICRY FOR PASSIVE THERMAL REGULATION

Format: **Natural Model(s) → Principle(s) → AEC Translation(s)**

OVERVIEW

A fun fact about passive thermal regulation is that hundreds of years ago traditional designs like wind catchers (badgirs) in Africa and Asia funneled cool air inside a structure while pushing hot air out—an early form of natural air conditioning if you will.

1. Termite Mounds (Macrotermes)

Natural Model

Termite mounds maintain consistent interior temperatures despite extreme external heat conditions

<u>This is achieved by using:</u>

- Vertical chimneys for buoyancy-driven flow
- Lateral flutes & porous walls for pressure equalization
- Daily thermal mass charging/discharging
- Driven convection from internal nest heat

Figure 2.11. – A termite mound in Nigeria, Afrika © By Gwanki – Wikipedia

Principle(s)

- Pressure differential ventilation
- Buoyant air column convection (stack effect)
- Porous, thermal-mass heavy walls buffer diurnal swings (think Trombe wall)

AEC Translation(s)

1) Stack Ventilation

- Central atriums or thermal chimneys draw warm air upward.
- Inlets at lower levels admit cooler air.
- Exterior flutes = architectural fins that induce cross-ventilation.

2) Night-Flushing

- Heavy mass walls (concrete, rammed earth, brick):
  - absorb heat during the day
  - release stored heat at night via controlled ventilation
- Eastgate Centre uses this principle with 90% HVAC reduction. (more about this in Part 4)

3) Pressure Equalization Façades

- Perforated double skins inspired by termite mound porosity.
- Stabilize indoor climate by dampening wind pressure and facilitating passive exfiltration.

2. Cactus (Saguaro, Barrel Cacti)

Natural Model

Cacti survive extreme desert heat using:

- Ribs/folds that expand, contract, and create self-shading
- Thick epidermis + waxy coating for radiative reflection
- Spines as micro-radiators + convective turbulence generators
- High thermal inertia (water)
- Nighttime carbon dioxide (CO_2) uptake (CAM cycle) = nocturnal "cooling cycle" because stomata open at night to collect carbon dioxide (CO2) and allow it to diffuse into the mesophyll cells.

Figure 2.12. – "…A difference between a saguaro cactus and a barrel cactus is size and height…" © Plantsnap

> **"…Crassulacean acid metabolism (CAM) is a photosynthetic adaptation to periodic water supply, occurring in plants in arid regions (e.g., cacti) or in tropical epiphytes (e.g., orchids and bromeliads). CAM plants close their stomata during the day and take up CO2 at night, when the air temperature is lower and water loss can be lowered by an order of magnitude…" – ScienceDirect**

Principle(s)

- Self-shading rib geometry
- Radiative heat reflection
- Thermal mass buffering
- Surface micro-texture to manage boundary layers

AEC Translation(s)

1) Radiant Barriers

- High-reflectivity façades inspired by cactus epidermis wax layers.
- Micro-texturing panels (similar to cactus ribs) reduce net solar gain.

2) Self-Shading Geometry

- Vertical fins or folded façades mimic ribbing, creating:
  - a rhythmic sequence of shade pockets
  - reduced surface temperature
  - enhanced wind-washing for convective cooling

3) Thermal Mass + Night-Flush

- Cactus water reservoir → architectural thermal mass in:
  - adobe/rammed earth
  - high-performance PCM walls
- Night-flushing purges stored heat, mirroring nocturnal cactus metabolism.

3. Kangaroo Rat

Natural Model

The kangaroo rat maintains internal water balance and stable temperatures in extreme environments using:

- Counter-current heat exchange in nasal passages
- Burrow microclimates with steady cool temperatures
- Remarkably low radiant heat absorption (fur reflectance)

Figure 2.13. – Kangaroo Rat © Wikipedia

Principle(s)

- Heat exchange via narrow passageways
- Cool subsurface microclimates
- Radiant heat rejection

Minimum evaporative loss

AEC Translation(s)

1) Earth Coupling (Ground-Connected Cooling)

- Partially buried rooms acting as coolth reservoirs, similar to kangaroo rat burrows.
- Stable subterranean temperatures reduce cooling loads.

2) Narrow Ventilation Passages

- Duct or facade systems incorporating counter-flow heat exchange (pre-cooling of incoming air).

3) Radiant Heat Control

- Light, reflective roofs and walls mimicking fur albedo.
- Optimized roof shapes to reduce solar exposure.

4. Prairie Dogs

Natural Model

Prairie dog burrows maintain interior comfort in extreme climates using:

- Two openings at different elevations creating Venturi effect pressure differences
- Wind scoops that funnel outdoor air downward
- Thermal stratification zones within networks of chambers
- Convective tunnel geometry

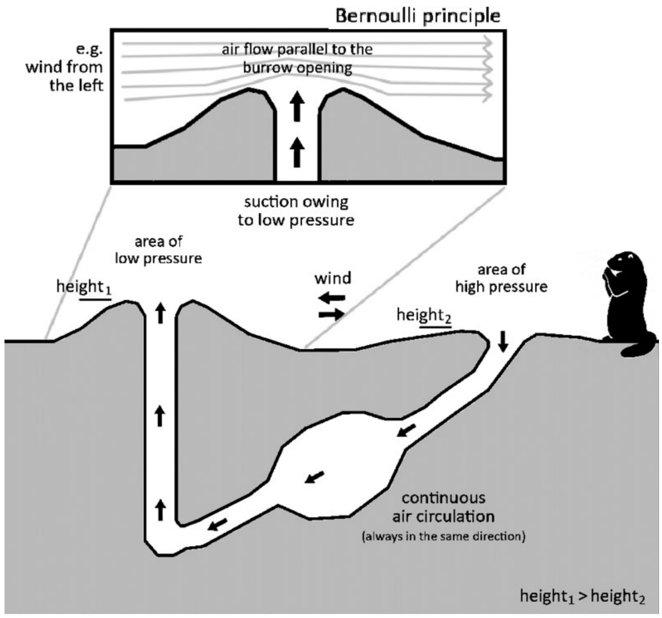

Figure 2.14. – A prairie dog burrow creates a Venturi effect which is a specific application or consequence of the Bernoulli Principle © Research Gate

Principle(s)

- Wind-driven exchange
- Pressure zoning across height differentials
- Subsurface insulation and thermal buffering

AEC Translation(s)

1) Wind-Scoop Ventilation

- Windward intakes + leeward exhausts replicate prairie dog burrow logic.
- Enhanced airflow even in low-wind conditions.

2) Venturi-Enhanced Stack Ventilation

- Chimneys tapered like burrow openings to accelerate air velocity.
- Works in passive schools/hospitals to improve fresh air rates.

3) Subsurface Temperature Zones

- Use of semi-buried spaces with stable temperatures:
  - garages
  - service corridors
  - thermal plenum zones

5. Beetle (Stenocara gracilipes)

Figure 2.15. – Beetle (Stenocara gracilipes) © Science.Org

Natural Model

The *Stenocara gracilipes* beetle survives in desert climates by collecting water from fog through its specialized exoskeleton.

The beetles back has a hydrophilic (water-attracting) and hydrophobic (water-repelling) surface pattern, which allows it to channel moisture from fog to its mouth.

It uses the thermal mass of the surface to store heat and regulate temperature.

Principle(s)

- Hydrophilic/hydrophobic surface patterning
- Micro-texture to capture and direct moisture
- Thermal mass for moisture condensation and temperature regulation

AEC Translation(s)

- **Fog Harvesting Façades**
  - Building skins or roof structures that capture water from fog using beetle-inspired hydrophilic/hydrophobic surfaces.
  - Water is then directed into storage systems or cooling towers.
- **Thermal-Activated Water Distribution**
  - Walls and surfaces designed to harvest and redistribute water through micro-textures, improving passive cooling and humidity regulation inside buildings.
- **Condensation-Enhancing Surfaces**
  - Micro-textured surfaces on windows or facades that encourage condensation for natural water collection and cooling, utilizing the thermally-regulated principles of the beetle's back.

6. Elephant Ear Leaves

Natural Model

The elephant ear plant, particularly its large leaves, utilizes transpiration *(the process of water movement through a plant and its evaporation from aerial parts, such as leaves, stems and flowers)* and the high surface area of its foliage to cool the surrounding environment.

The plant's large, flat leaves dissipate heat through evaporative cooling, increasing local humidity and reducing thermal load.

Principle(s)

- Large surface area for evaporation
- High transpiration rate
- Thermal mass to store heat

AEC Translation(s)

1. **High-Surface Area Green Walls**
   - Vertical gardens or green walls using large, broad-leaf plants (or biomimetic materials) to promote transpiration and cooling within building environments.
2. **Evaporative Cooling Roof Systems**
   - Roofs designed with plant-inspired forms (or synthetic analogs) that mimic the leaf's high surface area, improving evaporative cooling through natural ventilation.
3. **Thermal Mass Green Façades**
   - Incorporating foliage or vegetation in façade systems to help absorb and gradually release heat, reducing the need for mechanical air conditioning. The foliage acts as a buffer, controlling thermal fluctuations.

Figure 2.17. – Lotus Leaf (Nelumbo nucifera) © Illinois Wildflowers

7. Lotus Leaf (Nelumbo nucifera)

Natural Model

The lotus leaf is known for its superhydrophobic properties, meaning it can shed water efficiently due to the unique microstructure of its surface.

This reduces heat absorption by minimizing water's contact with the leaf *(the minimized water contact creates air pockets which are poor heat conductors i.e. less heat transfer via conduction)*, and the structure can also reflect light, helping to keep the surface cooler in hot environments.

Principle(s)

- Superhydrophobic surface for moisture resistance
- Solar reflectance properties
- Reduced heat absorption via water repulsion

AEC Translation(s)

1. **Water-Shedding Roofs**
   - Roof systems with micro-textured coatings inspired by lotus leaves, designed to shed rainwater efficiently while minimizing heat absorption, keeping roofs cooler in hot climates.
2. **Self-Cleaning Facades**
   - Glass or facade materials designed to repel water and dirt, reducing maintenance while improving thermal performance by minimizing moisture retention and increasing solar reflectivity.

3. **Hydrophobic Coatings for External Walls**
   - Buildings using hydrophobic materials to reduce the effects of rainwater, which can increase heat retention and reduce cooling load by preventing moisture buildup.

8. Marine Slugs

Natural Model

Marine nudibranchs have evolved adaptive mechanisms that allow them to regulate their temperature in varying underwater environments.

Figure 2.18. – Nudibranchs (Marine Slugs) © Géry PARENT Wikipedia

Their flexible, amorphous bodies can adjust their surface area to the surrounding water temperature, offering efficient insulation and reducing energy loss.

Principle(s)

- Surface area manipulation for heat regulation
- Amorphous, flexible structure for insulation
- Adaptive thermal resistance based on environmental conditions

AEC Translations(s)

1. **Dynamic Insulating Surfaces**
   - Building skins or facades that can adapt to environmental temperature shifts, using materials with responsive properties that expand or contract to regulate heat flow.
2. **Flexible Thermal Barriers**
   - Systems that mimic nudibranchs' body flexibility, employing dynamic materials that enhance insulation when the temperature rises, providing better passive thermal control.
3. **Adaptive Roof and Façade Panels**
   - Roof and façade systems that expand or contract based on temperature, reducing the need for mechanical heating/cooling systems and improving energy efficiency.

9. Sensitive Plant (Mimosa Pudica)

Natural Model

The sensitive plant Mimosa pudica can change the position of its leaves in response to sunlight, closing them when exposed to extreme heat. This self-adjustment helps the plant avoid excessive heat absorption and water loss. The plant's leaves use photo-responsive mechanisms to regulate their exposure to sunlight.

Figure 2.19. – Mimosa Pudica (Sensitive Plant) © House Beautiful

Principle(s)

- Photo-responsive movement for thermal regulation
- Self-adjusting geometry
- Dynamic response to environmental stimuli

AEC Translations(s)

1. **Photo-responsive Façades**
   - Dynamic façades that adjust their position and geometry throughout the day, opening or closing based on sunlight intensity, reducing solar heat gain and improving indoor thermal comfort.
2. **Self-Adjusting Shading Systems**
   - Exterior shading elements (e.g., louvers or panels) that automatically adjust to block direct sunlight and reduce heat absorption, inspired by the movement of *Mimosa pudica* leaves.
3. **Smart Window Films**
   - Window films or coatings that adjust opacity in response to solar heat gain, reducing the need for mechanical shading and cooling systems, enhancing passive temperature regulation.

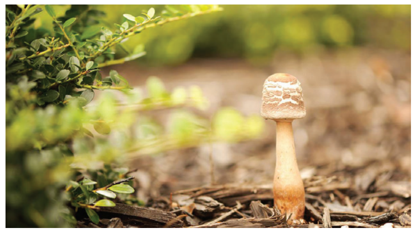

Figure 2.20. – Fungi Mycelium © TasteForLife.com

10. Fungi Mycelium

Natural Model

Fungi mycelium networks are highly effective at moisture regulation, able to absorb, store, and release moisture as needed.

The dense, fibrous structure of mycelium also serves as an excellent natural insulator, helping maintain a stable temperature in its environment.

