

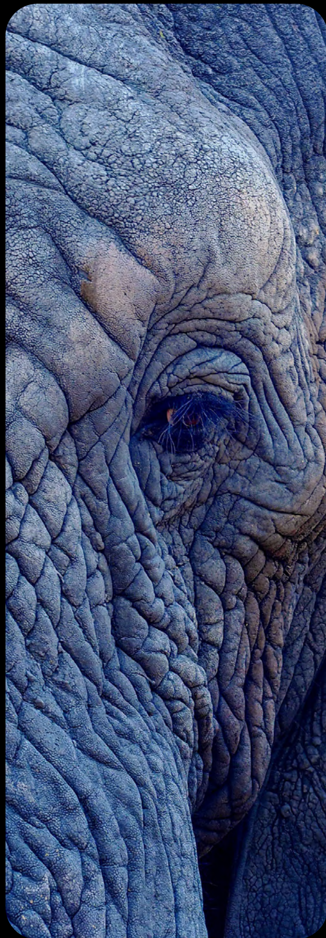

BIOMIMICRY FOR TROPICAL BUILDING SKINS

A Design Toolkit to Manage Thermal Comfort Using Nature's Genius

Edited by
Anuj Jain & Saloni Swaminathan

bioSEA

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Organizations - Lead by bioSEA, this project was supported by DesignSingapore Council through its Good Design Research Initiative. Strategic Partners include the Biomimicry Singapore Network, Singapore University of Technology & Design, Temasek Polytechnic and Nanyang Technological University.

ISBN no. (eBook) 978-981-18-7102-3

First Edition published in April 2023 by bioSEA Pte. Ltd., Singapore.

Video
Watch the introductory video on the biomimicry design toolkit project at https://vimeo.com/746567806

Watch the elephant skin feature and launch video on the biomimicry design toolkit project at https://vimeo.com/818110466

Recommended Citation
Jain, A & Swaminathan, S (Ed.) (2023). *Biomimicry for Tropical Building Skins - A Design Toolkit to Manage Thermal Comfort Using Nature's Genius.* Published by bioSEA, Singapore.

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About the Editors

Dr. Anuj Jain

Anuj works at the intersection of biomimicry, ecology and nature conservation. As the Founding Director and Principal Ecologist & Biomimic at bioSEA, he creates ecologically functional and nature-inspired designs. He is a firm believer of placing nature and people at the centre of design. Anuj is also a National Geographic Explorer, consultant for BirdLife International (Asia) and founding member of the Biomimicry Singapore Network. Anuj holds a Biomimicry Professional Certification with Biomimicry 3.8 and has conducted workshops and courses on biomimicry for architectural students and designers.

Saloni Swaminathan

Saloni comes from a background in Zoology and has a passion for biodiversity conservation and education. As a design & research ecologist at bioSEA, her expertise lies in using ecological principles to integrate biodiversity into the urban fabric. Imbued by a fascination and appreciation for nature, she has since gained familiarity with biomimicry concepts and seeks to translate knowledge into practice through her work at bioSEA.

bioSEA

About bioSEA
Rooted in South East Asia (SEA), bioSEA is an award-winning ecology and biomimicry design consultancy firm that strives to make the built environment green, beautiful and biodiverse. Our services include ecological planning, biodiversity surveys and impact assessments, ecosystem service assessments, wildlife-infrastructure design and biomimicry design particularly for the built environment.

We collaborate with renowned architects, landscape architects, urban planners, government and research agencies, ecologists and other established organizations who share our values. Over time, we have seen our work shape design decisions to build urban spaces that function like a rainforest.

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Acknowledgements

Thanks to Duleesha Kulasooriya, Gregers Reimann, Jo Soh, Judea Cheong, Letitia Tan, Lim Xiao Wei, Lim Wei Xi, Mark Wee, Michelle Fehler, Richard Hassell, Richard McCowan, Serene How, Sriram Nadathur, Tan Szue Hann, Tai Lee Siang, Wong Mun Summ and Yuan Chao for advice and inputs.

Special gratitude to Janine Benyus, Dayna Baumeister and the Biomimicry 3.8 team for the biomimicry training and resources that helped the team in its formative years and continues to do so.

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Their Contributions

Anuj Jain conceived the project and worked on all sections. Celine Tan supported the initial kick-off and coordination alongside work on the essential resources research. Saloni Swaminathan took over and supported the work particularly in editing all sections of the toolkit. The initial toolkit framework development and many visuals were supported by Ruiee Dhuri.

Lisa Teo was critical from the start and spearheaded the industry survey, supported the Design Charrettes alongside providing industry & policy guidance. Madhvi Chulet, Atticus Cummings and Leanne Haan supported the essential resources research and graphic design together with Ilina Shah who supported materials research, with guidance from Christian Delacruz and Hortense Le Ferrand. Nathan Hays spearheaded the elephant skin and desert beetle design explorations. Bu Jing Yi helped with biomechanics involved in the design work. Nicholas Loh, Eugene Soh and Teoh Jia Heng did prototyping and 3D printing of elephant skin tiles in mycelium with support from Hortense Le Ferrand. Alysa Marie Tan, Janee Lim, Lynus Ng, Wei Shi Yun and Shayna Naik from Temasek Polytechnic worked on the elephant ear design explorations supported by Shruti Pilare. Jodie Monteiro supported the clay fabrication of elephant skin tiles. Munshi Mukhtar Toh led the designs for termite mound design explorations supported by Zheng Kai and Rupert Soar.

Katharina Hecht, Kelly Siman, Kuan Chee Yung, Kuowei Chiu, Lidia Badarnah and Petra Gruber provided advice on biomimicry designs, frameworks and content development. Maitreyee Fadnavis, Shruti Sunil and Johannes Fuchs supported additional visuals. Priyanka Sancheti handled the project finances and kept us sane. Grace SY Lim helped turn the toolkit into the user-friendly manual we hope it is today.

Opening Remarks

Image credits: Biomimicry3.8

Dr. Dayna Baumeister
Co-founder of Biomimicy 3.8 | USA

"Before I discovered biomimicry 25 years ago, I dreamed of building a wall that breathed like skin. Our crude facades are nothing more than many materials sandwiched together with no real integration—each with different functions, different installers, different manufacturers…Look down at your arm. Consider your marvelous, elegant skin. It breathes, it manages heat, protects from UV, withstands moisture loss, keeps out pathogens, and holds all your contents inside. Multiple function, one installer, one manufacturer. And when you are done with it, the materials could easily enter a biological cascade to add value to the ecosystem. We have much to learn.

Dreaming up walls that breathe like skin isn't enough. We need to conceptualize them, design them, prototype them, build and manufacture them. The building facade toolkit from bioSEA is such a critical step to help dreamers become doers. I'm thrilled that Anuj and his colleagues are helping bring nature's genius to the design table to cultivate real, tangible solutions for a world demanding regenerative innovations."

Executive Summary

The world is warming up and its effects are palpable. Our efforts to cool the world down are a double edged sword releasing close to 5 billion tonnes of carbon emissions which makes up a whopping 10% of global greenhouse gas emissions. With Asia rapidly urbanizing, the demand for cooling services is expected to increase exponentially. Biomimicry - a practise that mimics strategies found in nature to solve human design challenges - may hold some answers.

Nature has solved for thermoregulation across a diversity of species that live in our tropical climate. Many of these creative solutions are expressed via the organisms' skins, the largest interface in contact with the outside environment.

Biomimicry is Novel among Professionals

We asked experienced professionals in the Singapore built industry what they know about biomimicry in the industry and found that only 41% of them were familiar with Biomimicry. However, familiarity in biomimicry does not translate into its application. There remains a large gap between the design process and the integration of biomimicry in it. See Chapter 1 for details.

A Diverse and Connected Team

Just like nature, we thrived on diversity and global knowledge, as we garnered the expertise of a team of local and global biomimicry designers from the biological, architectural, engineering, material science, and other related fields to put together this toolkit. The core team comprised of editors and authors who benefitted from contributions from more than 25 experts from literally the world.

A Different Approach

The toolkit aims to be your practical guide in applying biomimicry for thermoregulation especially in the tropical built environment. It differs in its approach from other writings on this topic in which it draws from published case studies and bioSEA's own designs and translates this work for an industry audience. The toolkit comes with checklists, flowcharts, self-guide questions and case studies classified by scale, taxonomy and type of projects featured that can become an easy guide for designers starting this work. For the experienced professionals, it can be a reference of well-known and new biomimicry projects.

The Vision

Our vision is for biomimicry solutions to be integrated into the wealth of existing thermoregulation strategies, to achieve ultra low energy and place-based solutions for thermoregulation in the tropical built environment. We have also taken efforts to distinguish biomimicry from other bio-inspired approaches and show how it can be integrated with them.

Finally, we aim to develop a community of practice, that will inspire new ideas which will support Singapore, and the ASEAN region's transition to a net positive, regenerative and climate-resilient future.

For young practitioners in this field, we understand and appreciate the challenges you may be undergoing in implementing biomimicry ideas in real projects, as the field is still novel and relatively niche in our part of the world. We encourage you to stay steadfast in your ambitions. Biomimicry – it's time!

We wish you an exciting biomimicry design journey!

Anuj Jain & Saloni Swaminathan
The Editors | bioSEA

Biomimicry is a practise that learns from and mimics strategies found in Nature to solve human design challenges.

About this Toolkit

Aims
To help you create a bedrock for biomimetic façade innovation and mainstream the adoption and implementation of biomimicry to solve the persistent challenge to thermal comfort in the built tropical environment

Audience
This toolkit is aimed at architects, facade designers, consultants and professionals in the built environment industry, especially students in the industry and early career professionals.

The Chapters
Chapter 1 explains the "whys" that sets the backdrop:

- Why is the need more pertinent in ASEAN and Singapore?
- Why not consider biomimicry in built designs?
- Why not use it to drive innovative ideas?
- Why not combine established and biomimicry methods?

Chapter 2 helps you jump start authentic and meaningful biomimetic designs, by introducing you to the principles in biomimicry and its six-step design process, with questions experts will ask. It discusses scale of application , key points to note for each step, so you can avoid the pitfalls of designing, and become adept at integrating biomimicry into your usual design flow. Finally, biophilia, bio-morphism and bio-utilization is compared with biomimicry and case studies of integration are presented.

Chapter 3 guides you as you apply the six-step design process. Delve into designing for your clients and the tropics, before considering primary and secondary functions of built environments, and how these problems are solved by living things! The authors have applied the design processes on the three wall panel designs developed by bioSEA, to help you visualise what design plans could look like. These designs were inspired the elephant skin, termite mound and Namib desert beetle (also on the cover page).

Chapter 4 is a treasure trove of resources to help you in your research for your biomimetic design

• Case Studies – These selected case studies are significant façades from buildings from around the world which have been inspired by different species. The approach is designer centric, and information for each case study include the functions addressed, scale, geography, materials, stage of industry development (conceptual to built) and type of biomimicry they utilize (form, process or system). The case studies lightly touch on the biology behind the strategy but their main focus is on the implementation of strategies in the built environment. The case studies are classified by scale, taxonomy and type of projects.

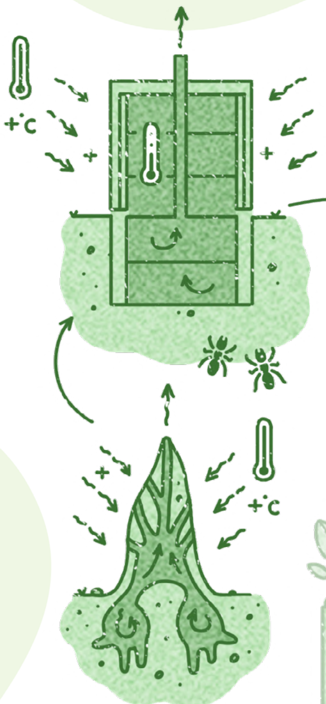
• Materials Synopsis - This materials review delineates bio-inspired and biomimetic materials and how they can be applied to case study projects presented earlier.

• Other biomimicry design links - The final section of this resource section are links to online and print resources to supplement and expand on information covered in the toolkit.

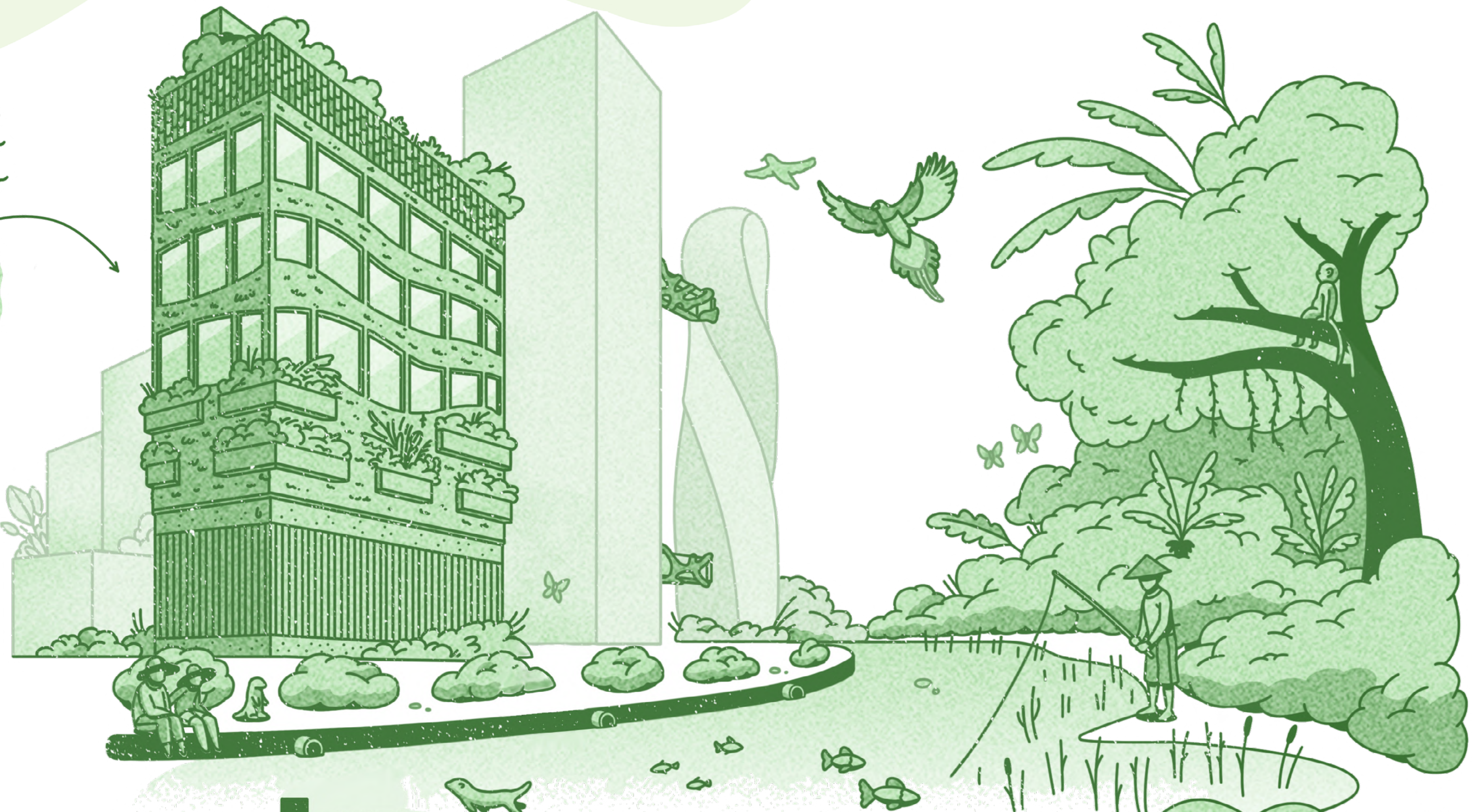
• A diversity of resources can also be downloaded from the bioSEA's Biomimicry Toolkit website.

Chapter 5 paints our visions for biomimicry to be naturally and deeply integrated into mainstream design processes for the built environment. Dream with us as we showcase a melting pot ecosystem of biomimetic and non-biomimetic solutions.

An invitation to imagine an integrated bio-inspired future...



Mimicking Termite mounds for Efficient Cooling on Buildings



Integrating biomimetic designs with biodiverse and biophilic environments that provide a multitude of ecosystem benefits

Ecosystem benefits provided by Nature vs. Buildings

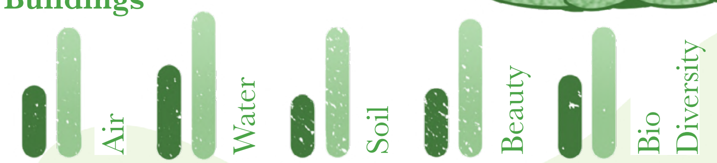


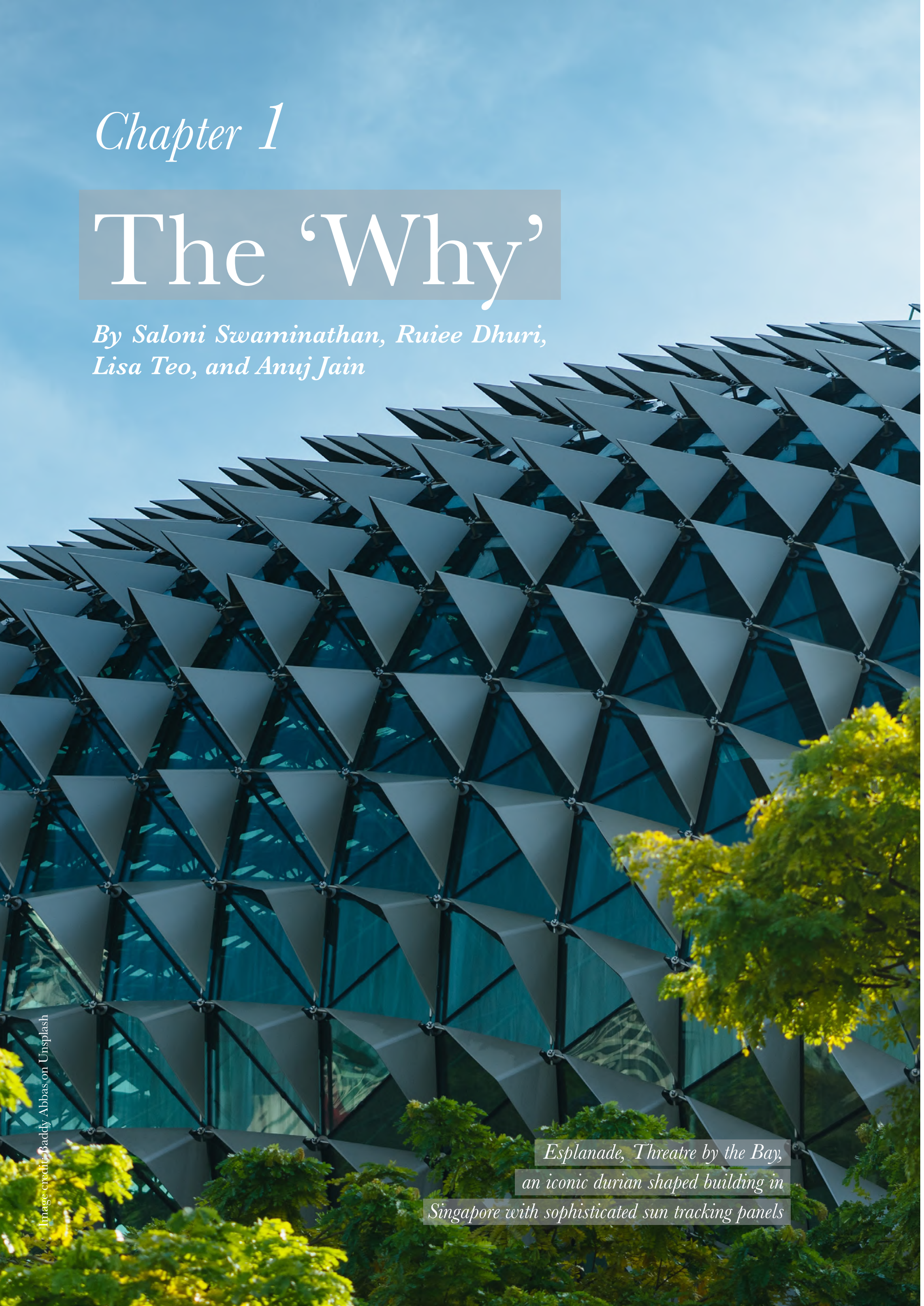
Illustration by Johannes Fuchs for bioSEA

Contents

Chapter 1

The ‘Why’

By Saloni Swaminathan, Ruiee Dhuri, Lisa Teo, and Anuj Jain



Esplanade, Threatre by the Bay, an iconic durian shaped building in Singapore with sophisticated sun tracking panels

Image credit: Baddy Abbas on Unsplash

Contents

Cooling the World is Warming the Planet

A desire for thermal comfort, the ability to afford it and a growing need to combat human induced urban heat island effects and climate change has seen a steady rise in space cooling needs globally. In the past decade alone, **energy demand for space cooling has been rising at a steady pace of 4% every year.**

10% of **global greenhouse gas emissions** can be attributed to the **cooling services industry**[2]

16% of **energy consumption** by buildings is attributed to **space cooling** in 2021[1]

6.5% increase in **energy demand** for **space cooling** in 2021[1]

A brief history

Before the advent of modern cooling technologies, there was a heavy reliance on architectural interventions to regulate temperatures. Temperature control was a pertinent aspect of building design without which a building could lack comfortable, inner climate control. What traditionally began as just openings in load bearing walls coupled with cladding, eventually transformed into a multitude of creative expressions with the introduction of modern materials and building technology.

In hot and humid zones, building facades provided protection against sun radiation and optimized the flow of cooling night breezes. In harsh Northern environments, they insulated against the winter cold. Careful thought went into the construction material being used, the shape and configuration of windows, building orientation, and heating strategy to optimise thermal comfort.

Over time, advancements in technology gave rise to artificial space cooling techniques. The widespread adoption of these novel cooling strategies was almost instantaneous. Unbeknownst to us then, our progress was a double edged sword.

Cooling Southeast Asia

Rapid urbanization in the last few decades has given rise to megacities across Southeast Asia (SEA). The densely packed cities play home to close to 280 million people today and that proportion is expected to increase to 373 million by 2030[3]. With temperatures in cities skyrocketing as a result of the human induced urban heat island (UHI) effect, an alarming number of people will become increasingly vulnerable to its resultant ill health outcomes.

Thermal comfort, health and productivity

At least ***30% of the total heat related mortality*** in Ho Chi Minh city between 2010-2013 could be attributed to UHI alone[4]. Growing exposure to heat stress is expected to ***reduce labour productivity and outdoor working capacity***, particularly in the tropics and subtropics[5]. An analysis of user thermal comfort in Singapore showed that even under completely shaded conditions, ***building occupants*** spend most of their time in the ***'caution' and 'extreme caution' sections for the Outdoor Work Heat Index***[6].

It came as no surprise when the Energy Outlook Report for Southeast Asia highlighted space cooling as one of the fastest growing uses of electricity[7].

An energy guzzler and carbon culprit

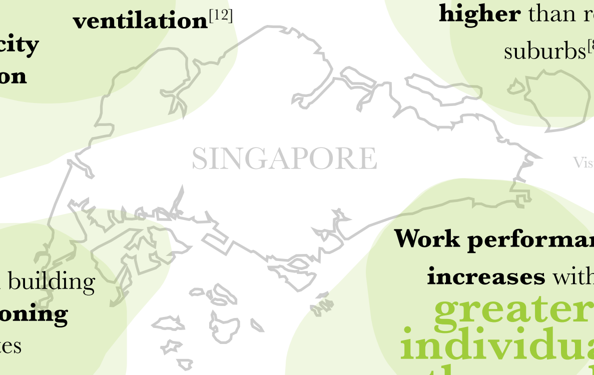
From 1990-2017, electricity use for space cooling in residential and commercial buildings has increased by 7.5% in SEA[11]. SEA's electricity demand for space cooling is expected to quadruple by 2040 and with it, our carbon footprint.

Co-ordinated policy action on energy-efficient, climate-friendly space cooling measures could reduce carbon emissions in SEA by over ***55 million tonnes in 2040***[15]. So what does the Southeast Asian roadmap to a net zero future look like?

Air cooling in non-residential buildings accounts for **60%** of all **electricity consumption**

10% used on **mechanical ventilation**[12]

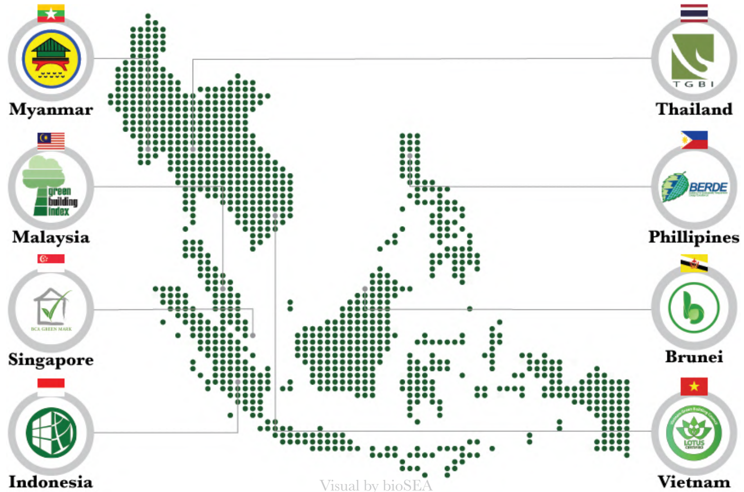
Daytime temperatures in cities can be **4 - 10 °C** **higher** than regional suburbs[8]



Visual by bioSEA

Household and building **air-conditioning** constitutes **19%** of **Singapore's carbon emissions**[14].

Work performance increases with **greater individual thermal comfort** [9]



Above: ASEAN Green Building codes and Assessment Tools

The ASEAN effort

The building sector plays a key role in decarbonizing the global economy. Regional shifts in policy support the deployment of more efficient cooling systems and encourage innovation in improving building envelope efficiency[15]. The creation of country specific green building rating tools, certification and awards further incentivises the adoption of carbon neutral building practices[16].

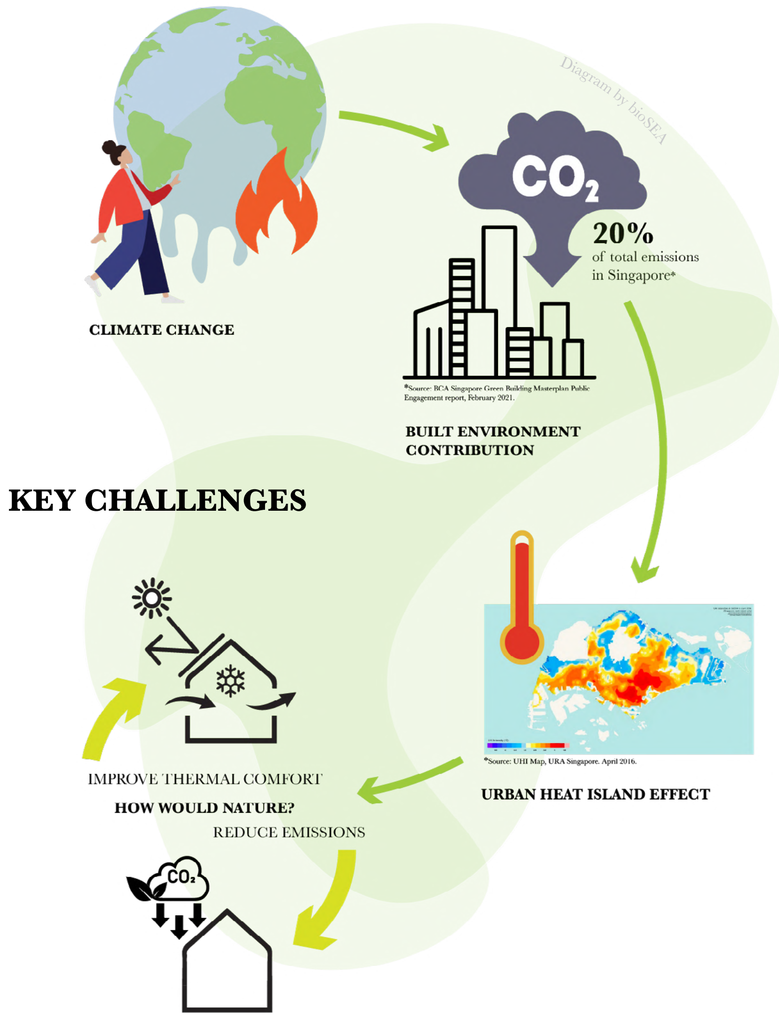
The Singapore effort

Singapore's Green Mark 2021 aims to raise energy efficiency standards by mainstreaming the uptake of Super Low Energy buildings; and aligning with the United Nations (UN) Sustainable Development Goals (SDGs) [17]. Under the Green Mark's Building Code (Environmental Sustainability) Amendments 2021, tighter base requirements for Envelope and Roof Thermal Transfer and new

Above: Green Mark 2021 alignment with SDGs, Building and Construction Authority (BCA), Singapore

indicators for carbon reduction measures are required to satisfy the regulatory requirements. These indicators include enhanced building envelope performance and naturally ventilated space design. In other words, this is a call for new, improved net zero thermoregulation strategies.