Principle(s)

- Moisture absorption and release
- Natural insulation through fibrous structure
- Biodegradable, sustainable material properties

AEC Translations(s)

1. **Mycelium Insulation Panels**
   - Mycelium-based insulation materials used in building envelopes, providing natural thermal regulation and moisture control while being biodegradable and eco-friendly.
2. **Moisture-Regulating Building Materials**
   - Walls and flooring systems using mycelium or mycelium-based composites that adapt to humidity levels, absorbing excess moisture in humid conditions and releasing it in drier environments, maintaining a balanced indoor climate.
3. **Biodegradable Thermal Barriers**
   - External cladding materials that act as natural thermal insulators while being environmentally sustainable, offering high thermal resistance while also reducing the building's carbon footprint.

11. Whale Blubber

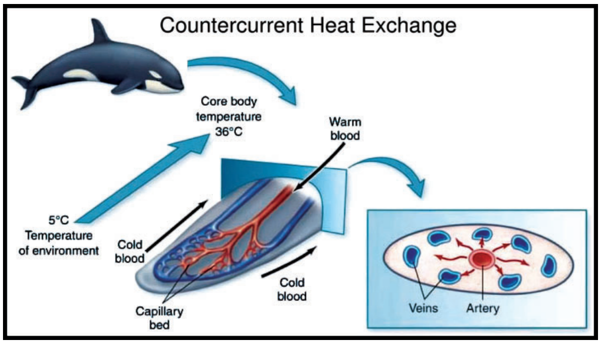

Figure 2.21. - Whales regulate their internal temperature to keep it constant regardless of the environmental temperature © Pcristales3

Natural Model

Whales have thick layers of blubber that provide both insulation and buoyancy. This fat layer helps to maintain stable internal body temperatures by reducing heat loss in cold waters and preventing overheating in warmer environments.

Principle(s)

- Thermal insulation via fat layers
- Adaptive thickness based on environmental temperature
- Heat storage and retention

AEC Translations(s)

1. **Fat-Layered Insulation**
   - Multi-layered thermal insulation systems in buildings inspired by whale blubber, using materials that store and release heat depending on ambient temperature.
2. **Thermal Insulating Walls**
   - Walls incorporating bio-inspired insulative materials (e.g., fat-based composites or foam materials) to store heat in cold conditions and release it in hot conditions, reducing heating and cooling demands.
3. **Adaptive Building Insulation**
   - Insulating systems that change their thickness or composition depending on external temperature, much like the varying thickness of whale blubber, providing more efficient insulation during seasonal temperature fluctuations.

12. Penguin Feathers

Natural Model

Penguins' feathers are designed to keep them warm in extremely cold environments. Their feathers have a unique structure, with a dense layer of insulation that traps air and helps retain body heat.

Additionally, their outer feathers are highly waterproof, preventing heat loss from water exposure.

Figure 2.22. - Penguins have 100 feathers per inch © Photo by Jean van der Meulen, Pexels.com

Principle(s)

- Microstructural air pockets for insulation
- Waterproof outer layers for thermal retention
- Feather density for efficient heat trapping

AEC Translations(s)

1. **Micro-Textured Insulating Surfaces**
   - Building facades or roof systems with micro-structured coatings inspired by penguin feathers, which trap air and reduce heat loss, providing insulation without bulk.
2. **Waterproofing Building Envelopes**
   - External cladding or roofing systems that mimic the waterproof nature of penguin feathers, using hydrophobic materials that keep the interior dry and maintain thermal performance.
3. **High-Density Insulating Materials**
   - Wall systems with densely layered insulating materials, creating air pockets similar to the feathers' structure, to enhance thermal insulation in extreme climates.

13. Swallowtails (Butterfly Wings)

Natural Model

Swallowtail butterflies have evolved wings that help regulate their body temperature by reflecting sunlight and promoting evaporative cooling. Their wings have a unique microstructure that helps dissipate heat and reflect infrared radiation, which prevents overheating in hot environments.

Figure 2.23. - Swallowtail Butterfly © By Uoaei1 - Wikipedia

Principle(s)

- Reflective surfaces to minimize solar gain
- Microstructure for enhanced heat dissipation
- Evaporative cooling through wing surface area

AEC Translations(s)

1. **Reflective Façades**
   - Building envelopes designed with highly reflective surfaces, inspired by butterfly wings, to reduce solar heat gain while maintaining aesthetic appeal. These surfaces can use materials that reflect infrared radiation while allowing visible light to pass through.
2. **Evaporative Cooling Systems**
   - Roofs or exterior walls that mimic the swallowtail butterfly's wing texture, facilitating heat dissipation through evaporation. This could involve micro-textured panels or coatings that promote passive cooling.
3. **Adaptive Shading Systems**
   - Façades or shading devices with biomimetic patterns inspired by butterfly wings, where the surface changes to reflect more or less sunlight based on temperature or time of day, providing active solar control.

14. Whip Spiders (Tailless Whip Scorpions)

Natural Model

Whip spiders, living in hot, dry environments, regulate their temperature by controlling evaporative cooling.

Their long, flexible legs and body surfaces allow for more effective heat dissipation, and they make use of small-scale geometry to enhance heat loss and reduce thermal stress.

Figure 2.24. – Tailless whip scorpion spotted at a home in Hermosillo, Sonora, Mexico © José Eugenio Gómez Rodríguez Blogs.ucl.ac.uk

Principle(s)

- Large surface area for heat dissipation
- Evaporative cooling through surface geometry
- Enhanced convection by long, flexible body structures

AEC Translations(s)

1. **Evaporative Cooling Facades**
   - Buildings designed with long, flexible shading elements or façade systems, inspired by the whip spider's legs, that maximize surface area for increased heat dissipation and passive cooling.
2. **Thermal Buffering Materials**
   - Wall systems using geometries that enhance airflow and evaporative cooling by mimicking the whip spider's surface structure to create an increased surface area for heat exchange.
3. **Flexible Shading Systems**
   - Adjustable external shading systems that increase or decrease surface area based on external temperature, similar to the whip spider's ability to adjust body posture to optimize cooling.

15. Honeybee Hives

Natural Model:

Honeybees build their hives in highly efficient hexagonal patterns, which optimize space utilization and thermal insulation. The honeycomb structure creates minimal air resistance, maximizing internal thermal stability.

Figure 2.25. – Honeybee Hives © Archana GS , Pexels.com

Principle(s):

- Hexagonal tessellation minimizes material use while maximizing space and strength.
- Optimal airflow through the hive's structure allows for precise temperature control without energy-intensive cooling or heating systems.

AEC Translations(s):

1. **Hexagonal Facade Patterns for Thermal Insulation:**
   - Modular hexagonal tiles for walls and roofs that trap air in natural cavities, offering passive cooling or insulation.
2. **Beehive-Inspired Thermal Mass:**
   - Wall sections designed to mimic the honeycomb structure for passive thermal management in buildings.

Real-World Example(s):

- **The Eden Project** (Cornwall, UK): The hexagonal honeycomb-inspired geodesic domes that make up the biomes mimic the thermoregulation properties of beehives.

Figure 2.26. – The Eden Project © edenproject.com

The structure maximizes natural light while maintaining a stable internal temperature, minimizing the need for artificial heating and cooling.

PART 2 – BIOMIMICRY IN STRUCTURE AND THERMAL SYSTEMS | KNOWLEDGE CHECK (5 QUESTIONS)

1. **What principle does trabecular bone demonstrate that is applied in structural optimization?**
   A. Stress-aligned lattices and void optimization
   B. High thermal mass and buoyancy-driven flow
   C. Hydrophilic and hydrophobic surface patterning
   D. Reflective surfaces and evaporative cooling

2. **Which natural model inspired the design of diagrid systems with angle-optimized diagonals?**
   A. Termite mounds
   B. Diatoms
   C. Bone and trabecular architecture
   D. Nacre (Mother of Pearl)

3. **What is a key feature of diatom-inspired façade panels?**
   A. High reflectivity to reduce solar heat gain
   B. Perforation fields optimized for bending and shear
   C. Hydrophobic coatings for water resistance
   D. Layered composites for crack arresting

4. **How does nacre (Mother of Pearl) achieve its exceptional toughness?**
   A. MX3D Bridge, Amsterdam
   B. Centre Pompidou-Metz, France
   C. Al Bahar Towers, UAE
   D. Striatus Bridge, Zaha Hadid Architects

5. **Which building example demonstrates tree-inspired branching load paths?**
   A. MX3D Bridge, Amsterdam
   B. Centre Pompidou-Metz, France
   C. Al Bahar Towers, UAE
   D. Striatus Bridge, Zaha Hadid Architects

This concludes Part 2 of the course.

Let's continue to Part 3.

PART 3 – BIOMIMICRY IN WATER MANAGEMENT AND MATERIAL SURFACE SCIENCE

Learning Objective No. 3: Identify existing natural systems that are being developed into advanced solutions for water management and material surface science.

BIOMIMICRY FOR WATER MANAGEMENT OVERVIEW

Pop quiz question, what does every high-rise have on its rooftop? Yes, of course a roof but they always have a roof rig for the window washing equipment. Now imagine not needing that equipment at all and thus no line item for that cost. So, what cleans the windows? Rainfall. Look to the Lotus Leaf and learn how below.

Figure 3.1. – Lotus Leaf (Nelumbo nucifera) © akwrite.blogspot.com

1. Lotus Leaf (semi-aquatic plant)

Natural Model

- How do Lotus leaves remain so beautiful amidst the muddiest ponds?

  The "Lotus Effect". It is comprised of several self-cleaning properties and mechanisms as follows: A superhydrophobic surface, a unique contact angle (higher than 160° with a sliding angle lower than 5°) and a dense layer of wax tubules on the upper epidermis.

"...On the lotus leaf surface, the adhesion between the water droplet and dust particle is stronger than the adhesion between the dusts and the surface, hence the spherical water drops pick up the dust particles while rolling off the lotus leaf..." – PMC NCBI NIH.gov

- The microscopic architecture of the Lotus leaf means that water can't penetrate nanofolds on the surface, leaving air pockets below. The water droplets become suspended in the Cassie-Baxter state/law/equation (see below) and are able to roll off the leaf picking up dirt as they do so, thus *cleaning* the leaf.

"...The more commonly encountered equation is that of Cassie-Baxter [2]. It describes the contact angle on a porous surface. Instead of having two different surface chemistries as in Cassie law, the surface is now composed of solid surfaces and areas where the drop is in contact with air..." – Biolin Scientific

- **Principle(s)**
  - Hierarchical micro/nano texture + low-surface-energy epicuticular wax
    - Low-surface-energy epicuticular wax is a waxy coating that forms a whitish film *(refer to Figure 3.2.1, page right)* on the outer surface of leaves, fruits and other plant organs. It has the highest ultraviolet light (UV) reflectivity of any known naturally occurring biological substance.

Figure 3.2.1. – Epicuticular wax on a plant © Dudleya brittonii, Wikipedia

  - Cassie-Baxter wetting state
  - Minimal lag which equates to a ultra-low roll-off angle that is less than five degrees
  - Superhydrophobic Self-Cleaning + Water Repellency

- **AEC Translations(s)**
  - **Self-Cleaning Façades & Roofs**
    - Nanotechnology textured paints/coatings *(widely used on buildings like the Technoseum in Germany)* keep exteriors clean with rainfall only which equates to reduced maintenance and very little chemical cleaning.

Figure 3.2.2. – Technoseum in Mannheim, Germany © Museu.ms

- **Anti-Fouling Building Envelopes**
    - Applied to glass, metal, or concrete prevents mold/algae growth and reduces urban heat island effect by keeping surfaces reflective with a high albedo.
- **Water-Repellent Membranes**
    - Roofing membranes that shed water instantly which in turn reduces leakages, ice damming, and material degradation.
    - Provides protection against rust, corrosion, graffiti, and provides electrical circuit protection preventing outages due to moisture infiltration.

2. Shark Skin

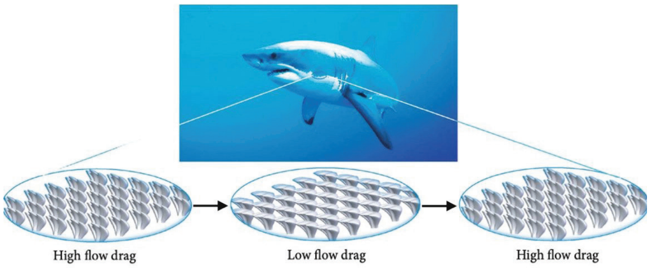

Figure 3.3. - Shark skin is covered in tiny scales called dermal denticles which reduce drag for faster, quieter swimming © Arstechnica

Natural Model

- Why are sharks silent assassins of the sea?
    - Because of their skin – which is covered by dermal denticles (i.e. miniscule and flat "V" shaped overlapping scales) with three to five longitudinal riblets or grooves per denticle. These denticles allow for sharks to decrease their drag and turbulence which permits them to swim faster, more quietly while also preventing organism attachment.