Further outlined in the SG Green Building MasterPlan are raised energy performance levels, environmental sustainability standards and key targets for industry practitioners to aim for and achieve by 2030[18]. The Masterplan is pushing its 80-80-80 target. 80% of new developments are to be Super Low Energy by 2030. How will we achieve this?



Existing Solutions

Above: (Left) Low-tech Jaali solutions used in traditional houses in India and (Right) High-tech building facade system by WOW Architects in Camo House, Singapore to deal with thermoregulation.

Evolution of thermoregulatory design

In the earlier days, thermoregulation was mainly achieved through building orientation, use of context specific local materials and their design and placement. Deep overhangs, thicker walls, smaller windows and use of clay and dung were a few strategies, and it did not take long for these strategies to become a little more decorated. They took on an added aesthetic purpose, while their design in the classic sense focused on their proportion, fenestration, and materiality.
However, these strategies, with modern contexts, concerns and densities, now pose a whole new set of challenges when it comes to adequate ventilation and temperature control.

And yet, despite the changed technological, cultural, and economic parameters, the principal task of architecture is the creation of habitable and comfortable spaces.

As a transition between inside and outside, the building skin plays an especially important role in providing protection from the external elements and creating privacy while the surface also provides a canvas for artistic expression and identity. Today we see a plethora of buildings that range from low tech solutions to high tech approaches for climate sensitive thermoregulation in modern buildings, that differ both in materiality and reactivity to the environment.

Existing Design Interventions

Here are a few design interventions commonly used in existing architectural designs and some examples that exemplify these approaches.

Permeable Facades
Perforated building skins creating way for ventilation and filtered light.

Evaporative Cooling Structures
Facades systems that use cooling properties of water vapor to absorb heat from the incoming air.

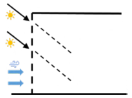
Passive Ventilation Structures
Air is exchanged in the building through openings in the envelope using the stack and wind pressures.

Sun Tracking Roofs
Building facades intentionally designed in response to sun, intended to control solar heat gain.

Self Shading Structures
Emphasised forms integrated in the structure especially designed to cut out harsh sunlight. The building “self shades”.

Double Skin Facades
Double facades provide a barrier for the air to move in, while the internal building is protected from the harsh rain and sun.

Refer to the next page for examples.



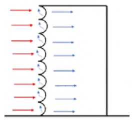
Click or scan to find out more

Permeable Facades

The **Termitary House** in Vietnam by Architect Vo Trong Nghia [19] in 2014 is constructed like a lattice screen. Bricks are crossed and fastened together with square spaces left in between which allows for air to flow in and out of the house via cross ventilation creating a natural air conditioning mechanism.

Evaporative Cooling Structures

The **CoolAnt facade** in India by Ant Studio [20] in 2018 comprises of terracotta clay pots that were designed with inspiration from the structure of beehives. The large surface area of the pots maximizes the cooling effect all while being sustainable. The water running on the surface of the cylinders cools the hot air that passes through the clay pots.



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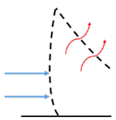
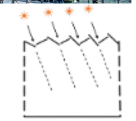


Click or scan to find out more

Passive Ventilation Structures

The **Caledonia Cultural Center** in Caledonia was built by Architect Renzo Piano[21] in 1998. Comprised of rounded, airy shells emanating high-rise ventilation – a solar chimney (passive cooling system that can be used to regulate the temperature of a building as well as providing ventilation). The interrelated clustered buildings are inspired by the layout of the traditional Kanak villages.



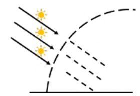
Click or scan to find out more

Sun Tracking Roofs

The **Esplanade roof** in Singapore by DP Architects and Michael Wilford and Partners [22] in 2002 is covered with panels that are fixed in a grid structure based on the sun's path. The panels reflect the sun's rays and retain heat during the day, allowing thermal comfort. The rooms are made of reinforced concrete for acoustic insulation.

Self Shading Structures

The **Arc** in Bali by Architects IBUKU[23] built in 2021 is an intersecting bamboo design constructed from anticlastic (having opposite curvatures at the same plane) grid shells. The structure is composed of a series of porously connected pavilion-like enclosures, which overlap to allow sunlight and provide shading for the occupants.



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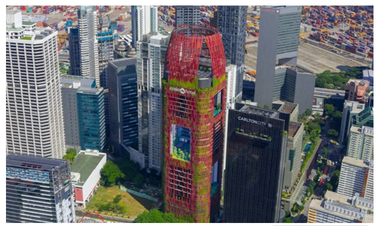


Click or scan to find out more

Double Skin Facades

The **Oasia Hotel** in Singapore by WOHA Architects[24] was built in 2016. It has a porous aluminum mesh cover allows the integration of biodiversity within the facade and creates a "green skin." The openings allow for ventilation and filters rain, keeping guests cool and dry inside.

Net Zero in the Tropics

An example of energy saving solutions using conventional form making, best practices of conventional facade design methods and cutting edge cooling systems.

+ Permeable
+ Passive Ventilation
+ Self-shading Structures

Click or scan to find out more

Operational since January 2019, the **School of Design and Environment (SDE4)** at the National University of Singapore is Singapore's first new-build net-zero energy building. Built by Serie x Multiply Architects [25], it is a prime example of how sustainability doesn't need to look funky. Conventional forms and established methods when applied properly can be highly functional and effective.

Energy efficiency at SDE4 is achieved by optimizing the use of solar energy, natural lighting and air for tropical living and efficient cooling systems to name a few approaches. It's large overhanging roof hosts more than 1,200 photovoltaic panels that harness solar energy. Its innovative hybrid cooling system that supplies 100 per cent fresh pre-cooled air at higher temperatures and humidity levels than in a conventional system, and augments this with an elevated air speed provided by ceiling fans. Buffer spaces are set behind a screen of wavy, perforated aluminium panels that allow natural light and air to permeate through the building.

Have you considered Biomimicry?

What is biomimicry?
The Biomimicry Institute, USA defines biomimicry as -

"an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies. The goal is to create products, processes, and policies—new ways of living—that are well-adapted to life on Earth over the long haul."

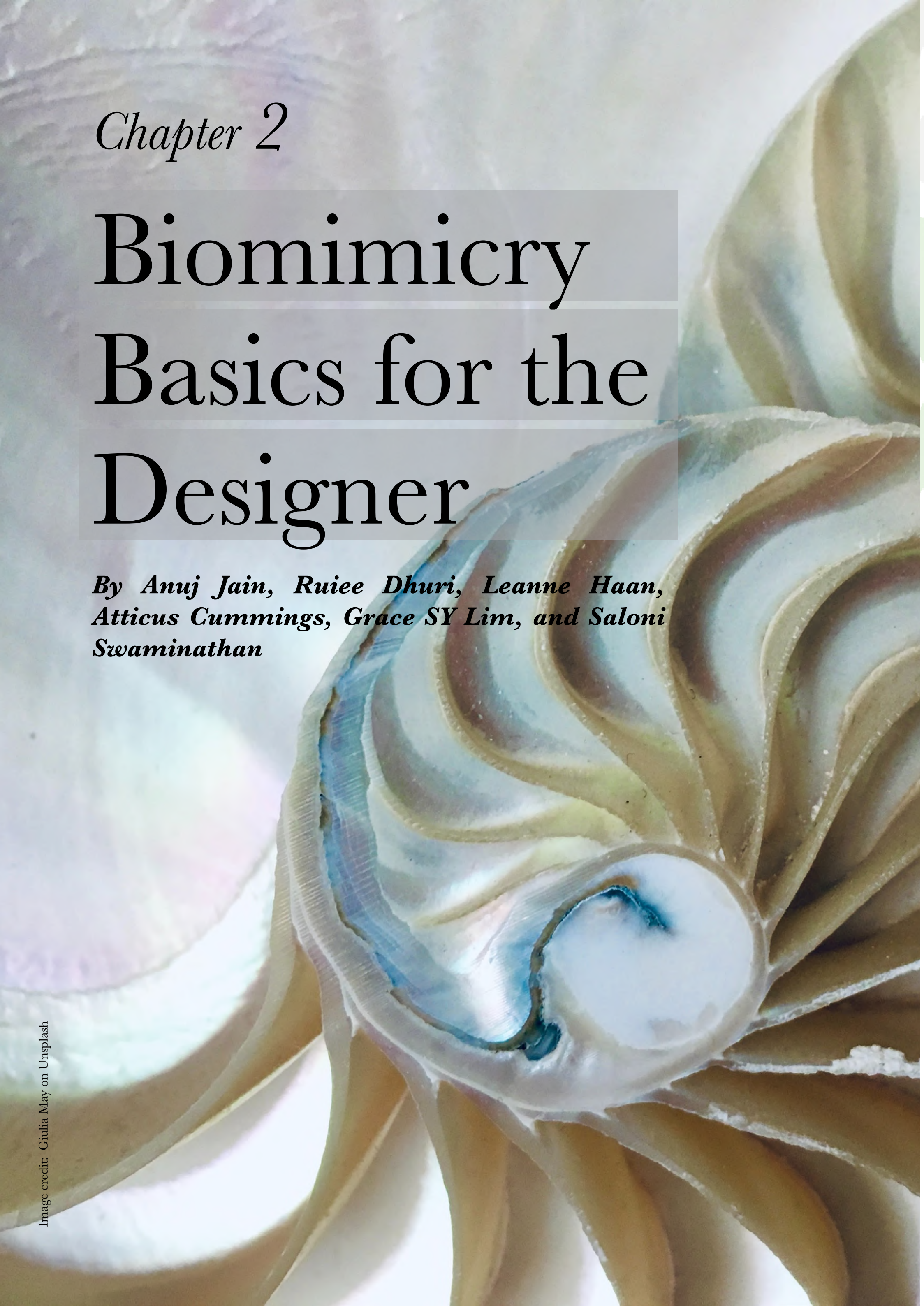
Going Beyond?
Biomimicry can be a pathway to innovation. The question is how can bio-inspired design approaches be combined with conventional best practices to help to achieve net positive and regenerative designs?

How much does the industry know?

In October 2021, bioSEA conducted an online survey amongst a network of 41 professionals involved with the built industry in Singapore to ascertain the level of awareness associated with biomimicry in the industry. Two-thirds of respondents had over 10 years of experience in the field. 73% were built industry professionals, 20% from the real estate sector.

41%
of built environment professionals were familiar with Biomimicry

This result indicates the novelty of biomimicry in the built sector. Also, familiarity does not lead to know how about application. There still remains a large gap between the design process and the integration of biomimicry in it. These results were followed up (see Chapter 2) to understand what could lower the resistance to utilizing biomimicry in design while simultaneously increasing its popularity and adoption.



Chapter 2

Biomimicry Basics for the Designer

By Anuj Jain, Ruiee Dhuri, Leanne Haan, Atticus Cummings, Grace SY Lim, and Saloni Swaminathan

Image credit: Giulia May on Unsplash

Contents

Biomimicry Principles

The adoption and implementation of biomimicry in the built environment requires a foundational understanding of its guiding principles and the different means in which it can be integrated into the architectural design process. This chapter explains the levels and essential elements of biomimicry, dives into the six step design process and how it can be a guiding framework for using the toolkit. We explain how to approach biomimicry using the six step process for a thermoregulation example, what scale to apply biomimicry and steps that need to be undertaken to integrate biomimicry in the design flow. Finally, we compare and contrast biomimicry with other bio-inspired approaches.

"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

Three Levels of Biomimicry[26]

There are three levels at which biomimicry design can be emulated.

(i) FORM = mimicking the morphological features of an organism to fulfil a similar purpose the trait initially evolved for in the organism

(ii) PROCESS = mimicking the behaviour of an organism(s), given restrictions on available resources

(iii) SYSTEM = mimicking the ecosystem and embodying the principles of a 'circular economy' in design where resources are optimised and waste generation is minimised.

Interface™ ENTROPY Carpet Tiles

Interface Inc. is a global manufacturer of carpet tiles and other flooring options that is well known for its sustainability efforts. The example below illustrates how Interface has applied biomimicry in the company across all three levels.

FORM

Inspired by the form of the forest floor, the designers at Interface Carpets created multi-colored and modular tiles such that any tile could be replaced to fit in with tiles of other colors.

PROCESS

Interface designers mimicked the process of interlocking mechanisms in nature and created interlocking tiles eliminating the need for toxic glue to stick tiles together.

SYSTEM

Finally, they mimicked nature's circular systems by incentivizing fishermen in the Philippines to collect discarded fishing nets and used them as a raw material to make carpet tiles.

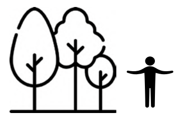
Interface™'s wider biomimicry efforts [27]

Inspired by the forest floor and through contributions from Biomimicry 3.8's advisory, Interface has been creating biomimetic and modular carpet files since the 1980s. They have been advocating and expanding their sustainability efforts since and achieved (third-party verified) carbon neutrality in their operations in 2019. Since 2016, Interface has also announced a new mission of being carbon negative through its Climate Take Back initiative. Partnering with Biomimicry 3.8, they are implementing a bold vision of a ***'Factory as a Forest'*** that aims to apply biomimicry and wider sustainability concepts in their factory design, construction processes and operations. Interface is truly attempting to integrate biomimicry, circularity and other bio-inspired approaches and showing to the world that being regenerative is possible.

Essential Elements of Biomimicry [26]

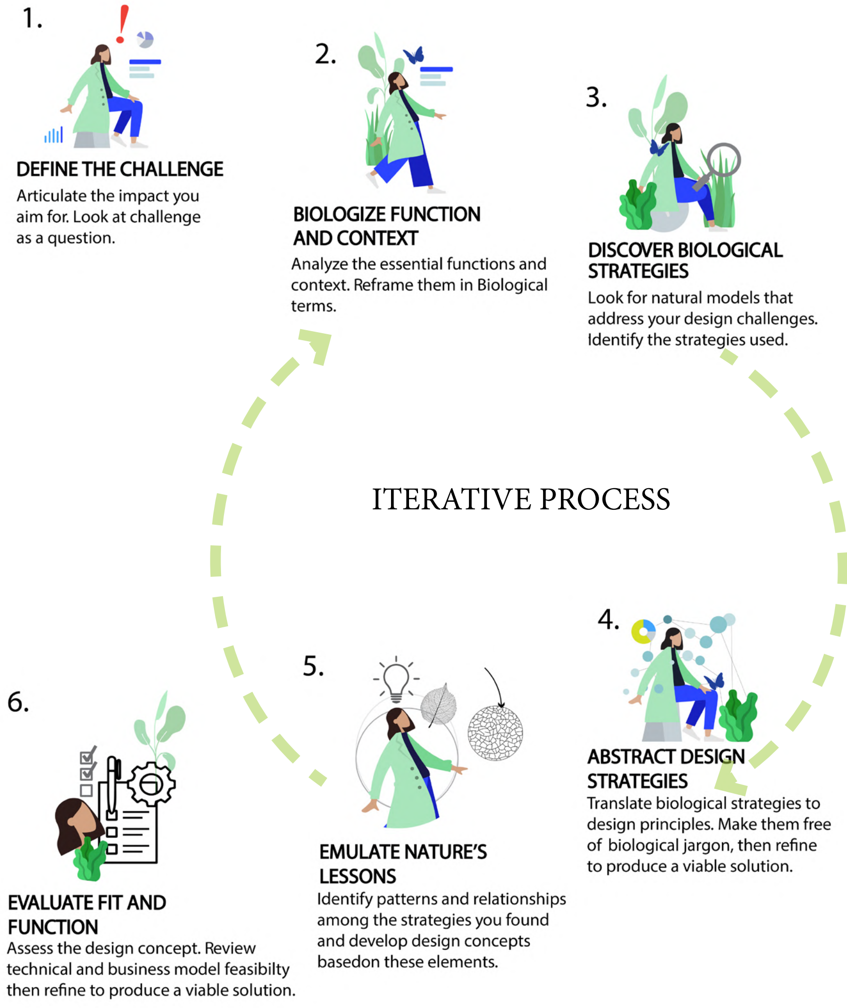
Three elements of Emulate, Ethos & Reconnect act as the guiding principles for innovators as they begin their foray into turning bio-inspired design into biomimetic design.

EMULATE	ETHOS	RECONNECT
Emulate is the translation of biomimicry knowledge into practice. It happens at 3 levels, as elaborated below the form, process, and system.	Ethos encapsulates the ethics and intention for respect and responsibility towards the species or system being emulated.	Reconnect is about stepping out and enhancing the deep human connection we have with the natural world when we explore biology in the practice of biomimicry.



Six Step Design Process

The six-step design process is a step-wise guide to solve your design challenge. It includes the six most important steps and considerations to take into account as a designer when approaching a project that could benefit from a biomimetic solution.



Visual by bioSEA is adapted from Baumeister D. 2014. Biomimicry Resource Handbook. A Seed bank of Best Practices. Biomimicry 3.8, USA.

Using the Toolkit

Asking The Right Questions

a. BACKGROUND

Key client requirements
What is the:
1. Design brief
2. Intent
3. Solution

Aim/Intention
1. What are the key elements /intentions of the project?

Site Scan
1. Identify the strengths
2. Look for weaknesses
3. Highlight challenges
4. Potential opportunities

Begin the Design Process

b. THE 6 STEP DESIGN PROCESS

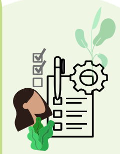
Define
1. What are the thermoregulation challenges for the project/ design?
2. How does this challenge translate to a function of thermoregulation?

Biologize
1. How does nature display this function and thus solve this challenge?

Discover
1. What are the existing mechanisms/systems that help resolve the challenge?
2. Which biological strategy suits the challenge best?
3. Is the biological strategy sufficiently well understood?

Abstract
1. What are they key design elements of the biological strategy that
would be useful to designers?
2. Diagram/sketch of the strategy applicable to your project.
3. What are the Keywords? E.g., Fur, Fibre, Skin, Membrane.
4. Is there enough research to back up the abstraction?

Emulate
1. Revisit the abstracted strategies in the project constraints
2.Get creative and apply the abstracted strategies to design (but stay
true to biology).
3. Can the strategies be applied to project scale?
4. Is it manufacturable?
5. Can the biomimicry strategies be combined with existing industry approaches?



Evaluate
1. Test it out - build Prototype/Model!
2. Evaluate Sustainability Wins - how is the design better than business the usual?
3. How well does the solution address Life's Principles?
4. Assess the feasibility - consider Cost/Regulations
5. Identify limitations and barriers to scaling up

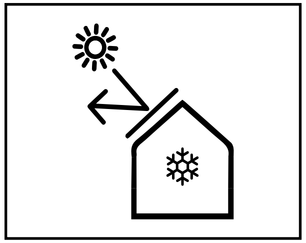
How to Approach Biomimicry?

The **six-step biomimicry design process** (Define, Biologize, Discover, Abstract, Emulate and Evaluate; see Chapter 3 for details) can be used to explore solutions to problems.

Here a design flow concept is presented using a thermoregulation example. The challenge is to limit heat gain & the elephant skin is studied as a potential solution.

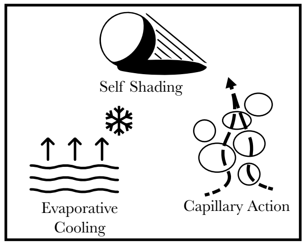
The **scale of application** is important because nature and its organisms operate at multiple scales. Thus, biomimetic principles can be applied at different scales - material, product (e.g., wall panel), building, district scale. The stakeholders that need to be engaged and the implications that emerge can be very different.

EXAMPLE

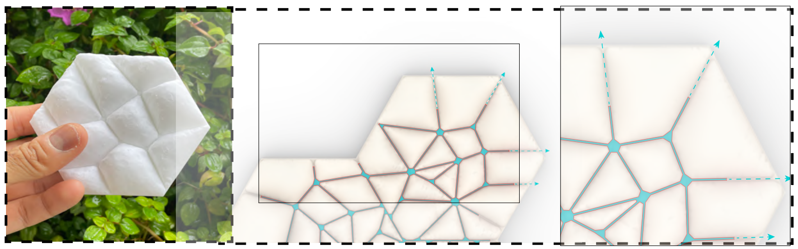


Limited Heat Gain

Elephant Skin (**Form**)



Key Inspirations



Textured tiles (see Chapter 4 for Details)

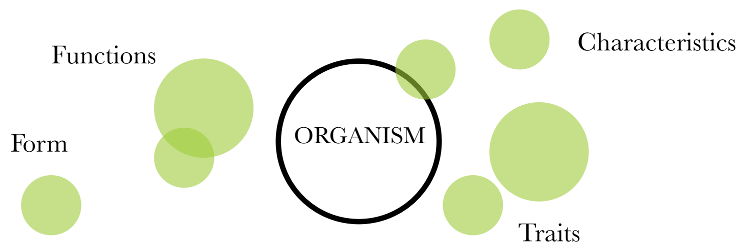
HOW DO I BEGIN WITH MY IDEA?

Identify desired building function → Analyse building context → Look to nature

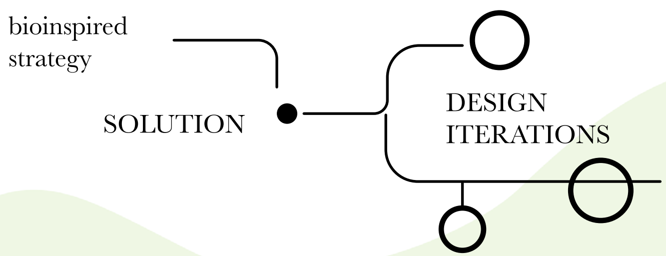
What is my key challenge?
How to classify the strategy to mimic?

FORM • PROCESS • SYSTEM

What could be the possible inspirations from nature?



How does this translate into bio inspired/biomimetic design?



DEFINE

BIOLOGIZE & DISCOVER

ABSTRACT & EMULATE

EVALUATE

Scale of Application

Nature

Termites use humidity to cue construction of porous mound walls using clay and saliva

Material Scale

Surface channels and branches inside mounds have tunnels that create airflow

Wall Panel Scale

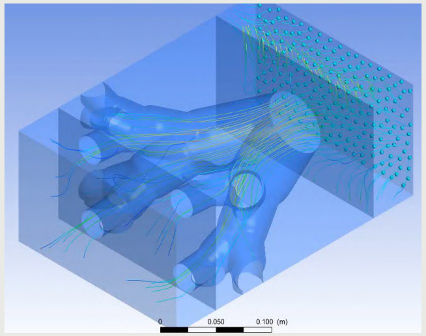
Together, nest tunnels regulate air flow, humidity, and temperature

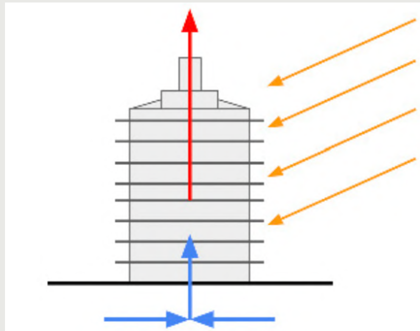
Building Scale

Termite mound colonies communicate with each other and synergize use of natural air flow in the environment

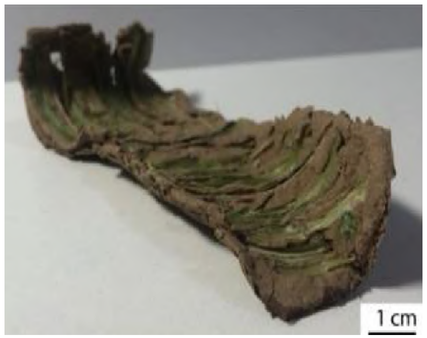
District Scale

Biomimicry

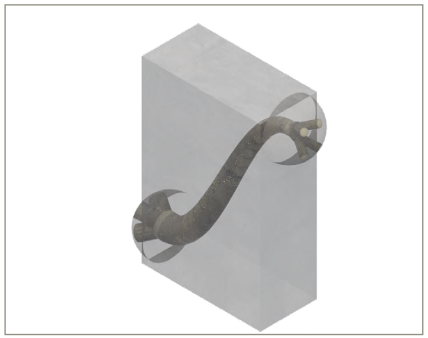




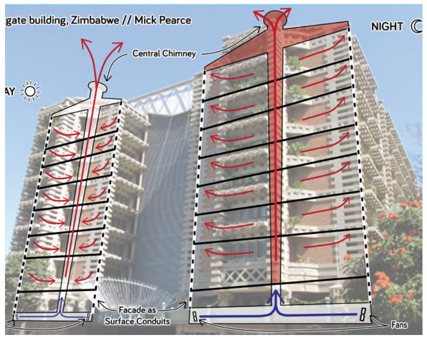
Opportunities



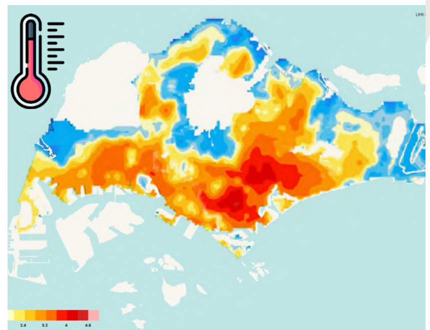
Self-shaping clay is inspired by cellulose fibers inside plants that deform upon swelling and drying.



Efficient branching - bioSEA's termite mound inspired modular wall panels create airflow through a building.

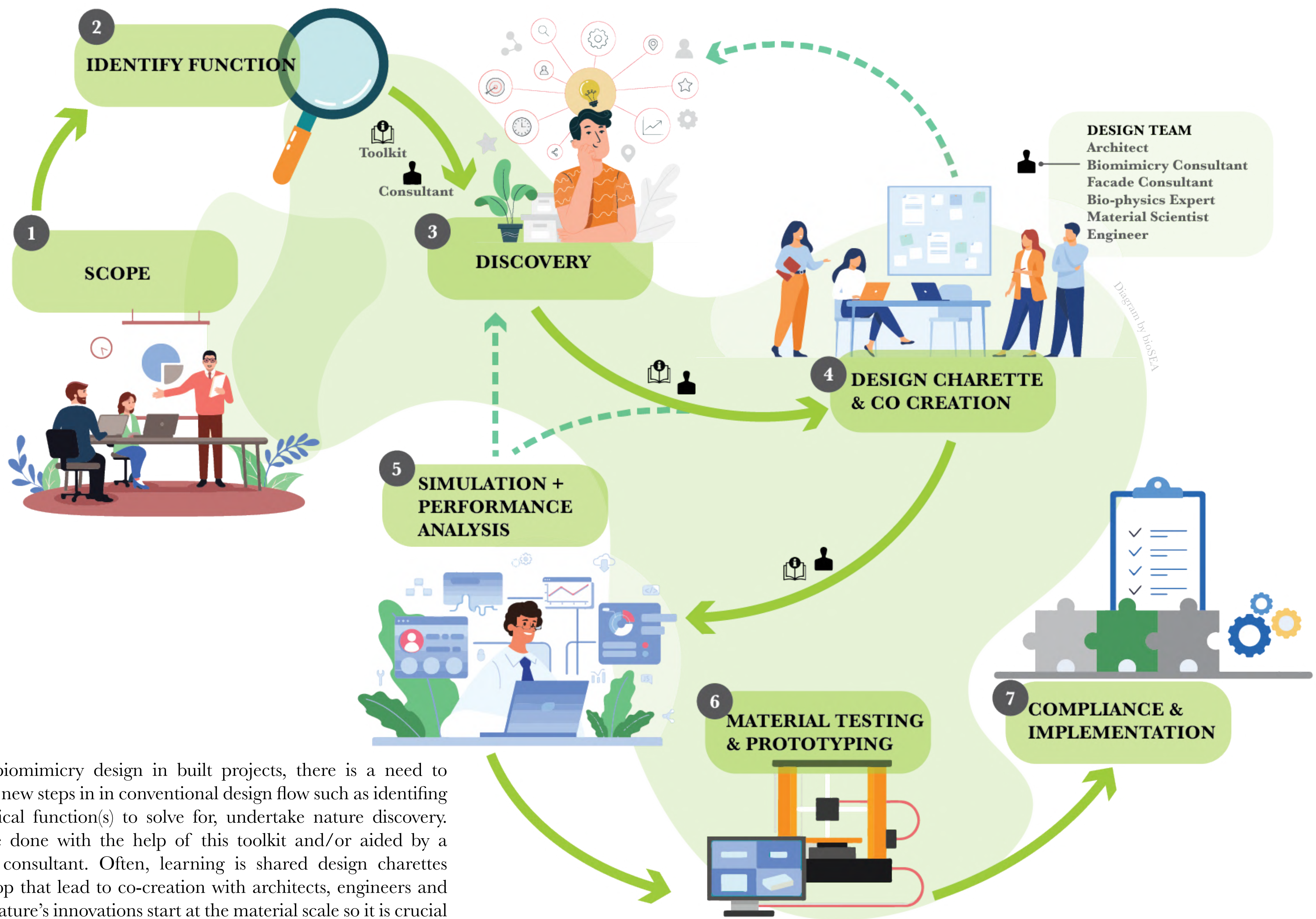


The East Gate Center mimics termite mounds' passive ventilation strategy and reaps **massive energy savings** as a result; however, fans are still required to circulate air. Could we create a truly passive air flow without fans?