"...Olympian swimsuit designers have taken a page from the shark's playbook and created a fabric that mimics the exact proportion of the shark's denticles, hugely improving a swimmer's speed..." – Ocean SI Edu

- **Principle(s)**
    - Riblets and how they function reduce friction/drag and lower wall shear stress
    - Denticles prevent bacterial settlement
- **AEC Translations(s)**
    - **Anti-Fouling Finishes**
        - "Sharklet® is a synthetic surface inspired by the skin of sharks that deters colonization by certain disease-causing microbes. Because the artificial surface works without killing microbes, there is no selection for resistance. The surface topography is made of millions of microscopic diamonds that disrupt the ability for bacteria to adhere, colonize, or develop into biofilms. The Sharklet pattern is manufactured onto adhesive-backed skins that may be applied to high-touch areas to reduce the transfer of bacteria among people." – AskNature.Org
    - **Wind Turbines**
        - "When air passes over the turbine blade at the contact point between the blade and air, the velocity of the air comes to rest and the result is turbulence and skin friction," said University of Minnesota Professor Roger Arndt. "Riblets help to organize and channel that turbulence so it's less energetic and results in less energy loss. This delays lateral wind movement." The channeling effect was first noted in shark skin research in the 60s and 70s." – CSE UMN.edu

3. PINECONES

Natural Model

Pinecones exhibit hygroscopic properties, where their scales open and close in response to humidity.

In dry conditions, the scales close tightly to preserve moisture, while in high-humidity environments, they open to allow water absorption and dispersion.

Figure 3.4. - Pinecone ©Pineconee De Boever, Pexels.com

Principle(s)

- Hygroscopic movement driven by moisture changes
- Responsive geometry that adapts to environmental humidity
- Capillary action for water absorption and dispersion

AEC Translations(s)

1. **Responsive Cladding Systems**
    - Building skins or cladding systems that expand or contract in response to humidity levels, optimizing natural ventilation and moisture control within the building envelope.
2. **Water Dispersion Roofs**
    - Roof systems inspired by pinecone scales that open to capture rainwater and direct it into storage or distribution systems, particularly in humid environments.
3. **Humidity-Responsive Ventilation**
    - Humidity-sensitive windows or façade systems that open or close based on internal moisture levels, improving indoor air quality and passive water management.

4. MANGROVE ROOTS

Natural Model

Mangrove trees have adapted to live in saltwater by developing specialized root systems that filter out salt and conserve freshwater.

Their intricate root networks provide a way for the plant to trap sediments while filtering saltwater and retaining essential nutrients.

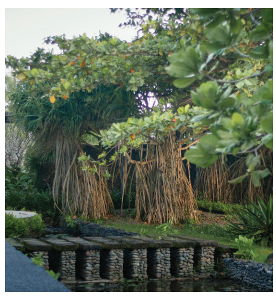

Figure 3.5. - Mangrove forest in its natural habitat. © Ksu&Eli Studio, Pexels.com

Principle(s)

- Filtration of saltwater through specialized root structures
- Capillary action for water retention and filtration
- Efficient nutrient absorption through complex root systems

AEC Translations(s)

1. **Saltwater Filtration Façades**
   - Vertical garden systems or building facades inspired by mangrove root structures that filter and purify water for irrigation or other uses, particularly in coastal regions.
2. **Water-Conserving Landscaping**
   - Building-integrated landscapes with root structures that help manage and filter rainwater runoff, preventing saltwater contamination and maintaining freshwater supply.
3. **Biomimetic Water Purification Systems**
   - Advanced filtration systems for buildings or neighborhoods, mimicking the natural filtration properties of mangrove roots to purify greywater or rainwater.

5. PINEAPPLE PEELS

Natural Model

The fibers in pineapple peels are highly absorbent, capable of soaking up water and holding it for long periods. These fibers naturally wick moisture, making them ideal for water retention in arid climates.

Figure 3.6. – Pineapple peels © SHVETS, pexels.com

Principle(s)

- Hydrophilic properties of lignocellulosic fibers
- Capillary action for water absorption
  - Capillary action can be defined as the ascension of liquids through slim tubes, cylinders or permeable substances due to adhesive and cohesive forces interacting between the liquid and the surface.
  - Moisture retention through natural fiber networks

AEC Translations(s)

1. **Water-Absorbent Facades**
   - Building exteriors made from natural materials inspired by pineapple fibers to absorb and retain moisture, improving passive water management in dry environments.
2. **Moisture-Buffering Building Insulation**
   - Non-mold producing insulation materials made from pineapple-derived fibers that absorb excess moisture during humid periods and release it when needed, helping to stabilize interior temperature and humidity.
3. **Rainwater Harvesting Systems**
   - Rainwater collection systems using pineapple fiber-based materials to absorb and store rainwater for later use in irrigation or cooling.

6. SPIDERS' SILK

Natural Model

Spiders' silk is highly water-repellent and extremely strong. The silk's microstructure allows it to capture moisture from the environment while remaining structurally intact, making it ideal for applications requiring both strength and moisture resistance.

Figure 3.7. – Spiders' Silk © Jiří Mikoláš, Pexels.com

Principle(s)

- Water-resistant microstructure
- Tensile strength and flexibility
- Nano-scale surface hydrophobicity

AEC Translations(s)

1. **Water-Resistant Building Materials**
   - Advanced textiles or coatings for building exteriors inspired by spider silk's water resistance, providing superior weatherproofing and longevity to building materials.
2. **High-Strength, Lightweight Facades**
   - Spider silk-inspired materials for lightweight but structurally strong cladding systems that also prevent moisture infiltration, reducing energy demands for heating and cooling.

7. WORMS (EARTHWORMS)

Natural Model

Earthworms play a crucial role in maintaining soil moisture levels. Their burrowing activity allows water to infiltrate the soil more efficiently, while their bodies filter and redistribute nutrients and moisture within the soil.

Figure 3.8. -Worms © Hanniel Yaks , Pexels.com

Principle(s)

- Soil aeration and moisture distribution through burrowing
- Filtration and redistribution of nutrients and water
- Improved soil porosity for better water retention

AEC Translation(s)

1. **Soil Moisture Management Systems**
   - Landscape architecture that mimics earthworm activity by creating permeable surfaces and soil channels to enhance water infiltration and moisture retention in urban areas.
2. **Water Retention Green Roofs**
   - Green roofs inspired by earthworm burrows that facilitate water retention and filtration, allowing for better stormwater management in urban settings.
3. **Water-Absorbing Ground Covers**
   - Sustainable landscaping materials for ground covers or walkways that simulate the effects of earthworm burrows, improving water absorption and reducing runoff.

8. CORAL REEFS

Natural Model

Coral reefs act as natural water filters by trapping particles and promoting nutrient cycling within their ecosystems. The porous structure of corals allows water to flow through, while beneficial organisms within the coral structure filter out pollutants and enhance water quality.

Figure 3.9. – Brown Coral Reef © Francesco Ungaro, Pexels.com

Principle(s)

- Porous, bioactive structures for water filtration
- Nutrient cycling within a complex ecosystem
- Increased water flow through porous architecture

AEC Translation(s)

1. **Bio-Active Water Filtration Systems**
   - Coral-inspired porous membranes or filtration units integrated into building façades or urban infrastructure that filter pollutants and improve water quality. This should be normalized in every downtown city, especially those over a certain population threshold.
2. **Self-Cleaning Water Features**
   - Architectural water features or ponds designed to mimic coral reef structures, enhancing water filtration while providing aesthetic and environmental benefits.
3. **Integrated Stormwater Management**
   - Urban rainwater management systems inspired by coral structures that filter and purify water before reusing it for irrigation or other purposes, improving water quality and reducing waste.

9. MOUNTAIN PINE BEETLE

Natural Model:

The Mountain Pine Beetle burrows into trees and creates pathways through the bark that guide sap flow to specific areas, increasing the moisture retention capacity of the tree.

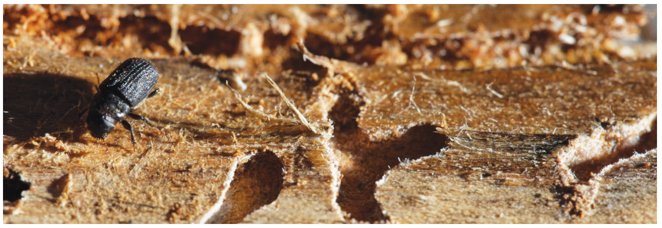

Figure 3.10. – Mountain Pine Beetle © csfs.colostate.edu

Principle(s):

- **Capillary action** within the beetle-carved channels increases moisture retention and water directionality.
- **Hydrophobic/hydrophilic gradients** allow water to flow efficiently through the tree's vascular system.

AEC Translation(s):

1. **Beetle-Inspired Water-Channeling Building Facades:**
   - Surfaces that mimic beetle pathways, capturing and channeling water to storage or cooling systems.
2. **Hydrophilic-Gradient Roofs:**
   - Roof structures that mimic beetle burrows, using capillary action to direct water from condensation into storage systems for reuse in arid climates.

Real-World Example:

- **Warka Water Towers** (Cameroon, Africa): These water-harvesting towers, akin to the mountain beetle, collect atmospheric moisture in arid and rural environments. The towers are designed to capture fog and dew, improving water collection in regions with limited rainfall.

10. CACTUS SPINES

Natural Model:

Cacti use their spines as a defense mechanism and to reduce water loss through transpiration. The spines serve as a solar shading system, blocking sunlight and creating localized air turbulence that reduces evaporation rates from the plant's surface.

Figure 3.11. – Cactus Spines © Lachlan Ross, Pexels.com

Principle(s):

- Localized air turbulence creates micro-climates around the cactus, reducing heat absorption and water loss.
- Spines as shade structures protect the plant while conserving water in extreme heat.

AEC Translation(s):

1. **Cactus-Inspired Shading Systems:**
   - Facade shading systems that mimic cactus spines, creating air turbulence to reduce solar heat gain.

2. **Desert Adapted Skin Layers:**
   - Building skins with embedded spine-like structures that reflect and diffuse sunlight while reducing heat absorption.

11. PANGOLIN SCALES

Natural Model:

The Pangolin is covered in tough, overlapping scales that provide protection against predators and harsh environmental conditions. The scales are arranged to allow flexibility while offering high impact resistance.

Figure 3.12. – Pangolin © Graeme Travers, Pexels.com

Principle(s):

- Flexible armor made of overlapping, interlocking scales absorbs and dissipates force.
- Self-adjusting armor that provides protection without compromising resilience.

AEC Translations(s):

1. **Pangolin-Inspired Protective Facades:**
   - Overlapping, flexible panels that absorb and distribute impacts from storms, seismic activity, or human interaction.
2. **Dynamic Building Skins:**
   - Flexible, impact-resistant surfaces that adjust based on external forces (e.g., wind, vibrations) for optimal building resilience.

Real-World Example:

- **Pangolin Pavilion** (*version of the pavilion was built in India by ANT Studio, refer to Figure 3.13.1*): A Pangolin-inspired façade that can be created using local materials to create clay tiles resembling the scales of a pangolin.

Figure 3.13. – Pangolin Pavilion © Valerie Schweitzer Architects

Figure 3.13.1. – Pangolin Pavilion in India © Jaidev, ANT Studio

> **"Installed at the School of Planning and Architecture in Delhi, the Pangolin Pavilion was created with a two-pronged motive – to educate young architects and students about the concept of Parametricism and to draw attention to the widespread poaching of Pangolins, the most trafficked mammals in the world..."**
> **– Home & Design TRENDS**

12. MIMOSA PUDICA (SENSITIVE PLANT)

Natural Model:

The Mimosa Pudica plant adjusts its leaves in response to environmental stimuli, such as touch or sunlight, by altering the *turgor pressure* in its cells.

This allows the plant to optimize energy absorption and conserve resources.

Figure 3.14. – Mimosa Pudica © TheSpruce.com

> **"...What is turgor pressure?**
>
> **In a biological context, turgor pressure is the pressure that is exerted by water on the wall of a cell. Think of a balloon that is being filled up with water as a turgor pressure example. The balloon swells as more water draws in. The pressure that the water exerts against the walls of the balloon is similar to the turgor pressure exerted against the wall..."**
> **– Biology Online**

Principle(s):

- Turgor-driven response to environmental stimuli causes rapid leaf movement.
- Self-adjusting systems that can react to changes in light intensity or temperature.

AEC Translations(s):

1. **Self-Adjusting Solar Panels:**
   - Panels that adjust their angle based on sunlight intensity to maximize energy capture, inspired by the plant's leaf movement.
2. **Adaptive Shading Facades:**
   - Mimosa-inspired facades that open or close based on sunlight, wind, or temperature conditions, reducing solar heat gain while optimizing natural daylight.

Real-World Example(s):

- **The Bosco Verticale (Vertical Forest)** (Milan, Italy): The facades of the towers feature plants that respond dynamically to environmental conditions, thus improving thermal comfort, air quality, and energy efficiency.