Applying termite mound strategies at district level could help create passive district cooling and **mitigate urban heat island effect.**

Integrating Biomimicry in Design Flow



To realize biomimicry design in built projects, there is a need to accomodate new steps in in conventional design flow such as identifing what biological function(s) to solve for, undertake nature discovery. This can be done with the help of this toolkit and/or aided by a biomimicry consultant. Often, learning is shared design charettes and workshop that lead to co-creation with architects, engineers and designers. Nature's innovations start at the material scale so it is crucial to bring material scientists and biologists at design table.

Distinguishing the Bio's

Biomimicry is one type of bioinspired design,

but not all bioinspired design is Biomimicry.

Eden Project, England

BIO MIMICRY

functions like nature

Mimics the shape of soap bubbles, which adapt to any surface. In this case, corresponding to uneven shifting sands of the site.

BIO UTILISATION

uses nature

An alternative to liquid fossil fuels that utilises algae as its source of energy-rich oils.

Algae fuel

BIO MORPHISM

looks like nature

The temple looks like a lotus leaf but doesn't mimic the organism's performative benefits.

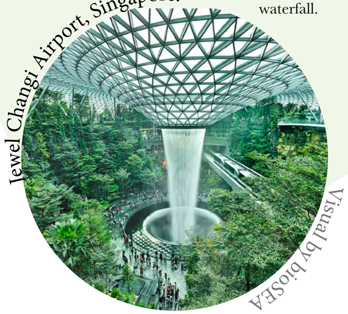
Lotus temple, Delhi.

BIO PHILIA

reminds of nature

The space is designed in a way that it reminds one of a rainforest and a waterfall.

Jewel Changi Airport, Singapore.



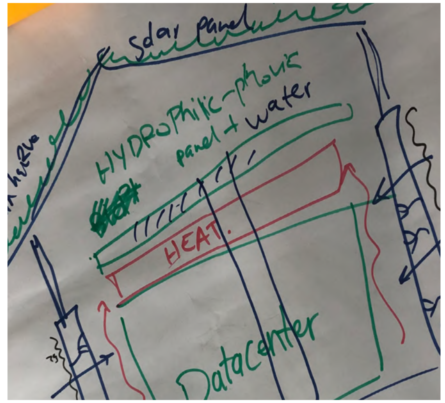
Visual by bioSEA

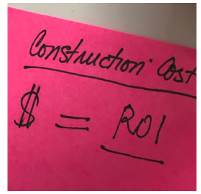
A design can combine various bioinspired approaches to suit context, style and challenge.

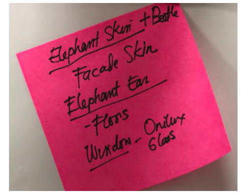
Integration is natural

bioSEA ran a design workshop titled 'What buildings can learn from Nature: Biomimicry 101' as part of Singapore Design Week 2022 at the National Design Centre, Singapore. It was aimed at mostly young architects & designers that were new to applying biomimicry concepts to a real-life problems.

Yet, they made a bold attempt to combine a multitude of biomimetic strategies across organisms to optimize derived benefits. It was natural for them to strategically integrate biomimetic design with well-established net-zero practices such as harvesting rainwater and solar power.







Backed by experience

There could be biophilic and biomimetic master plans that apply natural breeze corridors at the urban design level for example. These strategies haven't been explored much at the master plan scale in Singapore yet and are something that urban planners could be interested in."

Richard Hassell
Architect |
Co-founding Director |
WOHA Architects,
Singapore.

Image credits: WOHA

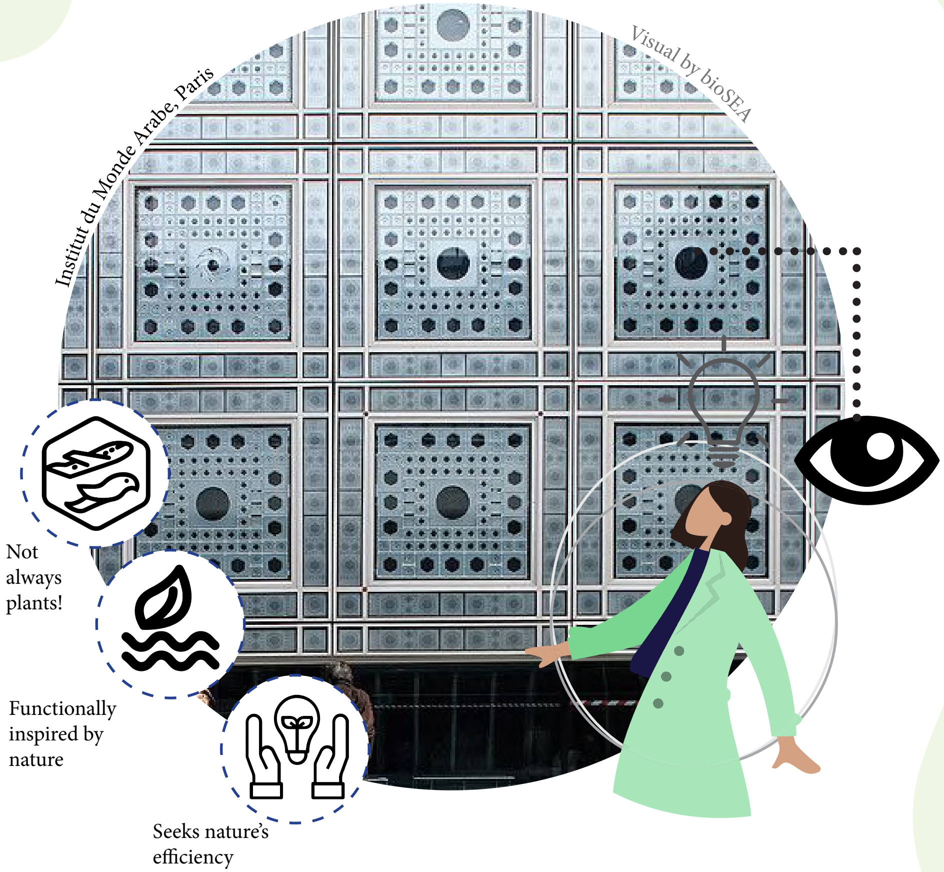
"Biomimicry and bio-inspired ideas can definitely give life to a facade and bring benefits. We are realizing it now just as Nature Based Solutions are taking root. It also comes down to maintenance, safety issues. Could products be designed such that nature maintains itself?

Kuan Chee Yung
Architect | Global Head
Place Innovation |
Consulus, Singapore.

Image credits: Consulus

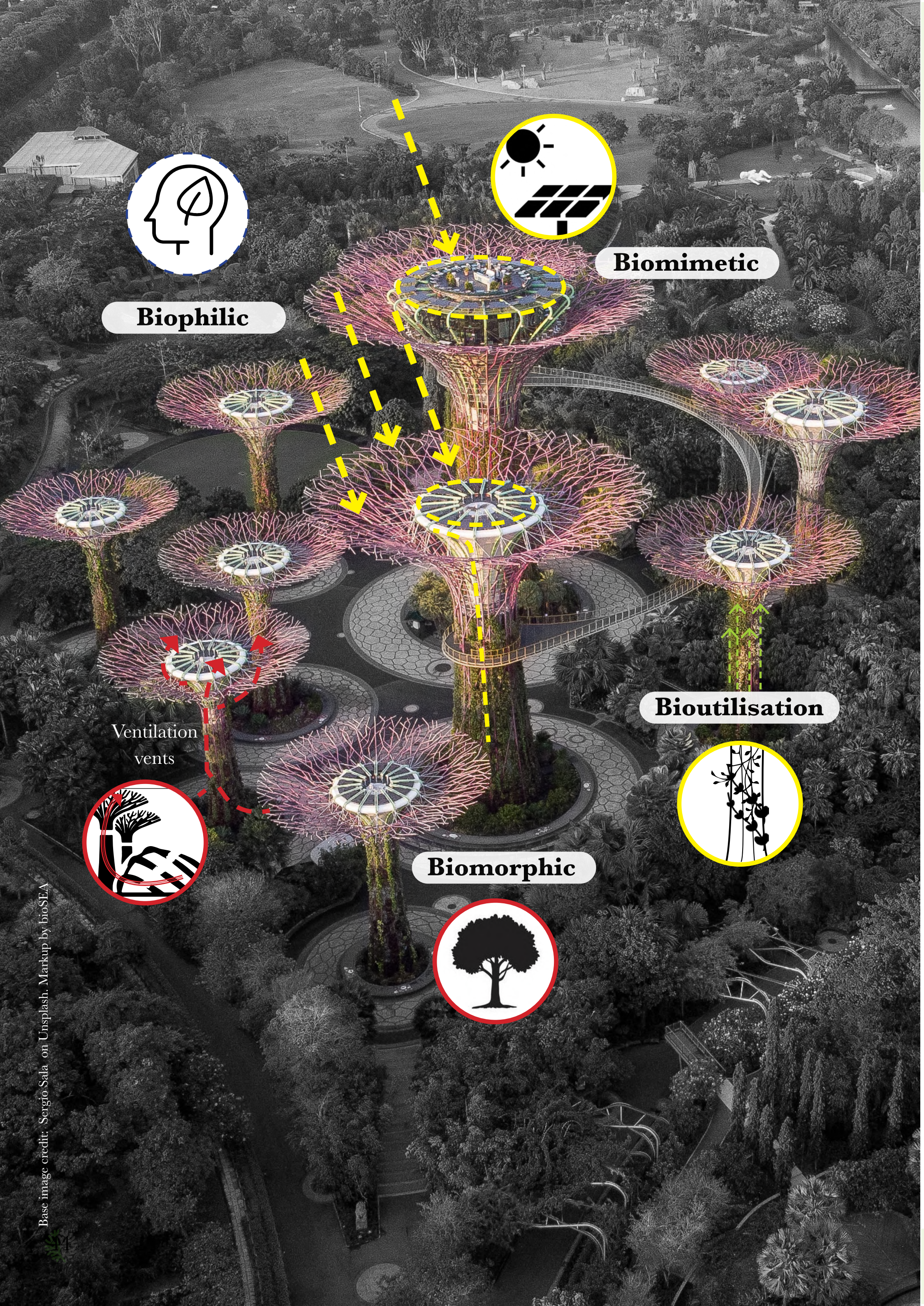
What is the difference between Biomimicry & Biophilia?

Biophilic design seeks to connect built environment users with nature through the use of direct nature (such as through live plants), indirect nature (such as natural shapes and patterns) or through space & place conditions (such as through organic shapes) to better human health and productivity.



Biomimetic design seeks to mimic design strategies found in nature to solve human problems. The emphasis in biomimicry is to mimic an organism's function and strategy and not to look like it. Biomimetic designs may not look like nature (or be biophilic) but they are poised to function like nature.

Biomimicry and biophilia do overlap. Most commonly, biomimicry and biophilic design come together in *biomorphism*, or the mimicry of natural forms.



Case Study 1:
Combining various bio-inspired approaches

Supertree Grove, Gardens by the Bay

One of the landmark projects in Singapore, Gardens by the Bay is a 101 hectare nature park comprising of the Supertree Grove, three air conditioned conservatories and several themed parks and gardens. The Supertree Grove comprises of soaring, surreal tree-like structures that span 25 - 50 metres in height.

The Supertrees are bio-inspired and multi-functional. Apart from being a visual spectacle, they house vertical gardens, create shade on the ground, harvest rainwater, generate energy with solar panels on top of the trees and work as ventilation vents for the conservatories.

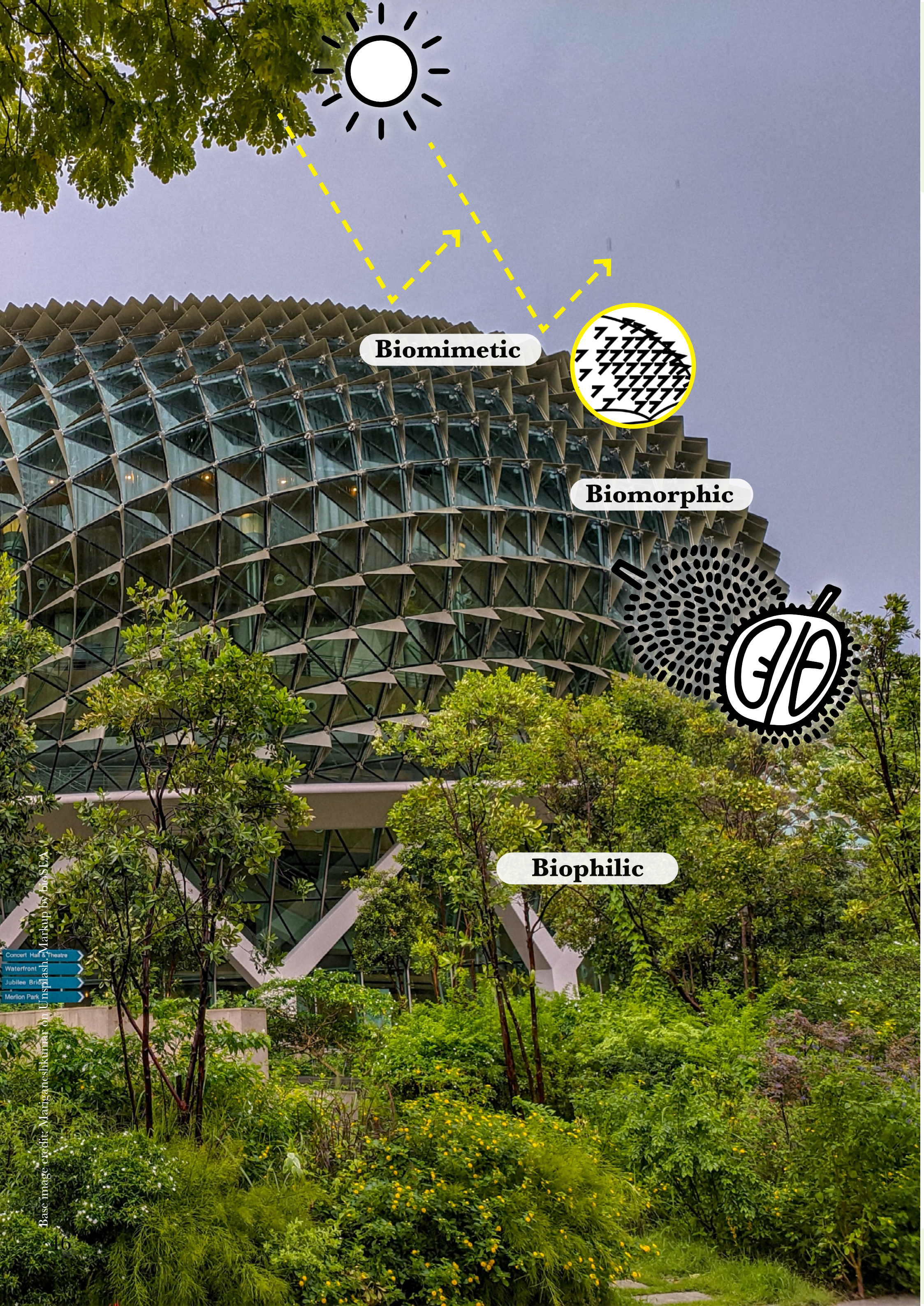
Let's break down the various bio-inspired approaches used by the Supertrees.

Biomorphic - Visible tree-like structure that double up as giant vents to expel hot air from the nearby conservatories.

Biomimetic - Uses solar panels to make energy and harvests rainwater like real trees.
Provides tree-like conditions (height, wind etc.) for the climbers and air plants to grow on vertical columns.

Bioutilisation - Use of real climbers and air plants to express an iconic structure.

Biophilic - Seeks to connect the users of this space with nature through the use of live plants and natural shapes and patterns.



Base image credit: Mariganeshkumar on Unsplash. Markup by bioSEA

Case Study 2:
Combining various bio-inspired approaches

Esplanade, Theatres on the Bay

Another iconic project within the same precinct, locally known as 'the durian' building. This six hectare complex is a world class performing arts and urban center on the banks of the Singapore river. The concert hall and the theatre are designed to resemble the appearance of a durian. The durian-shaped sunshades on the building shell have elaborately designed fins angled in various directions to track and catch the sun rays as it moves across the sky. The allows optimal heat and light management in the interiors of the building.

Biomimetic - Effective sun tracking panels on the building shell. Sun tracking technologies are derived from nature specifically phototropism which is the ability of a plant to grow in response to a light stimulus. This typically involves reorientation of the shoot growth directed towards or away from the light source, in this case, sunlight.

Biomorphic - Form and elaborate skin inspired from the morphology of durian fruit.This intervention is not biomimetic because the durian shape mimicry does not allow the building to perform like a durian. In fact, spikes on a real durian shell are rigid and are not known to perform sun tracking.

Biophilic - Seeks to connect the users of this space to the natural form of a durian fruit and natural landscaping around the building.

Chapter 3

Ready, Set, Design!

By Anuj Jain, Nathan Hays, Munshi Toh, Maitreyee Fadnavis, Lisa Teo, and Saloni Swaminathan

The environment is a source of data, it forces us to follow its behaviour.

- Ines J. Pedras, Architect

Image credit: Danist Soh on Unsplash

Contents

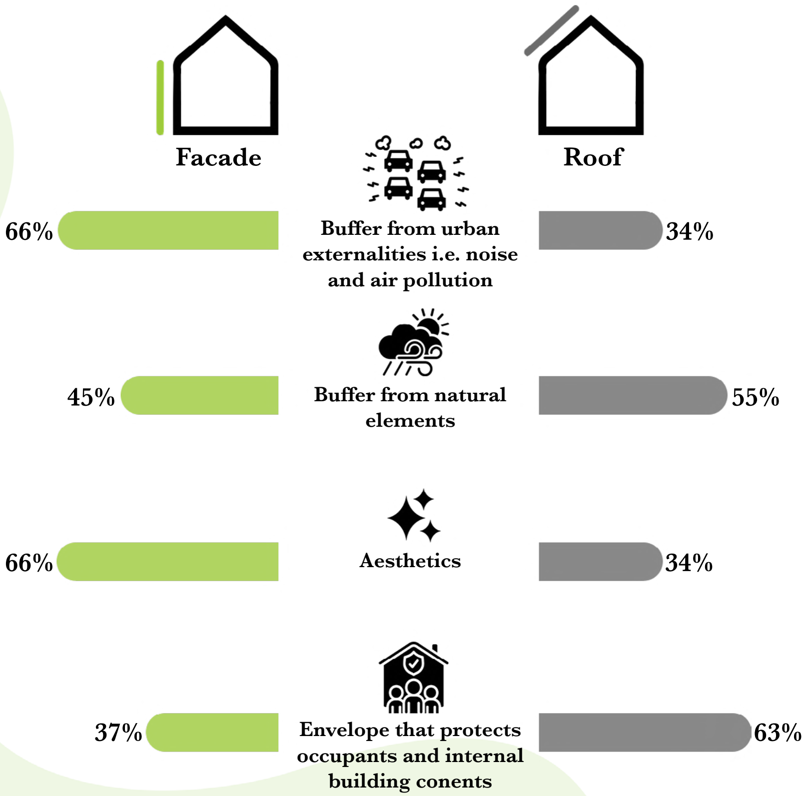
Desirable Building Features

Once a firm understanding of the process is established, the next step involves understanding what building traits and functions a building developer looks for in a construction project. With these objectives cleared, the final steps include an investigation into the environmental conditions in which a project is being undertaken and deciding what key building functions a biomimetic solution can potentially be fulfilled.

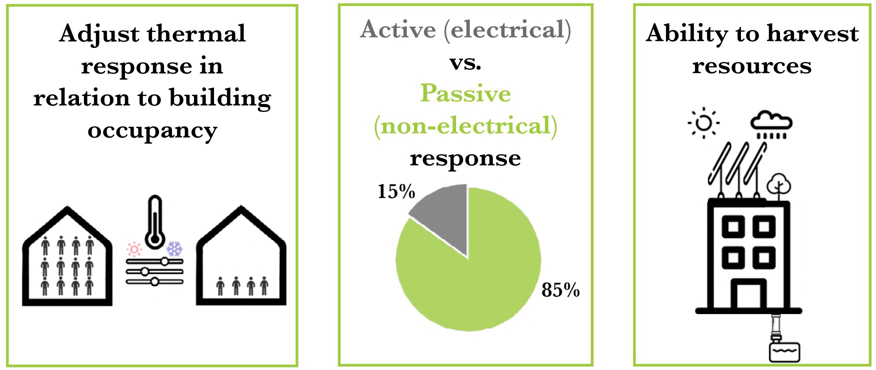
Understanding the needs of building professionals

Before we dive into creating biomimetic building designs, we need to understand the needs of building developers and its eventual beneficiaries. An online survey conducted by bioSEA in October 2021 for building professionals provided insight into the desirable traits and functions building professionals look for (see Chapter 1 - *Have you considered biomimicry?* for respondent profiles).

Important functions of a building envelope



Top 3 additional useful features of facades & roofs



Professionals were asked what were some of the most important features of building envelopes i.e. roofs and facades as they are the main interface between the internal and external space. There was a consensus that both facades and roofs fulfilled the need for a buffer against natural elements such as rain, direct sunlight and humidity, but facades were voted as more important in terms of protecting against urban externalities such as noise or air pollution.

Results showed that the aesthetic of an envelope matters but more so for facades than roofs. Roofs were perceived to play the more important role of upholding structural integrity which promotes the protection of inhabitants within a building.

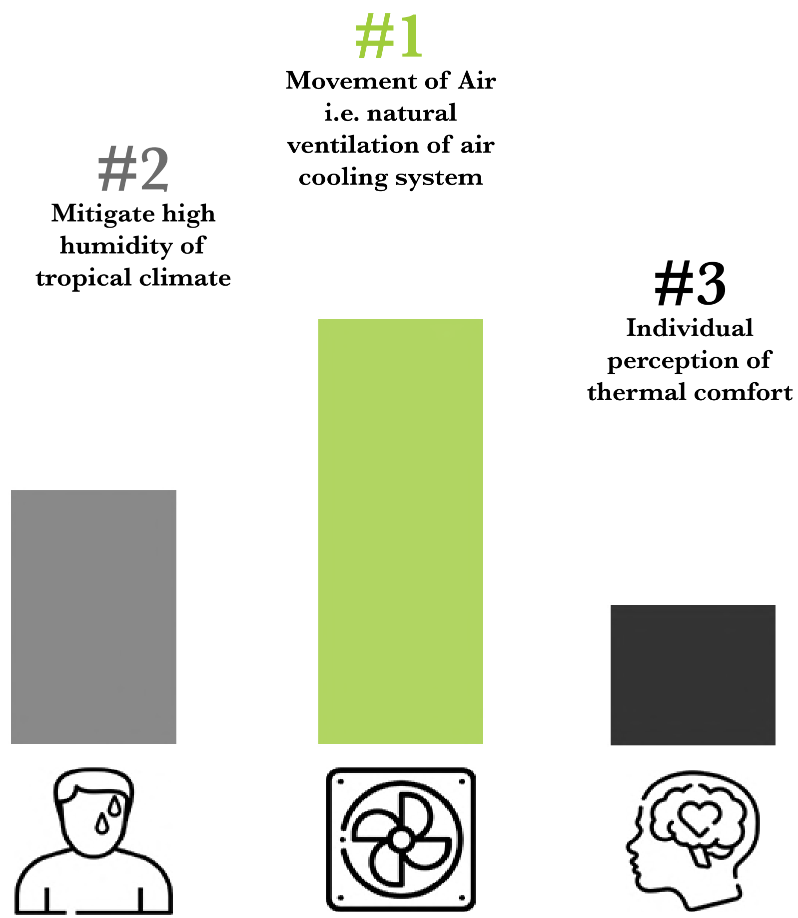
Additional functions professionals would like to see included the use of more passive than active responses to environmental variables. Passive strategies refer to non-electrical interventions such as the use of membrane panels to facilitate air flow and mitigate direct sunlight permeation. Active strategies refer to mechanised versions of passive solutions such as the use of roller blinds that can be controlled to attenuate wind, sun and rain action. This preferences builds a compelling case for the integration of biomimicry solutions.

Other features include the ability to adjust the thermal response in relation to building occupancy to minimise the use optimise the efficient use of energy and the ability to harvest resources such as rainfall and solar energy to power building functions.

It was then evaluated what elements could assist in achieving thermal comfort. Movement of air or rather the utility of cooling systems (passive/active) was the top pick followed by a drive to mitigate the tropical humidity.

Interestingly, perceived individual thermal comfort was not a popular option despite the notion of greenery having both actual and assumed effects of cooling the environment.

Important considerations that aid in achieving thermal comfort

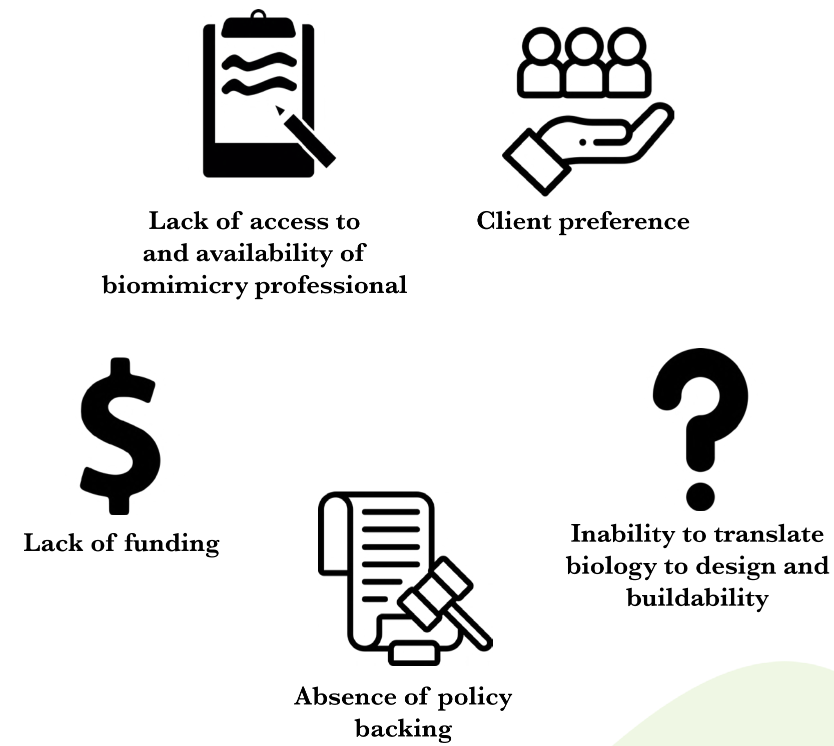


Challenges to implementing Biomimicry as a design process in Singapore

Lastly, the challenges in implementing biomimicry were explored and five main issues were raised. Built industry professionals believe biomimicry implementation is a black box due to not having access to a network of biologists who understand how to read jargon and interpret biological strategies.

Without biological expertise, the ability to translate biological knowledge and accurately mimic and adapt it to architectural design interventions is stunted.

The lack of incentive to adopt biomimicry strategies from a policy point of view further disincentivizes its employment. A lack of access to funding to innovate and implement as well as client unfamiliarity and preference against novelty add further barriers to entry for the application of biomimicry.



This survey provides a primary understanding of the design considerations building professionals are concerned with and aids in deciding what biomimetic innovations are necessary to fulfil the identified building functions.