Figure 3.15. – Bosco Verticale, Milano, Italia © pedestal-eternoivica.com

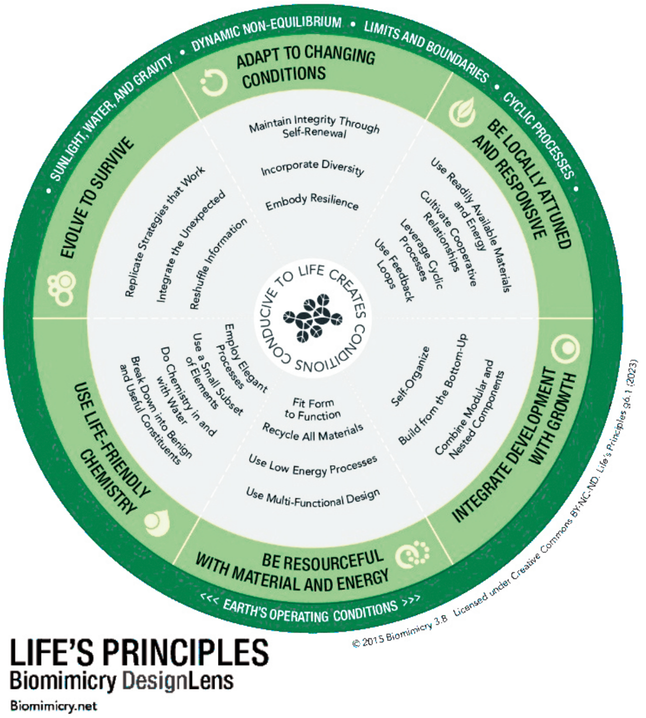

Figure 4.1. – Life's Principles © biomimicry.net

You will find below, buildings that function like healthy ecosystems, actively healing and enriching the environment versus being "sustainable" i.e. minimizing the damage they do to the environment.

As we have repeated numerous times, these buildings emulate or parallel nature's cyclical processes i.e. purifying air/water, producing food/energy, and adapting to change.

REAL-WORLD AEC EXAMPLES OF BIOMIMICRY AND ITS LIFE'S PRINCIPLES IN ACTION

Building: Al Bahar Towers (LEED Silver)

Biomimicry Life's Principle Applied: Adapt to changing conditions

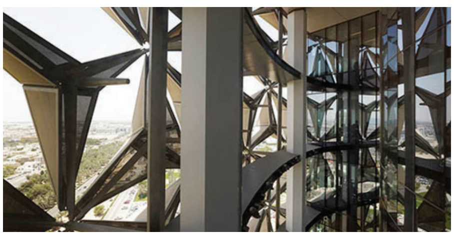

Figure 4.2. – Al Bahar Towers, Abu Dhabi, UAE © Christian Richters, chi-athenaeum.org)

Architect: Aedas Architects (now AHR)

Location: Abu Dhabi, UAE

How?: Computer-controlled mashrabiya screens* open/close daily with sun position

**Mashrabiya screens are intricate, latticed wooden screens common in African/Asian architecture, used for privacy, shade, and ventilation, creating beautiful patterns of light indoors while allowing occupants to see out without being seen.*

"…The building facade is the modern interpretation of mashrabiya that transformed into a dynamic facade system comprising over 2,098 umbrella-like shading devices. Each element opens and closes in response to the sun's position, creating a building envelope that breathes with the desert heat. The skin of the Al Bahar Towers was developed using parametric and computational design tools…" – Parametric-Architecture

The high rises (+/- 475'-0") with a combined square footage of +/- 559,723 GSF were designed specifically with the UAE's hot desert climate ("BWh" per the Köppen system) in mind. The mashrabiya screens are comprised of 2,098 of the flower shaped responsive elements which allow the façade to respond to the diurnal (daily) cycle of the sun in real time.

Here is a great video on how the screens work and a mention is made of the reduced energy consumption which ties into the solar heat gain which is reduced amazingly by more than 50%! The occupancy classification of both high rises are business occupancy classifications and thus with this design it affords everyone access to sunlight which has been proven time and time again to elevate one's mood and improve productivity.

"…Workers in windowless environments reported poorer scores than their counterparts on two SF-36 dimensions–role limitation due to physical problems and vitality–as well as poorer overall sleep… Compared to the group without windows, workers with windows at the workplace had more light exposure during the workweek, a trend toward more physical activity, and longer sleep duration as measured by actigraphy.

Conclusions: We suggest that architectural design of office environments should place more emphasis on sufficient daylight exposure of the workers in order to promote office workers' health and well-being…" – PMC NCBI NIH.gov

Honestly every building should have a similar narrative no matter where it is located.

Building: Khoo Teck Puat Hospital (KTPH) aka "the Hospital in a Garden"

Biomimicry Life's Principle Applied: Be locally attuned and responsive

Figure 4.3. – Khoo Teck Puat Hospital,Yishun, Singapore © living-future.org)

Architect: Collaboration between CPG Consultants Pte Ltd (the executive architect) and RMJM Hillier (the design consultant)

Location: Yishun (formerly Nee Soon), Singapore

How?: The entire hospital was designed with only the local tropical climate, native plants, and Singapore's rainfall patterns in mind. The design reduces energy consumption drastically and has the option to be naturally ventilated.

As you can see from the image *(refer to Figure 4.3, page left)* and quote below, biophilic design and biomimicry are combined, biophilic design is very important and even moreso in healthcare settings when people are not feeling their best or are fighting hard to recover from an illness.

"Yishun Pond itself grew to be a central feature of the design; inpatient units face the pond, whose shoreline is to be reclaimed for exercise paths and food pavilions.

The pond provides a soothing waterscape view for staff and patients in the nursing towers at the eastern edge of the 32,000 sqm site,

while the garden landscape greets visitors, patients and staff at the entry to Yishun Central Avenue at the western extremity. A series of planted terraces between upper floor patient towers culminate the "garden hospital" experience." – RMJM

Another amazing "green" fact is that the total surface area of the horizontal and vertical greenery is close to 4x the size of the lot the hospital is placed on. Aside from incorporating an existing pond (Yishun Pond) into its design which increased visitors and promoted health and fitness (they added a walking trail around the pond that linked to other businesses and residential areas, they also only used local plant life which in turn brought local animals and creatures native to the area. More specifically, over 83 butterfly species have been observed on hospital grounds. It is said a butterfly represents the soul of a deceased family member or loved one visiting you from the afterlife.

Now imagine being in the hospital by yourself and you see numerous butterflies outside of your patient suite, you will know that you have the support of your loved ones that have passed on. This will add to your resolve and strength to fight whatever you are fighting or to accept your fate and rest assured that you will soon be a with your family and a "butterfly" as well.

Building: Bullitt Center

Biomimicry Life's Principle Applied: Use life-friendly chemistry

Figure 4.4. – Bullitt Center, Seattle, WA, USA © bullittcenter.org

Architect: Miller Hull Partnership

Location: Seattle, Washington, USA

How?: The building excludes 362 "Red List" elements that are toxic, carcinogenic, mutagenic, or endocrine disrupting, this includes materials and furnishings as well. The list is produced by the International Living Future Institute (ILFI).

The building also has a rainwater collection and filtering system, on-site treatment of sewage, and composting toilets.

The Bullitt Center also became the first office in the United States to receive a project certification from the Forest Stewardship Council. Here is a great article on the Bullitt Center.

Building: The Edge

Biomimicry Life's Principle Applied: Be resource efficient

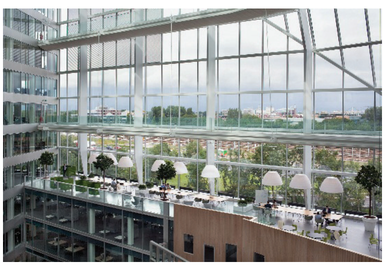

Figure 4.5. – The Edge, Amsterdam, The Netherlands © bloomberg.com

Architect: PLP Architecture with local support from OeverZaaijer as architect of record (AOR)

Location: Amsterdam, The Netherlands

How?: By being extremely efficient and generating more energy than it consumes. The building utilizes solar panels, rainwater harvesting system, et. cetera to support its integrated, digitized energy network that uses smart meters to manage and optimize the production, distribution, and consumption of energy including renewable sources. The building has sensor-controlled lighting and heating and reduces carbon emissions. From the beginning the building was designed to be "energy-positive", which means as we stated before – the building generates more energy than it consumes.

"...Regarded as one of the world's greenest office buildings, The Edge achieved a BREEAM Outstanding rating with a record-breaking 98.36 percent score..." – Institute of Sustainability Studies

Building: Centre for Science and for Children aka The "Cradle-to-Cradle Pavilion" aka Terra – The Sustainability Pavilion

Biomimicry Life's Principle Applied: Break down into benign constituents

Figure 4.6. – The "Cradle-to-Cradle Pavilion" aka Sustainability Pavilion (Terra), Jebel Ali, UAE © construction21.org

Architect: Grimshaw

Location: Jebel Ali, UAE

How?: All materials certified Cradle-to-Cradle; Captures solar energy and water from the air, utilizes recycled products in some of its functions, and focuses on a closed loop system where all waste is repurposed to something useful for a new cycle. For example, the project utilizes carpet tiles that are compostable and can be returned to the soil.

"...Drawing inspiration from complex natural processes like photosynthesis, the dynamic form of the Pavilion is in service to its function, capturing energy from sunlight and fresh water from humid air..." – Grimshaw

TERRA – THE SUSTAINABILITY PAVILION EXPO 2020 DUBAI: CASE STUDY

This project made great use of local resources from placing an emphasis on the subsurface where the heat in the warmer months can not cause occupant discomfort.

What happens with those spaces above ground?

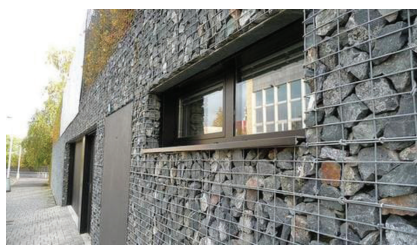

Figure 4.7. – Image of a Gabion wall veneer © gabionsupply.com

There is an earth roof system, which reduces the cooling load for the active system servicing the building.

The use of a light-colored gabion rainscreen wall comprised of local stone from the mountains nearby that acts as a thermal mass to absorb heat and reflect the sun. The same was done regarding the landscaping (flora and fauna) which interestingly enough included species never cultivated by humans. Water recycling and reuse occurs on-site as well.

> **"…Soaring over the courtyard, the Pavilion's canopy accommodates more than 6,000 sqm of ultraefficient monocrystalline photovoltaic cells embedded in glass panels. The combination of the cell and the glass casing allow the building to harness solar energy while providing shade and daylighting to the visitors below…"**
> **– Grimshaw**

Building: Park 20|20

Biomimicry Life's Principle Applied: Use cyclical processes

Architect: William McDonough + Partners, Master Planning

Nelson Byrd Woltz, Landscape Architect

Location: Beukenhorst Zuid, Hoofddorp, Haarlemmermeer, North Holland, the Netherlands

- **How?:** Modeled after natural nutrient cycles and creates "closed-loop" systems to sustainably manage waste, energy, and water.

"90% reductions in water use via the development's solar-powered grey-water treatment facility." – Healthy Urbanism

Figure 4.8. – Park 20|20 is the first Cradle-to-Cradle (C2C) urban development project in the Netherlands (in Hoofddorp) © healthyurbanism.net

"Responding to its unique cultural, environmental and contextual challenges, the…Park 20|20 masterplan creates a mixed-use development that synthesizes the issues of access and mobility, connectivity, passive design, and integrated energy, water and waste management systems…"
— William McDonough + Partners

Building: Venlo City Hall (stadskantoor (council offices))

Biomimicry Life's Principle Applied: Recycle all materials

Figure 4.9. – Venlo City Hall, Venlo, Netherlands © inhabitat.com

Architect:

Location: Venlo, Netherlands

How?: 99.8 % construction waste diverted + material passport for future disassembly

"Two solar chimneys also passively heat and cool the building."
– Ellenmacarthurfoundation.org

> **The "…top floor features a greenhouse with seasonal workplaces and room to grow regional products that also heats and humidifies the air that enters the building.**
>
> **The green air-purifying façade is the largest green building façade in the world and forms a protective shell against traffic and railway pollution…" – Kraaijvanger**

The building purifies air through the 'green lung' façade, recycles rainwater and waste water, is energy neutral and promotes wellbeing. In addition, the building produces no waste: it is in fact a temporary raw materials bank with guaranteed residual values for a number of products. The building's green façade creates (bio)diversity: like a vertical city park, it is a natural biotope for more than 100 plants, animals and insect species.

> **The air in Venlo's new city hall is purer than the air outside and purifies air in a 500m radius around the building. Cradle to cradle principles and holistic thinking in action in a city's buildings.**
> **– Ellen MacArthur Foundation**

Aside from your typical city hall programming there is also a lush garden with helophyte filters.

Helophyte filters are natural, earth friendly water purification systems that use wetland plants (for example reeds) and their root systems, along with filtering media (sand or gravel) and beneficial bacteria, to remove pollutants like nitrates, phosphates, and organic matter from wastewater or runoff.

There are two types of helophyte filters, up-flow and down-flow, up-flow is the better filter if your client can afford it.

HELOPHYTE (NATURAL WATER PURIFICATION SYSTEM) FILTER TYPES (Quantities, diameter and lengths vary per project)	
UP–FLOW	DOWN–FLOW
Required materials Up-flow: A Wall duct. B Grid with vegetation mat. D Clean lava or pond substrate. D Bio balls or Zeolite. E Emergency shaft.	**Required materials Down-flow:** A Drain collector. B PE drainage pipe with sockets. C Bio balls or Zeolite. D Clean lava or pond substrate. E PVC pipe. F Wall ducts
Features of Up-flow filtration – Excellent contamination management. – Lower impact on the substrate bed. – Lower maintenance frequency. – Pre-filtration possible. – Higher fitting costs.	**Down-flow filtration features** – Lower technical cost. – Higher maintenance frequency. – More bottom contamination. – Pre-filtration is not possible with this construction.
Source: https://tinyurl.com/2zsry5mc	

Building: Eastgate Centre

Biomimicry Life's Principle Applied: Leverage cyclic processes

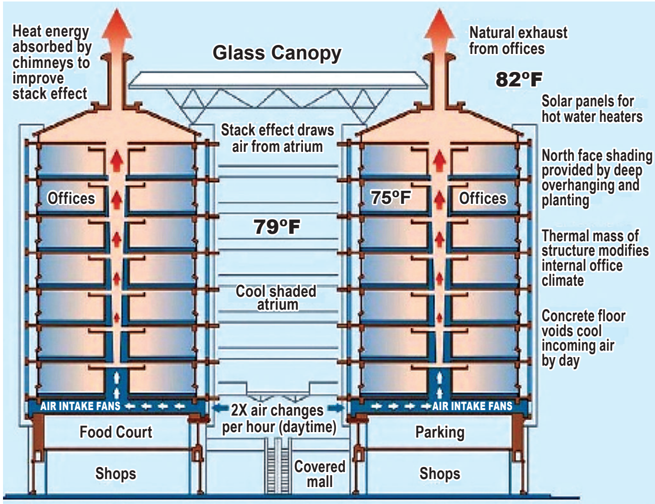

Figure 4.10. – Eastgate Centre, Harare © neverenougharchitecture.com

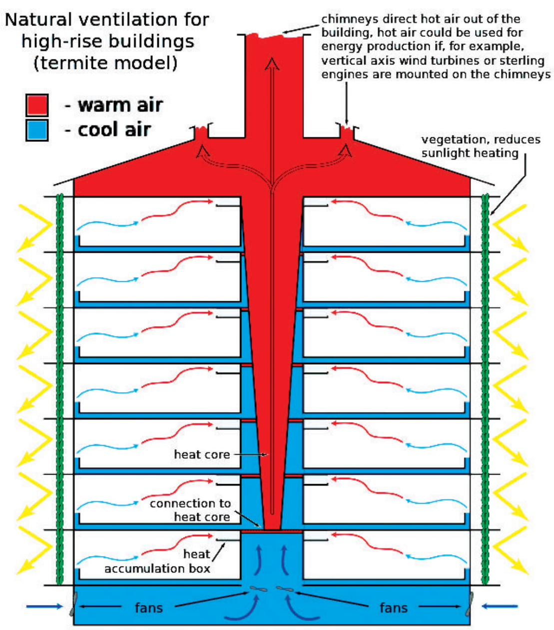

Figure 4.11. – A schematic showing the natural ventilation used in the Eastgate building in Harare. © AskNature.org

Architect: Mick Pearce in collaboration with Arup engineers (Enjoy this really great podcast with Mick Pearce)

Location: Harare, Zimbabwe, Afrika

How?: Uses passive systems and energy-efficient mechanisms to maintain occupant comfort and reduce energy consumption. The true definition of biomimicry as its natural ventilation system mimics indigenous Zimbabwean masonry mastery and self-cooling termite mounds as mentioned in earlier sections.

> **"…the $35 million building saved 10% on costs up-front by not purchasing an air-conditioning system. Rents are less expensive in this building compared to nearby buildings because of the savings in energy costs…" – AskNature.org**

The building has no conventional air conditioning or heating but has an interior temperature that stays regulated year-round.

"Outside air that is drawn in is either warmed or cooled by the building mass depending on which is hotter, the building concrete or the air. It is then vented into the building's floors and offices before exiting via chimneys at the top. The complex also consists of two buildings side by side that are separated by an open space that is covered by glass and open to the local breezes." – Inhabitat.com

Building: BIQ (Bio Intelligent Quotient) House

Biomimicry Life's Principle Applied: Use multifunctional design

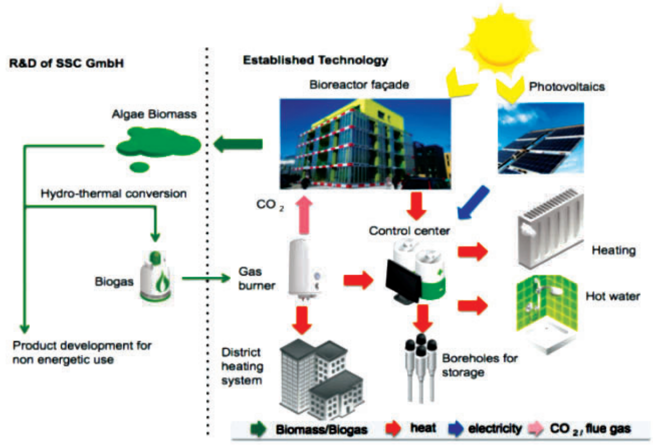

Figure 4.12. – BIQ House algae façade, Hamburg, Germany © Steemit

Architect:

Location: Hamburg, Germany

How?: This was the world's first pilot project to showcase a bioreactive façade and the world's first algae-powered building.

How is it bioreactive? Multifunctional?

Over 2K square footage of integrated photo-bioreactors, which generates biomass and heat as renewable energy resources.

Simultaneously the building also has dynamic shading, thermal insulation and noise abatement. The noise abatement plays well into the typology of the 4 storey building which houses 15 residential units.

> **"The microalgae used in the facades are cultivated in flat panel glass bioreactors measuring 2,5m x 0,7m. In total, 129 bioreactors have been installed on the south west and south east faces of the four-storey residential building. The heart of the system is the fully automated energy management centre where solar thermal heat and algae are harvested in a closed loop to be stored and used to generate hot water." – Architonic**

The bioreactors are placed to harvest the sunlight on all sun-facing sides of the building which the algae use as fuel to initiate its photosynthesis process and generate bioenergy.

What is even cooler (no pun intended) is that each bioreactor panel can rotate on its vertical axis to track the sun path and then in the evening close and act as a thermal buffer.

There are a total of 129 bioreactors (which contain 6 gallons of water each) which produce an annual net energy output of 4.5K kWH exceeding the average household at 3.5K kWh. This means even more given this is a residential building.

What is interesting is that there is some continuous maintenance required – compressed air injections done periodically to optimize algae growth *and* prevent overaccumulation. What truly ensures the algae growth and nourishment is carbon dioxide (algae's main food source) it is supplied from the exhaust of a ground-floor generator.

> "…excess heat produced by the algae-filled panels is harnessed and used to improve the building's overall energy efficiency. This heat is transferred to a heat exchanger and either used directly for domestic hot water and space heating or stored in saline water tanks beneath the building for later use. By repurposing the heat generated within the bioreactors, the BIQ House maximises (sic) energy savings and further demonstrates how living systems can contribute to sustainable architectural solutions…"
> – Re-Thinking The Future

Not really a maintenance item but something that must be planned and maintained – the algae is harvested weekly and transported to a nearby university for processing into methane and hydrogen.

Can this be adopted worldwide?

Yes and no. The BIQ House is successful almost exclusively based on its geographic location and climate.

Hamburg, Germany is located on the Elbe River where it meets the Alster and Bille rivers and has a temperate Oceanic Climate i.e. moderate temperatures, no dry season, and warm summers ("Cfb" in the Köppen classification system). Where a replica of the BIQ house would be most successful is the following locations that have a similar geographic location and climate:

North America

- Port Angeles, Washington, USA
- Victoria, British Columbia, Canada

South America

- Valdivia, Chile
- Curitiba, Brazil

Oceania

- Melbourne, Australia
- Auckland, New Zealand

Africa

- George, South Africa
- Dullstroom, South Africa

Asia

- Matsue, Japan
- Da Lat, Vietnam

Europe

- Amsterdam, Netherlands
- London, United Kingdom

If you are stateside or really smitten with bio-reactive facades and the like you will be glad to know that the University of North Carolina – Charlotte in Charlotte, North Carolina received a grant from the National Science Foundation to fund the development of a high-performing window system that "…reduces building energy consumption and carbon dioxide emissions…"

– Inside UNC Charlotte

Building: Basílica de la Sagrada Família

Biomimicry Life's Principle Applied: Fit form to function

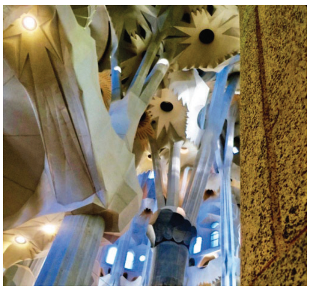

Figure 4.13. – Basílica de la Sagrada Família columns, Barcelona, Spain © wandering-through-time-and-place.com

Architect: Antoni Gaudi

Location: Barcelona, Spain

How?: Tree-branching, bone-inspired hyperboloid columns carry load with minimal material. Antoni drew his inspiration directly from nature.

> "The interior pillars resemble trees and, when looking up, the shapes of the pillars change as do those of the trees. Gaudí designed images of a turtle and tortoise on these pillars to represent the water and earth."
> – Catalonia Hotels

Gaudi was true to himself and to the world. His beliefs and love of nature shone through in all of his works, one example of many being Basílica de la Sagrada Família. As Gaudí said "*This tree by my workshop, this is my master!*"

> "…Gaudi had his own unique source, and that made him special and different from other artists/architects.
>
> It was NATURE – he loved nature…In addition, when he was sick in early ages, nature was his best friend – he observed nature everyday and inspired by it.
>
> The nature easily became his strength and specialty as an artist. There is none of his artworks that are not related to the nature. Nature was his artistic motivation and the most significant material. It soon became his own artistic identity and storytelling.
>
> Everything in his architecture is based on NATURE…"
> – So Sunny Project

Building: Powerhouse Kjørbo

Biomimicry Life's Principle Applied: Use only the energy needed

Figure 4.14. – Powerhouse Kjørbo, Norway © kommunikasjon.ntb.no

Architect: International architecture firm Snøhetta, Swedish contractor Skanska, the environmental NGO Zero, and various other partners

Location: Sandvika, Norway

How?: "Powerhouse Kjørbo, which is Norway's first energy-positive office building and may be the first renovated energy-positive building in the world" – Business Norway

To support making the renovation a success in the direction of being energy-positive, the existing façade was replaced with triple-glazing and insulated panels and certain existing windows repurposed with interior partitions.

> "…During construction, we prioritized recycling and reusing materials, resulting in over 90% of construction waste finding new life in other projects…"
> – Rise Design Studio

The existing roof was bolstered and modified to house over 16K square feet of solar photovoltaic arrays which produce 2x the energy the building needs to function.

This project also received (based on BREEAM-NOR, passive house standard NS 3701) an environmental classification of BREEAM-NOR Outstanding.

This project alone proves that with the right leadership and backing any existing building can go from blight to game changer overnight.

Building: Gando Primary School

Biomimicry Life's Principle Applied: Self-organize

Figure 4.15. – Students sitting in the shade of Gando Primary School, Gando, Burkina Faso, Afrika © Erik-Jan Ouwerkerk, kerearchitecture.com

Architect: Francis Kéré of Kéré Architecture

Location: Gando, Burkina Faso, Afrika

How?: Local communities self-build with modular clay blocks that evolve over time.

Local materials and resources near the site were used to construct the school including clay bricks as mentioned above but also a clay/cement hybrid brick.

Where the bricks were strong and acted as a thermal barrier they needed to be protected from the rain which damaged its composition.

The building has no need for an active system to provide HVAC as the entire school is naturally ventilated. The corrugated metal roofing system paired with a clay brick roof/ceiling and cool air coming in from interior windows supports the need for only natural ventilation.

> "…For this project, traditional building techniques and modern engineering methods were combined to produce the best quality building solution while simplifying construction and future maintenance. The success of the project can be attributed to the close involvement of the local population in the building process…" – Kere Architecture

Building: Earthship Biotecture

Biomimicry Life's Principle Applied: Use low-energy processes

Figure 4.16. – Earthships (global) made of tire walls © nbcnews

Architect: Michael E. Reynolds

Location: Worldwide

How?: "An Earthship is a style of architecture developed in the late 20th century to early 21st century by architect Michael Reynolds. Earthships are designed to behave as passive solar earth shelters made of both natural and upcycled materials such as earth-packed tires." – Wikipedia

This type of architecture is two-fold as it does use every day discarded items to build housing but unfortunately it did not resolve standard issues traditional houses never face or never face consistently which are leaky roofs or inadequate climate control i.e. poor occupant comfort.

If you have time on a Saturday night when you are not transforming the AEC industry, watch "Garbage Warrior" which tells the story of eco architect Michael E. Reynolds.