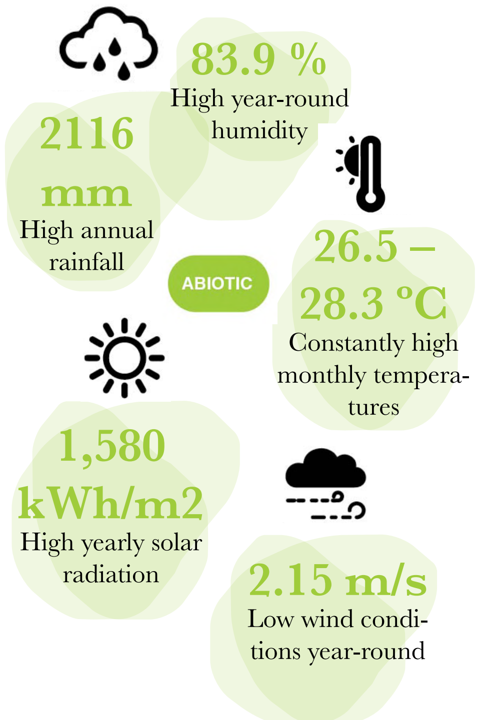
Building for the Tropics

Understanding the tropics

Having understood the needs of building professionals we now need to broaden our understanding of the environmental conditions the building will be subject to. The environment the project is built in, in this case – the tropics, will not only guide its design, but inspire its design.

36% of Earth's landmass plays home to the tropics[28]. Using Singapore's average monthly and yearly values as a point of reference - a tropical climate is characterised by the following series of abiotic conditions.

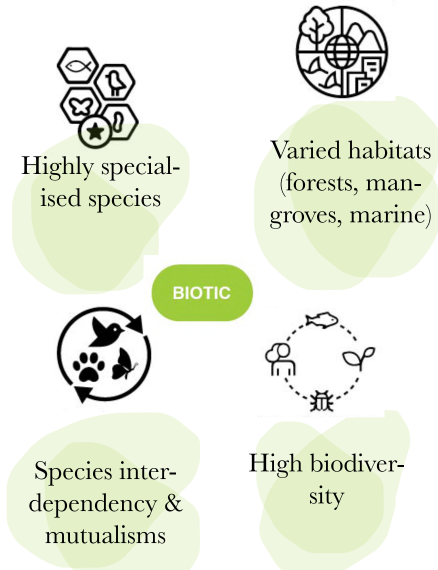
Heat dissipation remains one of the top priorities for building facades to solve for, whilst maintaining structural efficiency and other thermoregulation functions. High rainfall and humidity levels in the tropics makes this task challenging. The constant exposure to moisture makes buildings vulnerable to water penetration and subsequently structural damage. Coupled with low wind flow, ventilation is limited, further escalating the risk of material disintegration through rot and corrosion.



Building for the tropics, by the tropics

Despite these challenges, the tropics are **the most** biodiverse ecosystems playing home to **over 80%** of all species across the world [29]. Ironically, it is the high temperatures that provided an extremely productive environment and spurred the evolution of highly specialized species. These species are adapted to and overcame challenges posed by the tropical biome in a myriad of ways. Singapore alone has over **40,000** described species [30].

The incredible biodiversity of the tropics provides an abundant reference pool, an innovation catalogue of sorts, of both generalised and niche place-based thermoregulation strategies.



Within the tropical climate exists a variety of habitats. For example, Singapore sports the majestic lowland dipterocarp rainforests fringed by freshwater swamps, mangroves, seagrasses, corals and rich marine ecosystems. The diversity, interconnections and interactions between tropical habitats invites us to explore how biomimetic ideas can create place-based and synergistic building solutions that take into account a facades' context and interactions with its environment, not only at the precinct scale but also at the city-planning scale.

Tropical species have high interdependencies and mutualisms through closed loop nutrient flows, in which one animal's waste becomes another's resource.

This is the blueprint for a circular economy. The diversity creates a resilient network of organisms whose equilibrium relies on balancing the demand and supply of nutrient flows and natural resources. This tapestry of life encourages us to wonder how biomimetic and non-biomimetic solutions in the built world could come together to fully optimise available resources while minimising waste.

So, how much of our spectacular natural environment can our built environment mimic?

Nature vs. Building Skins

Skins of plants and animals, including our own, perform many functions by acting as an interface against dynamic outside (external) conditions and provide stable inside (internal) conditions.

a. Internal Conditions


Healthy


Clean


Consistent Temperature


Light Regulation


Connection to Nature


Comfortable Surface

Bird Nest (such as Baya Weaver) regulates Wind, Sunlight and Humidity and camouflages by Colours and Textures

Pomelo
The thick skin is strong yet porous and lightweight that allows for healthy gas exchange. It provides Structural Support and Resists Impact.

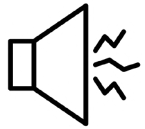
The leaves help photosynthesize and generate energy.

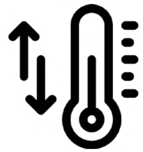
b. External Conditions

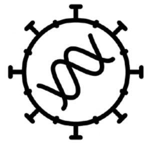

Wind

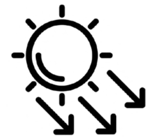

Pollution

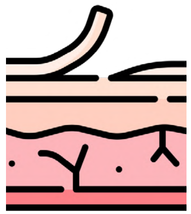

Heat


Noise

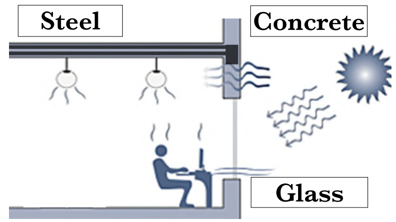

Temperature Fluctuations


Pathogens


Direct Sunlight



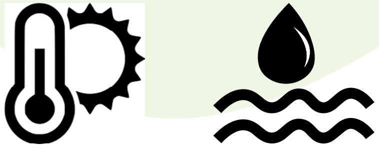
Human Skin thermoregulates by managing heat, pollution, pathogens, smells and sounds. It is also malleable, self-healing and there by possessing regenerative qualities.



Building skins typically perform only a subset of the functions performed by nature's skins.

Similar to Nature, our goal is to make building skins multi-functional and adaptive yet performative as natural skins.

Key Functions & Definitions



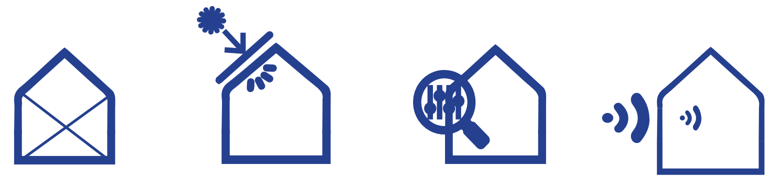
HEAT WATER

Several key functions are covered under the overarching primary function of thermoregulation of building skins that revolve around heat & water. The secondary functions cover a larger scope of building skins application from light, energy, habitat, sound and materials.

Primary Functions

Improve Ventilation | Heat Dissipation | Humidity Control | Limited Heat Gain

Secondary Functions



Structural Efficiency | Light Optimization | Material Optimization | Acoustics

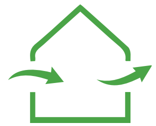
Energy/Carbon Capture | Water Capture | Surface for Flora & Fauna

Definitions

The toolkit addresses the overarching function of thermoregulation for building skins through the subfunctions of improved ventilation, heat dissipation, humidity control and limiting of heat gain. These are the main focus of the toolkit and are called ‘primary functions’.

The secondary functions cover a larger scope of building skin applications and include water harvesting and purification, material optimization etc. These are the secondary focus of the toolkit.

Primary Functions



Improve Ventilation

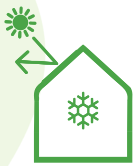
Because ventilation deals directly with air quality, proper ventilation is a key aspect of a healthful space. Occupant comfort is also directly impacted by ventilation as the flow of fresh air can be important in the regulation of temperature and humidity. By using biomimicry and passive design strategies, architects and engineers can optimize natural ventilation in buildings, working with the environment as nature does to harness wind and thermal buoyancy. These approaches not only help reduce energy consumption and carbon emissions, but also help create more resilient buildings that maintain comfort and fresh air through disturbances including potential power outages.

Heat Dissipation

In hot climates, heat dissipation is a critical aspect of maintaining a comfortable and energy-efficient space. Efficiently releasing heat collected from ambient air, solar radiation, or internal sources helps prevent excessive heat buildup and reduces reliance on energy-intensive cooling systems. By taking inspiration from nature's own cooling strategies, architects and engineers can effectively dissipate heat in buildings. Some approaches to heat dissipation include evaporative cooling, natural ventilation, and optimizing surface geometries. When heat dissipation is an inherent consequence of the building design, energy consumption and carbon emissions are reduced and indoor environments remain comfortable even through disturbances.

Humidity Control

Humidity control is essential in hot and humid climates to ensure a comfortable and healthful indoor environment. Excessive humidity can exacerbate heat-related discomfort and lead to issues such as mold growth and poor air quality. By integrating nature-inspired strategies in building design, architects and engineers can effectively manage humidity levels without relying solely on energy-intensive mechanical systems. Some approaches to humidity control include moisture-absorbing materials, natural ventilation, and surface geometries that induce or facilitate condensation. In humid climates, where the need for humidity control is more pronounced, there are unique opportunities to capture and repurpose water from the air.



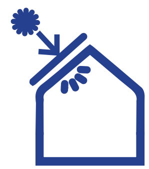
Limited Heat Gain

Limiting heat gain is a crucial strategy in tropical climates to maintain comfortable indoor temperatures and reduce the need for energy-intensive cooling systems. By minimizing heat absorption from the outside environment and solar radiation, maintaining a comfortable temperature is much easier. This function is closely related to, and sometimes resembles, Heat Dissipation. The focus here, however, is in avoiding the absorption of heat in the first place. Some of the same strategies can be used for both Heat Dissipation and Limit Heat Gain. The key distinction between them is the type of heat being addressed—i.e. if the heat has already been absorbed or if it is not yet embodied in the building. Nature-inspired solutions include self-shading, light colored or light-reflecting materials, living facades and roofs, and components that convert solar energy to usable (usually electric) energy.

Secondary Functions

Structural Efficiency

Structural integrity is a fundamental asset of a building. A building must support itself and withstand various internal loads and environmental stressors. While this aspect of building design may seem self-evident, it offers a wide range of possibilities for both creative expression and sustainable solutions. The structure of a building can be concealed or displayed as part of the design concept and aesthetics. A building that achieves structural efficiency minimizes material consumption, reducing the environmental impact. Moreover, the structure of a building can be intricately woven together with other functions, such as thermoregulation, ventilation, building program, view-framing, acoustics, lighting, water capture, and habitat creation. Nature is extremely efficient in its material use. In nature, lightweight structures are realized through elegant morphologies and clever material placement. By following nature's examples, architects and engineers can create multifunctional and adaptive structures that optimize resource use.



Light Optimization

A building that demonstrates light optimization fully embraces and intelligently integrates with natural light, a free and abundant resource. By carefully managing the balance between light levels and glare, buildings can provide a pleasant and functional environment while avoiding excessive heat gain. Light optimization in buildings not only minimizes energy consumption for artificial lighting but also enhances occupant well-being. Nature-inspired solutions for light optimization can weave together several functions. For example, while selectively lighting some spaces and shading others for program and comfort, colour and orientation can interact with light to create temperature differences and thermal buoyancy to drive airflow for passive ventilation and cooling.

Material Optimization

Material optimization goes beyond efficient structural arrangements and addresses the creative and thoughtful use of materials to minimize environmental impact and enhance occupant well-being. This function can relate closely to structural efficiency, but goes beyond to encompass a broad range of considerations, including the selection of materials with low embodied carbon, materials that are reusable and biodegradable, and materials that are safe for both the environment and occupants. Material optimization also includes embracing the unique strengths of the materials chosen. Architects and engineers can create multifunctional designs that contribute to various building needs, such as thermoregulation, light optimization, humidity control, acoustics, structural efficiency, aesthetics, and more. When the assets or behaviours required to achieve a function are embedded in a building's material, reliance on external energy is minimized and the building continues to give its value even in the most difficult scenarios.

Acoustics

Acoustics is a vital and often overlooked aspect of building design, playing a crucial role in the functionality and comfort of various spaces. The way a building manages sound directly affects occupant health and the success of designed spaces, from gathering areas to quiet study zones, research laboratories, and theaters. Buildings' forms, structures, fenestrations, and materials all contribute to the acoustic experience. Architects and engineers can draw inspiration from nature to optimize acoustics in building design, looking to organisms that use different sound wave manipulations for communication, and to those that have optimized for stealth. The management of sound not only impacts occupants' health and comfort, but also affects the health of surrounding ecosystems—noise pollution affects humans and non-human species. By prioritizing acoustics, designers can create spaces that fulfill their intended purpose while promoting occupant well-being and harmonizing with their surroundings.

Energy/Carbon Capture

Energy and carbon capture are essential functions in sustainable building design, addressing climate change from two different directions. Like organisms, most buildings require energy to operate, and they can harness this energy from their immediate environment. By utilizing renewable sources such as solar, wind, and geothermal energy, buildings can avoid reliance on fossil fuels, thereby reducing their contribution to atmospheric carbon. In addition to renewable energy generation, buildings can also capture carbon from the air, mitigating some of the existing environmental damage. Photosynthetic plants convert CO2 and water into oxygen and carbon building blocks using solar energy. Buildings can emulate these natural processes in their carbon capture strategies. These strategies can range from the technologically sophisticated, emulating the underlying mechanisms of photosynthesis, to the more simple and broadly accessible, by incorporating the living systems that have evolved to do this with green roofs and living walls.

Water Capture

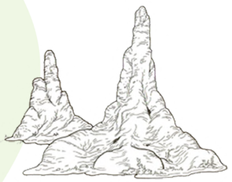
Water is a very precious resource and water capture is an important function in sustainable building design. Effective water management in buildings not only contributes to reducing the demand on municipal water supplies but also helps to protect local ecosystems and maintain the balance of natural water cycles. Incorporating water capture strategies in building design can minimize the reliance on external water sources for potable and non-potable uses, for living roofs and walls, for gardens, and for other on-site habitats. Water capture can be part of temperature regulation and humidity control strategies. Capturing water also helps manage stormwater runoff, reducing the risk of flooding and erosion.