Building: 3D Printed Stainless Steel Pedestrian Bridge

Biomimicry Life's Principle Applied: Use benign manufacturing

Figure 4.17. – MX3D 3D-printed steel bridge, Amsterdam (2021) © friedmanbenda.com)

Architect: MX3D; Joris Laarman Lab and engineered by Arup. Additional expertise was provided by ArcelorMittal, Autodesk, Heijmans, Lenovo, ABB, Air Liquide & Oerlikon, Plymovent, and TU Delft

Location: Amsterdam, the Netherlands

How?: Building a bridge using 3D printing which required 50% less steel, generated zero formwork waste, and cost savings up to 80%.

What is interesting is that such a forward-thinking bridge was used to cross "…one of the oldest and most famous canals in the center of Amsterdam…".

There is a sensor network on the bridge that collect structural measurements (like strain, displacement, and vibration) and measures environmental factors like air quality and temperature. This permits engineers to measure the bridge's structural health in real time and monitor how it changes over its lifespan.

Interested in bringing a 3D printed bridge to your jurisdiction? Here is the reality:

> "…Building a 3D-printed bridge in Amsterdam's Bridge District involves relatively high upfront costs, a multi-year timeline, and careful regulatory coordination. The project required significant investment in robotic 3D-printing technology, stainless-steel materials, engineering expertise, testing, and digital monitoring systems, making it more expensive than a conventional small pedestrian bridge at this experimental stage.
>
> The timeline extended over several years: the design and technology development started around 2015, the robotic printing itself took several months, and additional time was needed for structural testing, sensor integration, and approvals before the bridge was installed and opened to the public in 2021…" – MX3D

Building: Bosco Verticale (residential towers)

Biomimicry Life's Principle Applied: Build resilience through diversity

Figure 4.18. – Bosco Verticale, Milano, Italia © pedestal-eternoivica.com

Architect: Stefano Boeri

Location: Porta Nuova District, Milano, Italia

How?: This project embodies biodiversity due to having 900 trees, 1000s of plant species and shrubs. All of which attract local animal species and contribute to acting as a buffer to the wind.

What is interesting also is that landscaping was meticulously selected based on specific needs in terms of exposure, for example evergreens were placed on the southwest side and deciduous trees on the northeast side. With this their height development in relation to balcony design, and their impact on occupant health and well-being. You can see the strong biophilic design elements in this project as well. We know it will be greatly appreciated by the building occupants and their visitors.

Speaking of occupants, each apartment contains at least 2 trees, 8 shrubs, and 40 plants for each tenant, allowing for proximity to the green component and the related physical and psychological benefits. Again, the biophilic design aspect is coming into play.

In addition, there is a water management system that utilizes groundwater and recycles the building's greywater. On the roof, solar panels provide the energy required to pump water to all floors through the irrigation system for the plants.

> "…The Bosco Verticale houses vegetation equivalent to about five hectares of parkland on flat land, but concentrated on an area of approximately 1,000 square meters, which is fifty times less.
>
> It offers significant benefits in terms of fine dust and CO_2 absorption, oxygen production, optimization of water management, reduction of noise pollution, and improvement of the life quality–for humans, plants, and animals…" – Stefano Boeri Architetti

Building: Oman Botanic Garden

Biomimicry Life's Principle Applied: Create conditions conducive to life

Figure 4.19. – Oman Botanic Garden, Al Hajar Mountains, Oman © inhabitat.com

Architect: Grimshaw Architects

Location: Al Hajar Mountains, Oman

How?: Restores degraded wādī *(which means valley or dry riverbed)* ecosystem while housing the building; net-positive water & biodiversity.

Botanic diversity is shown in this project by the two biomes and surrounding external habitats which contain the country's most endangered and endemic flora.

> The garden contains "…Passive and active shading, UV light controls, cooling and plant irrigation are integrated throughout the gardens. Building form, shape and materials have been considered and selected in response to atmospheric conditions and the natural topography…" – Grimshaw

Building: Pixel Building

Biomimicry Life's Principle Applied: Optimize rather than maximize

Figure 4.20. – Pixel Building, Melbourne, Australia © inhabitat.com

Architect: Studio 505; Developer was Grocon

Location: Melbourne, Australia

How?: Along with being "Australia's First Carbon Neutral Building" – inhabitat.com.

This project generates its own power, practices on-site rainwater harvesting, waste reduction, is energy efficient, utilizes wind turbines, solar panels, and green roofs.

As expected with traits as those stated above, this project has earned a top Green Star rating and LEED rating.

> "…Pixel has achieved a perfect score of 100 under the Greenstar rating system, with 75 points the benchmark for 6 Star Greenstar. It gained an extra five points for innovation, equating to world leadership. Included in Pixel's five innovation points were points for carbon neutrality, a vacuum toilet system, the anaerobic digestion system and reduced car parking…" – Studio 505

Building: Masdar City wind towers & solar chimney

Biomimicry Life's Principle Applied: Use free energy

Figure 4.21. – Masdar City wind towers & solar chimney prototypes © solarchitecture.ch

Architect: Foster + Partners provided the sustainable vision and integrated the passive cooling/energy systems in the city's design

Location: Masdar City, Abu Dhabi, UAE

How?: Provides cooling by use of an ancient wind tower (or barjeel), which captures the prevailing wind, channels it down past cooling mist jets into a central courtyard.

Also this is the first building of its kind to be powered entirely by renewable solar energy.

> "A 10-megawatt solar field within the masterplan site provides 60 per cent more energy than is consumed by the Masdar Institute, all of which can be fed back to the Abu Dhabi grid." – Foster and Partners

Building: CH2 – Council House 2

Biomimicry Life's Principle Applied: Cross-pollinate & collaborate

Figure 4.22. – CH2 – Council House 2, Melbourne © inhabitat.com

Architect: Mick Pearce

Location: Melbourne, Australia

How?: Deep collaboration between all stakeholders and end users i.e. biologists, engineers, artists, and citizens from day one as the building was "…examined and rethought from first principles, evolving new precepts that are based in the desire to be as true as possible to the fundamental "laws of nature...".

Interesting energy and architectural facts:

Power consumption is 80% reduced, water consumption is 75 reduced, air intake is not recycled at all (100% filtered outside air), biophilic interior, non-toxic materials, a roof garden, and a plant-to-person ratio of 1.

> "…the first in the country to achieve the highest possible rating of six stars in Australia's Green Star environmental accreditation… CH2's public face is the tall facade overlooking Swanston Street, one of Melbourne's public boulevards. It is entirely composed of timber vertical slats covering a fully glazed wall. These slats pivot vertically, opening and closing in response to the time of day and the angle of the sun.
>
> The facade is thus animated in direct response to the external conditions. This is biomimicry at its very best – the building moving and becoming alive in response to the conditions surrounding it…" – Mick Pearce

Building: ETH Zurich Block Research Group

Biomimicry Life's Principle Applied: Build from the bottom up

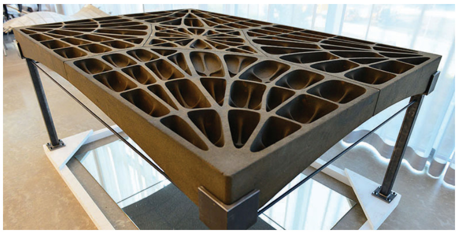

Figure 4.23. – Nacre-inspired concrete panels, ETH Zurich Block Research Group © Ethz.ch)

Architect: *ETH Zurich Block Research Group*

Location: Zurich, Switzerland

How?: "Researchers at ETH Zurich's Department of Architecture (D-ARCH) have developed a concrete floor system that does not require steel reinforcement and is 70 percent lighter than conventional concrete floors. Their design was inspired by historical construction principles." – Ethz.ch

Building: WikiHouse

Biomimicry Life's Principle Applied: Combine modular & nested components

Architect: Alastair Parvin and Nicholas Ierodiaconou (Nick Ierodiaconou) as part of the London design practice 00 (Zero Zero)

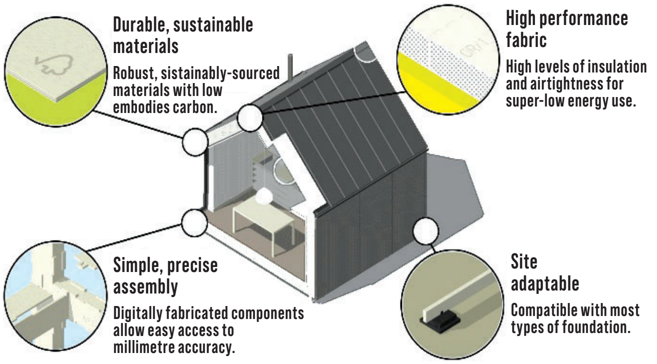

Figure 4.24. – WikiHouse open-source system (global deployments) © architizer.com

Location: Global

How?: By giving all people the ability to use a modular system to create a beautiful, high-performance, energy efficient, zero-carbon home.

"Free: Download a Construction Kit to Build Your Own "WikiHouse" This open-source construction kit can be turned into a home in just one day." – architizer.com

> "Advanced building technology, for everyone. WikiHouse uses digital fabrication to create timber building components that can be assembled in hours, to millimetre precision. We have a growing network of engineers, manufacturers and installers who can help you build your project better, faster." – Wikihouse

Building: Netherlands

Biomimicry Life's Principle Applied: Foster self-renewal & regeneration

Figure 4.25. – Sand Motor peninsula + Building with Nature, Netherlands Coast © climate-adapt.eea.europa.eu

Architect: Collaboration project led by H+N+S Landschapsarchitecten, involving Deltares and DHV, with construction by Boskalis and Van Oord

Location: Netherlands Coast

How?: Sediment is continuously renewed by wave action along the coastline.

> "With the Sand Motor pilot project, a large quantity of sand was deposited near the Dutch coast. Wind, waves and sea currents gradually distribute the sand along the coastline between Hook of Holland and Scheveningen." – H+N+S

These projects collectively prove that Biomimicrys' Life's Principles are already achievable today with existing technology and materials– no excuses. Regenerative, biomimetic, Living Building-level performance is not theoretical– it's built and tangible. We purposely did not show the dates but some of these projects are almost 20 years old.

Let's take a closer look at what could be considered in the USA as the definition of Biomimicry or as some even call it the World's Greenest Commercial Building.

The Bullitt Center (Seattle, Washington, USA)

Figure 4.26. – The Bullitt Center – Exterior View © bullittcenter.org

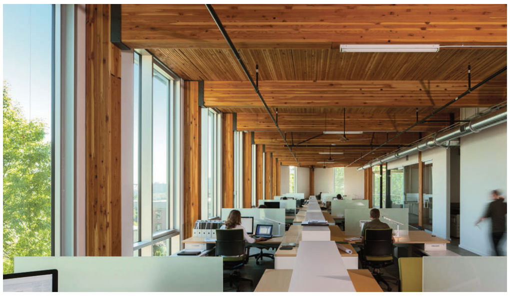

Figure 4.27. – The Bullitt Center – Interior View © bullittcenter.org

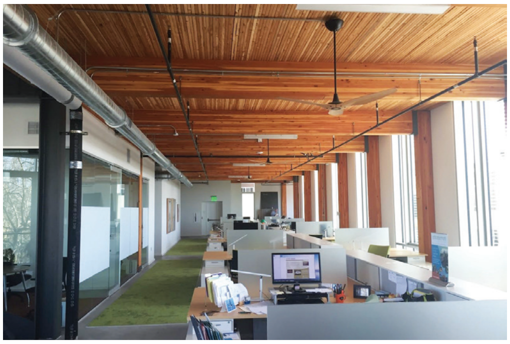

Figure 4.28. – The Bullitt Center – Interior Office View © lloydalter.substack.com

Figure 4.29. – The Bullitt Center – Lobby © bullittcenter.org

BIOMIMETIC STRATEGY / NATURAL MODEL	HOW THE BULLITT CENTER TRANSLATES IT	LIFE'S PRINCIPLE(S) EMBODIED	PERFORMANCE OUTCOME
FOREST AS THE ARCHETYPE (ECOSYSTEM-LEVEL BENCHMARK)	Reduction of the carbon footprint due to the FSC-Certified heavy timber structure. The timber was sourced locally within 621 miles from the project site. "Concrete is one of the most notorious carbon emitters in the construction industry." – Bullitt Center.org	Create conditions conducive to life, Be locally attuned and responsive, Evolve to survive	Certified as a Living Building by the International Living Building Institute
LEAF-LEVEL LIGHT CAPTURE + TRANSPIRATION	The building is "Net Positive" for solar as its over 500 solar panels generate more energy than the building uses annually	Leverage cyclic processes, Multifunctional design	"Net Positive" energy produced annually
TERMITE-MOUND / CHIMNEY-EFFECT NATURAL VENTILATION	The building has a living façade that adapts to the outside climate to ensure occupant comfort. This is done by using exterior louver shades, opening windows or heating or slightly cooling the radiant slab at each floor. Active systems are in place in case the façade is closed.	Use low-energy processes, Adapt to changing conditions	Naturally ventilated and opens, rotates, and closes different architectural elements to maintain occupant comfort.
CACTUS / NAMIB BEETLE WATER STRATEGY	"Net positive" for water by implementing rainwater harvesting and stormwater management. "Net positive" in this aspect means that the building creates more potable water than it uses.	Be resource efficient, Use readily available materials & energy	Building creates more potable water than it uses.
NACRE / BONE (MATERIAL HEALTH & EFFICIENCY)	Effort was made to ensure that products that did not contain "Red List" chemicals were used in the design and construction of the center.	Use life-friendly chemistry, Build from the bottom up	Did not use products with "Red List" chemicals

BIOMIMETIC STRATEGY / NATURAL MODEL	HOW THE BULLITT CENTER TRANSLATES IT	LIFE'S PRINCIPLE(S) EMBODIED	PERFORMANCE OUTCOME
FOREST FLOOR NUTRIENT CYCLING	100 % onsite composting toilets; Update: As of 2021, the onsite composting toilets have been replaced with a vacuum system that uses 70% less water!	Use cyclical processes, Break down into benign constituents	The vacuum pumps pull waste through a grinder... then into a collection tank. From the collection tank, waste goes into the public sanitary sewer system for treatment. Solids from the sewage treatment plant are converted into a human waste loop is then used as a fertilizer.
SALMON-RUN MIGRATION (DAYLIGHTING & VIEWS)	Daylight illuminates the interior "... for 90% of the time without the need for electric lighting... The lighting design incorporates simple lighting controls: manual dimming, occupancy sensors, photocells, and plain old wall switches...." – Bullitt Center	Be locally attuned (Pacific NW species), Create conditions conducive to life	The interior only needs electrical lighting 10% of the time during the day.

Quote from the Design Team:
"We didn't just want a green building. We wanted a building that functioned like the Pacific Northwest ecosystem that was here before Seattle existed – one that generates its own energy, captures and purifies its own water, operates efficiently with life-friendly materials, and ultimately gives back more to the environment than it takes."
– Denis Hayes (Bullitt Foundation President) & Jason F. McLennan (chief architect)

The Bullitt Center is one of the strongest biomimetic reference projects in the world because it proves the major Life's Principles can be achieved using today's technology and done so reasonably. The Bullitt Center remains the highest standard that every new Living Building (and every serious biomimetic project) is or should be measured against.

Find below more examples that show how biomimicry is being applied across the AEC industry in real-world projects and how emerging technologies are shaping future design possibilities.

1. SPIDER SILK (STRENGTH, FLEXIBILITY, ENERGY ABSORPTION)

Built Examples:

- **Beijing National Stadium (China)**
  - **Design Inspiration:** Spider silk's high tensile strength and flexibility.
  - **Key Features:** The stadium's intricate steel frame mimics spider silk's strength-to-weight ratio. The web-like structure provides flexibility and energy absorption, making it resilient to wind and seismic forces.
  - **Impact:** The "Bird's Nest" is a global architectural landmark demonstrating how biomimicry can inform structural efficiency.

Figure 4.30. – The National Stadium (国家体育场), a.k.a. the Bird's Nest (鸟巢) in Beijing, China © CEphoto, Uwe Aranas Wikipedia

- **The Eden Project (UK)**
  - **Design Inspiration:** Spider silk's strength and tensile properties.
  - **Key Features:** The geodesic biomes' lightweight, flexible ETFE (ethylene tetrafluoroethylene) panels mimic the properties of spider silk, providing high strength with minimal material use. The panels are resilient to environmental stress, similar to spider silk's behavior under tension.
  - **Impact:** The project is an exemplary of how natural materials and biomimetic design principles can create efficient, low-carbon buildings.
- **The Millennium Bridge (UK)**
  - **Design Inspiration:** Spider silk's ability to handle tensile loads with minimal material.
  - **Key Features:** The suspension bridge utilizes high-strength steel cables that exhibit a spider silk-inspired structure, focusing on strength, minimal material use, and efficient load bearing.
  - **Impact:** The bridge's design maximizes tensile strength while minimizing environmental impact, proving the efficiency of spider silk principles in large-scale infrastructure.

2. HONEYCOMBS (GEOMETRIC EFFICIENCY, STRENGTH-TO-WEIGHT RATIO)

Built Examples:

- **Al Bahar Towers (Abu Dhabi, UAE)**
  - **Design Inspiration:** Diatom-like perforated structures and hexagonal grids.
  - **Key Features:** The façade incorporates hexagonal shading panels that adjust dynamically to the sun's position, inspired by the perforation patterns of diatoms. This system reduces solar gain and improves energy efficiency.
  - **Impact:** Al Bahar Towers demonstrate how nature-inspired designs can mitigate extreme climate conditions, reducing energy consumption in the harsh desert environment.

Figure 4.31. – Al Bahar Tower 1 in Abu Dhabi, United Arab Emirates © Aedas, Skyscrapercenter.com

- **The Crystal (London, UK)**
  - **Design Inspiration:** Honeycomb and nacre-inspired composite materials.
  - **Key Features:** The building's façade and cladding are made with tough, lightweight materials that use honeycomb-like structures to balance energy efficiency and strength.
  - **Impact:** The Crystal serves as a model for energy-efficient, sustainable building designs, combining biomimicry with cutting-edge materials science.

3. DIATOMS (POROSITY, LIGHTWEIGHT STRENGTH)

Built Examples:

- **Al Bahar Towers (UAE) (Refer to Figure 2.13 above)**
  - **Design Inspiration:** Diatom-like perforated structures.
  - **Key Features:** The façade of Al Bahar Towers is composed of dynamic hexagonal panels inspired by diatom structures. These panels adjust based on the sun's position, maximizing shading and reducing energy consumption.
  - **Impact:** The towers demonstrate how lightweight materials and responsive, diatom-inspired perforations can reduce energy costs while improving structural performance.

- **The Gherkin (London, UK)**
  - **Design Inspiration:** Diatom-like geometries for perforation and material distribution.
  - **Key Features:** The building's double-glazed façade features a series of ventilated spaces inspired by the natural perforated structure of diatoms, optimizing the distribution of light and heat.
  - **Impact:** The Gherkin shows how diatom-inspired facades can create highly efficient, energy-conserving buildings.

- **The Edge (Amsterdam, Netherlands)**
  - **Design Inspiration:** Lightweight, energy-efficient structural materials inspired by diatoms.
  - **Key Features:** The building's façade is designed with thin, perforated panels that provide shading and heat dissipation while minimizing material usage, similar to diatom microstructures.
  - **Impact:** The Edge demonstrates how diatom-inspired principles can be applied to office buildings, resulting in cutting-edge energy-efficient solutions.

Figure 4.32. – Exterior elevation of The Edge
© By AValečka – Own work, CC BY-SA 4.0, Commons Wikimedia

4. TERMITE MOUNDS (PASSIVE CLIMATE CONTROL, NATURAL VENTILATION)

Built Examples:

- **Eastgate Centre (Harare, Zimbabwe)**
  - **Design Inspiration:** Termite mound cooling and ventilation strategies.
  - **Key Features:** The Eastgate Centre uses a passive cooling system based on the principles of termite mound architecture. The building's design includes thick concrete walls, natural ventilation, and chimneys that draw in cool air and expel hot air.
  - **Impact:** This innovative use of natural climate control has reduced the building's energy consumption by over 90%, showcasing the potential of biomimicry in low-energy design.

Figure 4.33. – The Eastgate Centre Shopping Centre & Office Building; The building is ventilated and cooled entirely by natural means.
© David Brazier – Wikipedia

- **The Louvre Abu Dhabi (UAE)**
  - **Design Inspiration:** Termite mound-inspired passive cooling techniques.
  - **Key Features:** The museum uses a large dome structure that mimics the natural thermal behavior of termite mounds. The dome's design ensures natural airflow and temperature regulation, reducing the reliance on artificial cooling systems.
  - **Impact:** The Louvre Abu Dhabi stands as an example of how biomimicry can be applied to large-scale, culturally significant buildings while achieving high energy efficiency.

- **The Green Building (USA)**
  - **Design Inspiration:** Termite mound-inspired natural ventilation systems.
  - **Key Features:** This office building in California uses passive cooling strategies derived from termite mounds, such as a ventilated double-skin façade, and a natural airflow system.
  - **Impact:** The building's energy consumption is significantly lower than that of typical office buildings, demonstrating how biomimetic design can optimize environmental performance.

5. TREES (BRANCHING, STRESS-BASED TAPERING, LOAD DISTRIBUTION)

Built Examples:

- **Sagrada Familia (Spain)**
  - **Design Inspiration:** Tree branching for structural optimization.
  - **Key Features:** Gaudí's design for the Sagrada Familia uses columns and arches that mimic tree-like structures, with tapered columns and branching supports designed to follow natural stress paths.

- **Impact:** The cathedral's iconic, nature-inspired design allows for efficient material use while achieving both beauty and stability.

- **Bosco Verticale (Milano, Italia)**
  - **Design Inspiration:** Trees for structural optimization and load distribution.
  - **Key Features:** The two residential towers in Milan are covered with thousands of trees and plants, which contribute to the building's natural cooling system and reduce energy consumption. The trees' branching patterns optimize wind resistance and structural integrity.
  - **Impact:** Bosco Verticale is a pioneering example of how tree-like design principles can enhance both sustainability and urban aesthetics.

Figure 4.34. – Bosco Verticale in Milano, Italia © Darsheni – Wikipedia

- **Chapel of St. Ignatius (USA)**
  - **Design Inspiration:** Tree branches and load distribution for architectural stability.
  - **Key Features:** The design of the chapel includes branching structural elements that mirror tree forms, with a central space supported by a network of slender, tapering columns.
  - **Impact:** The design maximizes space and creates a sense of openness, while the branching column structure efficiently distributes loads.

6. NACRE (MOTHER OF PEARL) – TOUGHNESS, LAYERED COMPOSITES, CRACK DEFLECTION

Built Examples:

- **City Hall in Newham formerly known as "The Crystal" (London, UK)**
  - **Design Inspiration:** Nacre's tough, layered structure.
  - **Key Features:** The building's façade and structural materials are designed using layered composites that mimic the tough, crack-resistant structure of nacre. This allows for high-performance, lightweight materials that can absorb impact and resist damage.
  - **Impact:** The use of nacre-inspired materials in the building reduces energy consumption while providing durability and resilience.

Figure 4.35. – Exterior View of City Hall, HQ for the GLA formerly known as "The Crystal" © By Matt Buck – Flickr – Wikipedia

- **Biomimetic Composite Materials (Various Locations, R&D)**
  - **Design Inspiration:** Nacre's alternating hard-soft layers for toughness.
  - **Key Features:** Researchers are exploring the use of composite materials inspired by nacre's structure, particularly in the aerospace and automotive industries. These composites combine lightweight materials with enhanced toughness, providing resistance to cracks and impacts.
  - **Impact:** These biomimetic composites could revolutionize material design for lightweight, high-performance applications.

- **Laminated Glass Panels (Global) – Nacre-Inspired Toughened Glass**
  - **Design Inspiration:** Nacre's layered structure for crack resistance.
  - **Key Features:** Some modern glass designs incorporate laminated glass with a soft core and harder outer layers, mimicking the structure of nacre. This improves the glass's ability to resist impacts and spread stresses across its surface.
  - **Impact:** This design makes glass more durable and safer in high-traffic or high-risk areas, such as façades and skylights.

7. FISH SCHOOLING (FLOW OPTIMIZATION, COLLECTIVE BEHAVIOR)

Built Examples:

- **The Al Bahar Towers (UAE)**
  - **Design Inspiration:** Collective, responsive behavior of fish schools.
  - **Key Features:** The façade of the Al Bahar Towers features dynamic, sun-responsive shading panels that open and close based on the movement of the sun, similar to the adaptive, collective behavior seen in fish schools.
  - **Impact:** The building's adaptive façade reduces energy consumption by blocking excess sunlight and heat while optimizing natural light flow into the building.
- **Burlington House (USA)**
  - **Design Inspiration:** Collective behavior and dynamic adaptation of fish schools.
  - **Key Features:** The building features an adaptive HVAC system that responds to real-time occupancy and environmental factors. This collective system, inspired by the schooling behavior of fish, optimizes energy use and indoor air quality.
  - **Impact:** By dynamically adjusting to changing conditions, the system reduces overall energy use and increases occupant comfort.
- **Olympic Village (East Village) (London, UK)**
  - **Design Inspiration:** Fish schooling's collective flow and energy efficiency.
  - **Key Features:** The village used a smart grid and natural ventilation systems inspired by fish schooling patterns, with systems that respond to collective usage patterns and external weather conditions.
  - **Impact:** This contributed to the village's energy-efficient design and its recognition for sustainability.

Figure 4.36. – East Village in Stratford; Originally an Olympic Village and now a Mixed-Use community © EG Focus – Wikipedia

8. BEEHIVES (GEOMETRIC EFFICIENCY, LOAD BEARING, HONEYCOMB STRUCTURES)

Built Examples:

- **The Gherkin** *(word for "pickled cucumber")* **(London, UK)**
  - **Design Inspiration:** Hexagonal geometry and structural efficiency of beehives.
  - **Key Features:** The building's façade incorporates a pattern of hexagonal glass and steel panels that optimize material use, much like the hexagonal efficiency of honeycombs. This design reduces the structural weight while maximizing stability and strength.
  - **Impact:** The Gherkin showcases how honeycomb-inspired geometric patterns can create energy-efficient, aesthetically pleasing buildings with optimal structural performance.

Figure 4.37. – The Gherki aka 30 St Mary Axe aka the Swiss Re Building © Wikipedia

- **Beijing National Aquatics Center (China)**
  - **Design Inspiration:** Honeycomb structure for optimized load distribution.
  - **Key Features:** The "Water Cube" uses a transparent honeycomb structure to create an aesthetically striking, energy-efficient building. The design maximizes the use of space and material while maintaining structural integrity.
  - **Impact:** The structure reduces energy consumption while providing an innovative and visually appealing solution for large-scale public buildings.
- **Maggie's Centre (UK)**
  - **Design Inspiration:** Beehive-like geometric efficiency for structure and stability.
  - **Key Features:** The building's design uses modular, geometric panels inspired by the efficiency of beehives to create a lightweight, stable structure. This allows for the creation of an open, inviting space for users while minimizing material use.
  - **Impact:** The project demonstrates how honeycomb and geometric principles can optimize space and material use in small to medium-sized structures.

PART 4 – INTEGRATED STRATEGY AND REGENERATIVE PERFORMANCE KNOWLEDGE CHECK (5 QUESTIONS)

1. **How does the Al Bahar Towers in Abu Dhabi apply biomimicry principles?**
   A. By using a bioreactive façade to generate renewable energy
   B. By incorporating dynamic mashrabiya screens that respond to the sun's position
   C. By using termite mound-inspired passive cooling systems
   D. By integrating a honeycomb structure for load distribution

2. **What biomimicry principle is applied in the Bullitt Center's rainwater harvesting system?**
   A. Use life-friendly chemistry
   B. Be resource efficient
   C. Leverage cyclic processes
   D. Build from the bottom up

3. **Which building uses a bioreactive façade powered by algae to generate energy?**
   A. The Edge, Amsterdam
   B. BIQ House, Hamburg
   C. Bosco Verticale, Milan
   D. Masdar City

4. **How does the Eastgate Centre in Zimbabwe mimic termite mounds?**
   A. By using a honeycomb structure for load distribution
   B. By using algae-powered bioreactors for energy generation
   C. By incorporating passive cooling and ventilation systems
   D. By integrating a dynamic façade that responds to sunlight

5. **What is the primary biomimicry principle applied in the Bosco Verticale in Milan?**
   A. Build resilience through diversity
   B. Use low-energy processes
   C. Adapt to changing conditions
   D. Use life-friendly chemistry

You made it to the finish line!
This concludes the final part, Part 4 of the course.
Continue to the Final Exam.

OUTLOOK AND CONCLUSION

As displayed in each part of this training on Biomimicry and Regenerative Design, it has been shown that mother nature has all the answers for the built environment. It is just a matter of the design professional implementing these tried and true, real-world solutions so much so that such design approaches become normalized.

In conclusion, use this information and the additional document (found at the QR code below) to start or continue your journey in biomimicry.

It has been a joy producing this training for you and us here at MRA Architecture & Design wish you a great day and everlasting success!

BIOMIMICRY AND REGENERATIVE DESIGN
QUIZ ANSWERS | PARTS 1 – 4

PART 1 – Biomimicry and Regenerative Design Knowledge Check (5 Questions)

1. What is the primary goal of Biophilic Design?

A. Improve the performance of buildings in relation to the environment; Incorrect.

B. Enhance occupant well-being and emotional connection to nature; Correct. Biophilic Design is a human-centric approach that focuses on improving the well-being of occupants.

C. Mimic nature's strategies for technical innovation; Incorrect.

D. Reduce energy consumption through passive cooling; Incorrect.

2. Which of the following best describes the goal of Biomimicry?

A. To create spaces that reduce stress and improve mental health; Incorrect.

B. To mimic nature's strategies to improve performance and sustainability; Correct. Biomimicry focuses on studying and emulating nature's systems, structures, and strategies to solve technical challenges in the built environment.

C. To enhance the aesthetic appeal of buildings through natural elements; Incorrect.

D. To increase biodiversity within urban environments; Incorrect.

3. Which of the following is an example of Biomimicry?

A. Adding indoor plants to an office space; Incorrect.

B. Designing a façade inspired by a pinecone's ability to open and close; Correct. Biomimicry involves using nature's strategies and systems to solve technical challenges.

C. Using natural wood for flooring; Incorrect.

D. Incorporating water features into a lobby; Incorrect.

4. What is the key difference between Biophilic Design and Biomimicry?

A. Biophilic Design focuses on technical innovation, while Biomimicry focuses on human well-being; Incorrect

B. Biophilic Design uses nature for experiences, while Biomimicry uses nature for solutions; Correct. The fundamental difference lies in their focus. Biophilic design is about creating experiences, while biomimicry is a technical approach.

C. Biophilic Design is used by engineers, while Biomimicry is used by architects; Incorrect

D. Biophilic Design is concerned with building performance, while Biomimicry is concerned with aesthetics; Incorrect

5. Which of the following is NOT one of the six overarching Biomimicry Life's Principles?

A. Be Resourceful with Material and Energy; Incorrect.

B. Use Life-friendly Chemistry; Incorrect.

C. Focus on Aesthetic Engagement; Correct. The six overarching Biomimicry Life's Principles are: Evolve to Survive, Adapt to Changing Conditions, Be Locally Attuned and Responsive, Use Life-friendly Chemistry, Be Resourceful with Material and Energy, and Integrate Development with Growth. While aesthetics may play a role in Biophilic Design, it is not a core principle of Biomimicry, which focuses on sustainability, efficiency, and resilience inspired by nature.

D. Adapt to Changing Conditions; Incorrect.

PART 2 – Biomimicry in Structure and Thermal Systems Knowledge Check (5 Questions)

1. What principle does trabecular bone demonstrate that is applied in structural optimization?

A. Stress-aligned lattices and void optimization; Correct. Trabecular bone distributes material only where needed.

B. High thermal mass and buoyancy-driven flow; Incorrect.

C. Hydrophilic and hydrophobic surface patterning; Incorrect.

D. Reflective surfaces and evaporative cooling; Incorrect.

2. Which natural model inspired the design of diagrid systems with angle-optimized diagonals?

A. Termite mounds; Incorrect.

B. Diatoms; Incorrect.

C. Bone and trabecular architecture; Correct. Bone's stress-based anisotropy supports the design of diagrid systems, where diagonal densities are optimized based on stress zones.

D. Nacre (Mother of Pearl); Incorrect.

3. What is a key feature of diatom-inspired façade panels?

A. High reflectivity to reduce solar heat gain; Incorrect.

B. Perforation fields optimized for bending and shear; Correct. Diatoms have porous silica exoskeletons with hexagonal micro-lattices and ribbed frameworks. These features inspire façade panels with perforation fields that optimize stiffness and reduce material use while maintaining structural integrity.

C. Hydrophobic coatings for water resistance; Incorrect.

D. Layered composites for crack arresting; Incorrect.

4. How does nacre (Mother of Pearl) achieve its exceptional toughness?

A. MX3D Bridge, Amsterdam; Incorrect.

B. Centre Pompidou-Metz, France; Correct. Nacre's structure consists of microscopic aragonite "bricks" and organic "mortar," creating a layered composite that resists cracking and absorbs stress.

C. Al Bahar Towers, UAE; Incorrect.

D. Striatus Bridge, Zaha Hadid Architects; Incorrect.

5. Which building example demonstrates tree-inspired branching load paths?

A. MX3D Bridge, Amsterdam; Incorrect.

B. Centre Pompidou-Metz, France; Correct. The roof of the Centre Pompidou-Metz is a branching hexagonal timber lattice inspired by tree canopies.

C. Al Bahar Towers, UAE; Incorrect.

D. Striatus Bridge, Zaha Hadid Architects; Incorrect.

PART 3 – Biomimicry in Material Science and Water Management | Knowledge Check (5 Questions)

1. **What is the primary mechanism behind the self-cleaning property of the Lotus Leaf?**
   - *A. Hydrophilic surface that absorbs water; Incorrect.*
   - **B. Superhydrophobic surface with a unique micro/nano texture; Correct. The Lotus Leaf remains clean due to its superhydrophobic surface, which has a unique micro/nano texture and a dense layer of wax tubules.**
   - *C. Capillary action that traps water droplets; Incorrect.*
   - *D. Hygroscopic movement driven by humidity; Incorrect.*

2. **How does shark skin inspire anti-fouling finishes in architecture?**
   - *A. By using hydrophilic properties to attract water; Incorrect.*
   - **B. By mimicking riblets that reduce drag and prevent bacterial settlement; Correct. Shark skin is covered with dermal denticles that have riblets, which reduce drag and turbulence while preventing bacterial attachment. This principle is applied in anti-fouling finishes, such as Sharklet® surfaces, to deter microbial growth and improve hygiene.**
   - *C. By creating a porous structure for water absorption; Incorrect.*
   - *D. By using capillary action to filter water; Incorrect.*

3. **What principle of pinecones is applied in responsive cladding systems?**
   - *A. Superhydrophobic surface for water repellency; Incorrect.*
   - **B. Hygroscopic movement driven by moisture changes; Correct. Pinecones exhibit hygroscopic properties, where their scales open and close in response to humidity. This principle is applied in responsive cladding systems that adapt to environmental moisture levels, optimizing ventilation and moisture control.**
   - *C. Riblets for drag reduction; Incorrect.*
   - *D. Turgor-driven response to environmental stimuli; Incorrect.*

4. **How do mangrove roots inspire water filtration systems in architecture?**
   - *A. By using ribbed frameworks for structural strength; Incorrect.*
   - **B. By filtering saltwater through specialized root structures; Correct. Mangrove roots filter saltwater and conserve freshwater through their specialized structures.**
   - *C. By creating superhydrophobic surfaces for water repellency; Incorrect.*
   - *D. By using capillary action to absorb and retain water; Incorrect.*

5. **What is the key feature of spider silk that inspires water-resistant building materials?**
   - *A. Hydrophilic surface for water absorption; Incorrect.*
   - **B. Nano-scale surface hydrophobicity and tensile strength; Correct. Spider silk is both water-repellent and extremely strong due to its nano-scale surface hydrophobicity and tensile properties.**
   - *C. Hygroscopic movement for moisture retention; Incorrect.*
   - *D. Capillary action for water dispersion; Incorrect.*

PART 4 – Integrated Strategy and Regenerative Performance | Knowledge Check (5 Questions)

1. **How does the Al Bahar Towers in Abu Dhabi apply biomimicry principles?**
   - *A. By using a bioreactive façade to generate renewable energy; Incorrect.*
   - **B. By incorporating dynamic mashrabiya screens that respond to the sun's position; Correct. The Al Bahar Towers feature 2,098 computer-controlled mashrabiya screens that open and close in response to the sun's position.**
   - *C. By using termite mound-inspired passive cooling systems; Incorrect.*
   - *D. By integrating a honeycomb structure for load distribution; Incorrect.*

2. **What biomimicry principle is applied in the Bullitt Center's rainwater harvesting system?**
   - *A. Use life-friendly chemistry; Incorrect.*
   - *B. Be resource efficient; Incorrect.*
   - **C. Leverage cyclic processes; Correct. The Bullitt Center's rainwater harvesting system creates a closed-loop process where rainwater is collected, filtered, and reused. This aligns with the biomimicry principle of leveraging cyclic processes, mimicking nature's ability to recycle resources efficiently.**
   - *D. Build from the bottom up; Incorrect*

3. **Which building uses a bioreactive façade powered by algae to generate energy?**
   - *A. The Edge, Amsterdam; Incorrect.*
   - **B. BIQ House, Hamburg; Correct. The BIQ House in Hamburg features a bioreactive façade with 129 algae-filled bioreactors. These panels generate biomass and heat, provide shading, and act as thermal insulation, showcasing the biomimicry principle of "Use multifunctional design."**
   - *C. Bosco Verticale, Milan; Incorrect.*
   - *D. Masdar City; Incorrect.*

4. **How does the Eastgate Centre in Zimbabwe mimic termite mounds?**
   - *A. By using a honeycomb structure for load distribution; Incorrect.*
   - *B. By using algae-powered bioreactors for energy generation; Incorrect.*
   - **C. By incorporating passive cooling and ventilation systems; Correct. The Eastgate Centre mimics termite mounds by using passive cooling and ventilation systems. Thick walls, natural ventilation, and chimneys regulate the building's temperature, reducing energy consumption by over 90%.**
   - *D. By integrating a dynamic façade that responds to sunlight; Incorrect.*

5. **What is the primary biomimicry principle applied in the Bosco Verticale in Milan?**
   - **A. Build resilience through diversity; Correct. Bosco Verticale incorporates 900 trees and thousands of shrubs and plants, creating a biodiverse environment that supports local wildlife, reduces energy consumption, and improves air quality. This aligns with the biomimicry principle of "Building resilience through diversity."**
   - *B. Use low-energy processes; Incorrect.*
   - *C. Adapt to changing conditions; Incorrect.*
   - *D. Use life-friendly chemistry; Incorrect.*