Surface for Flora & Fauna

Design that includes habitat for flora and fauna is an essential aspect of sustainable architecture. These spaces acknowledge the importance of biodiversity and interconnected ecosystems for the well-being of both humans and non-human species. Our physical and mental well-being is inextricably linked to the living systems around us, from the microbiomes within our bodies to the ecosystems that surround our cities. By incorporating habitats for flora and fauna in building design—such as green roofs, living walls, and urban gardens—designers can create more vibrant, attractive, and enjoyable spaces for occupants while supporting biodiversity and essential ecosystem services like air and water filtration, temperature regulation, stormwater management, and pollination.

Selected Nature's Strategies for Key Functions

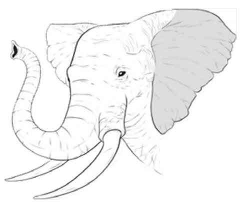
Primary Functions



Improve Ventilation

TERMITE MOUND

Passive airflow: Fungus harvesting termite species create vent structures to create a habitable environment for fungus farming. These mounds have an intricate pattern of branched air channels that tap onto stack effects driven by temperature differentials during the day and night to induce air flow and gas exchange.



Heat Dissipation

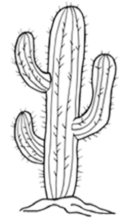
ELEPHANT EAR

Keep cool: Elephants flap their thin membrane-like ears similar to fans to create airflow and release heat from the densely packed blood vessels that are close to the thin skin surface.

Humidity Control

PINE CONE

Humidity Responsive: Pine cones have slender scales that open up in dry conditions to disperse seeds via the wind. When humidity rises, the scales curl up to prevent ineffective seed dispersal.

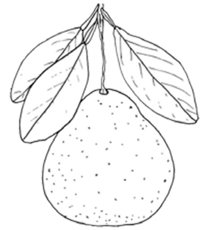


Limited Heat Gain

CACTUS

Shade: The Saguaro cactus grows with long spines and accordion-like folds that offer partial shade and cool the air in the shaded areas. Such a form creates circulation around the cactus that minimizes heat absorption.

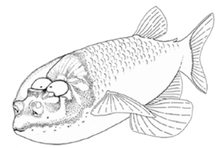
Secondary Functions



Structural Efficiency

POMELO

Resist Impact: The pomelo fruit has a thick compressible but lightweight skin to protect from impact when the heavy fruit falls on ground. The thickest layer of the skin has air pockets making it act like an open porous foam and absorbing energy like a cushion.



Light Optimization

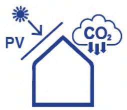
SPOOKFISH

Redirect light: Spookfish has unique eyes that have 2 connected parts – one pointing up, another pointing down at the same time. The up pointing eye sees sky light, the down pointing eye sees faint light coming from the sea below. This helps enhance vision in the dimly lit deep sea where it lives.

Material Optimization

BAMBOO

Lightweight, Strong & Fast Growing: The cellular structure of the bamboo wall reveals tighter cellular density near the outer surface of the wall and less density near the inner wall reinforcing the idea of maximum material efficiency when subjected to bending loads



Energy Capture

ALGAE

Produce energy: Microalgae have some of the highest carbon fixing capabilities as they photosynthesize.

Acoustics

OWL

Direct Sound: The edges of an owl's wings are jagged and hairy that helps reduce sound enabling silent flight to better surprise prey. The owl's face is also shaped to direct sound to its ears

Water Capture

NAMIB BEETLE

Fog water: Micro-sized bumps on the beetle's back (exoskeleton) help condense water from the foggy night air in its coastal desert habitat and direct it towards the beetle's mouth.

Surface for Flora & Fauna

TREE BARK

Living surface: Provides substrate for epiphytes like ferns and mistletoes and nooks for lichen and moss to grow. Woodborers live inisde , woodpeckers build holes that eventually becomes nesting space for wildlife.

What Design Plans could Look Like?

Three wall panel designs developed by the bioSEA team are presented in the pages below. They were inspired by the the elephant skin's evaporative cooling and self-shading ability, termite mound's ventilation and Namib desert beetle's water capture strategies.

Each design follows the six step design process. We start with Define & Biologize and relate the problem with the identified functions. In the Discovery stage, the rationale behind the choice of the inspiration organism is explained. Existing precedent biomimicry projects using this organism are briefly described. Following which an Abstraction of the design strategy is covered. The design approach, simulations results, prototypes and applications are covered under Emulate and Evaluate.

The chosen organisms live around the world from the tropical and subtropical elephants and termite mounds to the desert beetle that lives in hot and dry but foggy coastal desert. There is much to learn from each geography and context and abstract what applies to the project and climatic context.

We hope that the wall panel scale design explorations will spark your interest and help you embark on your biomimicry innovation. After you have read these designs, consider referring to the Scale of Application visual earlier in chapter 2 to brainstorm designs at other scales.

How can patterns on elephant skin help us keep buildings cool?

Elephant Skin

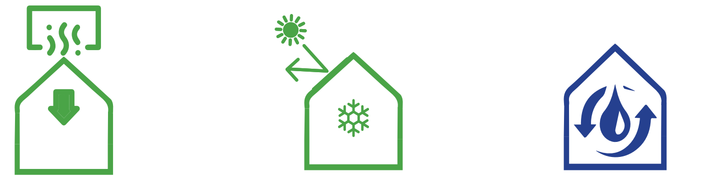
Summary

This design exploration showcases the bioSEA team's design of modular façade tiles inspired by the bumpy and textured skin of elephants. The tiles combine two key mechanisms for passive cooling (self-shading and evaporative cooling) and capillary action for water management.

Define & Biologize

Our primary goal is to minimize the heat flux across the back surface of the building facade tiles in a tropical hot & humid climate. This can be achieved by the following functions. We asked *"How does nature limit heat gain, dissipate heat in a tropical climate?"*

Functions addressed



Heat Dissipation (via evaporative cooling)

Limit Heat Gain (via self-shading)

Water Capture (via reducing runoff)

Discover - Why elephants? How elephant skin works?

Elephants live in tropical and subtropical climates, but most remarkably in savvanahs where they manage heat extremely well despite their large body size. They are said to go without drinking water for upto four days. This is partly possible due to the elephant's unique ways of staying cool. Unlike humans, elephants do not sweat or shed their dead skin. Instead, as the elephant ages, its dead skin accumulates as thick layers on the surface of the living skin. Eventually, the skin develops cracks due to the weight of accumulating layers.

The bumpy, cracked geometry combines several strategies for an effective passive thermoregulation system. The specific shape and scale of the bumps, and the size of the crevices between them, provide self-shading and promote evaporative cooling. The bumpy and textured surface increases the surface area to volume ratio and creates self-shaded areas between them. The resulting microclimate utilizes convection currents from adjacent hot and cool pockets of air thereby facilitating convective heat loss. Water seeps through these cracks using capillary action, which allows the skin to hold more water and for longer than other animals.

Let's remember that specific patterns on the elephant skin evolved within its climatic context. An as aspiration, the building façade tiles must also evolve a pattern that is specific to tropical climates.

Abstract & Emulate - The Design Approach

Building on past research by Peeks & Badarnah (2021)[31] and in continued collaboration with Dr. Lidia Badarnah, we abstracted the patterns on elephant skin to examine if emulating the surface morphology for building façade (wall panel) tiles may lead to better cooling. To emulate the geometry of bumps of the elephant skin, we used the Voronoi method since the outlines of the mid-scale bumps on the elephant skin resemble Voronoi cells (Figure 1).

Incident Radiation

We utilized an evolutionary algorithm to vary the pattern of the bumps (shape, height and angle) in order to see which blueprints code for shapes that provide the best cooling with respect to incident radiation (IR). We looked at heat flux across the back surface of the building facade tiles due to IR - direct (coming directly from the sun) and diffused (scattered by the atmosphere) that falls on facade surfaces at a specific location in Singapore (see Figure 2).

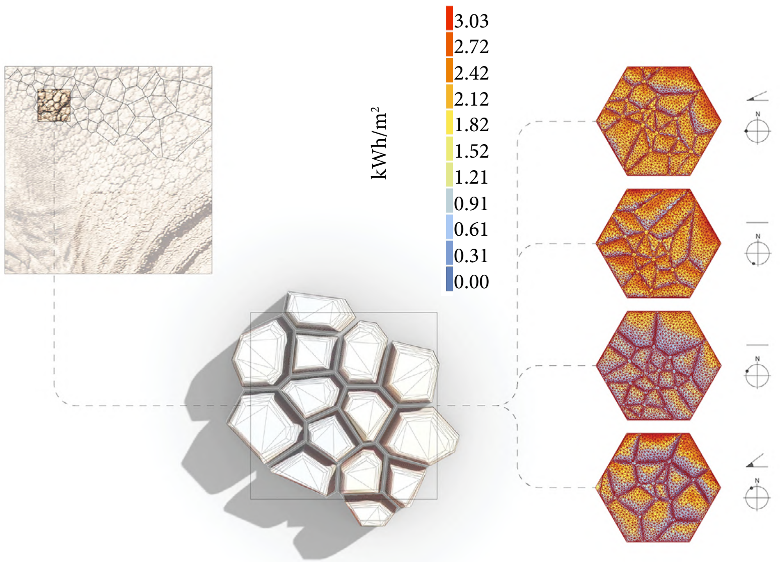
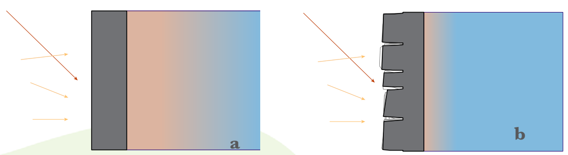


Figure 1 - The textured surface of the elephant skin when abstracted to wall panel tile design tells us that the IR received varies depending on the orientation of the surface (indicated by the line or angle and a circle with a dot). Each face of the tile is colored according to the amount of IR received per unit area.

Figure 2 - A conceptual diagram showing how direct radiation (long orange arrow) and diffuse radiation (short yellow arrows) falls on a flat surface [a] and a bumpy surface [b] contributing to a rise in the indoor temperature (blue).



When the four textured tiles (Figure 1) and compared with four flat tiles in matching orientations, textured tiles taken together shows a 33% improvement compared to the flat tile on average IR, and a 44% improvement on hot spot reduction.

Interplay with water

A key function of the elephant skin that contributes to evaporative cooling is its capacity to pull water across the surface and hold that water on the surface. Water movement across the surface is driven by capillary action which is the pull of a fluid through a narrow space. This pull is due to an attraction between fluid molecules and molecules in the material of the tube or crevice. Because there is a slight attraction between the water molecules and the surface molecules, water moves to cover more of the surface. The distance water will travel depends on the material and is inversely related to the diameter of the tube or crevice (Figure 3).

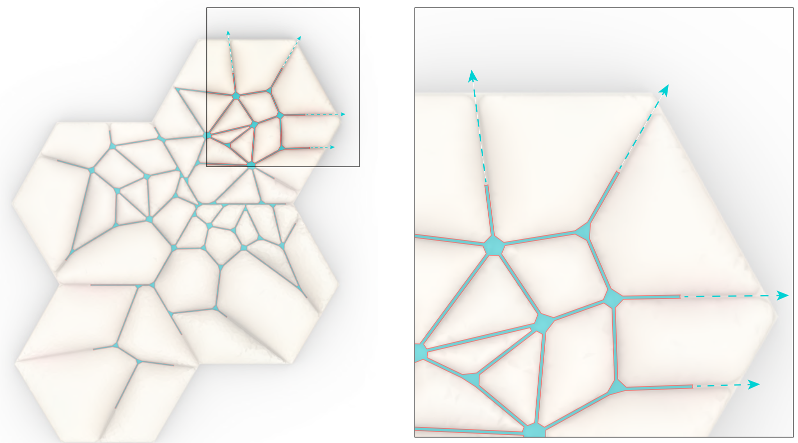


Figure 3 - This graphic shows the movement of water across the surface through the crevices by capillary action. If an appropriate crevice diameter is chosen (0.7mm in this case on 10 cm wide hexagon tiles), and if an appropriate material is chosen, then capillary action can pull water even against the force of gravity. This helps cover the entire surface with water thereby letting heat accumulated by the surface go first to phase change the water: evaporative cooling.

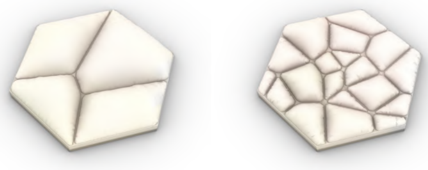
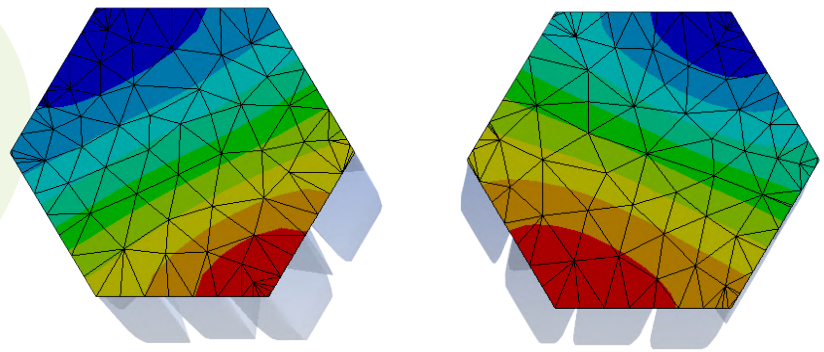


Figure 4 - Different tile orientations draw different combinations of feature from the same "genetic code". Examples are a code which produces a tile with a low density of Voronoi cells in one orientation and a high density in another

Radiation & Temperature

We brought radiation data into ANSYS, along with temperature data for different days for Singapore's climate, to do more sophisticated thermal analyses. Our goal is to identify specific pattern characteristics that relate to particularly good thermal performance, to see how pattern performances vary in different locations and at different orientation (e.g., if some patterns perform well in some scenarios and poorly in others), and to see if we could monotonically relate our constructed fitness values to thermal performance measures in ANSYS.

We measured both the temperature and heat flux on the back of our tiles in ANSYS. Our results show that bumps, similar in shape and scale to those on elephant skin, do help with cooling. Our models suggest that this is due to the increase surface area, much of which is shaded. Because of the added surface area, the heat that is generated by radiation (now in smaller, more concentrated areas), has more opportunities to escape to the ambient environment instead of continuing through to the other side of the tile. Future research will look at widths and depths of crevices, the networked character of crevice patterns, along with materials that work with the desired capillary action effects.



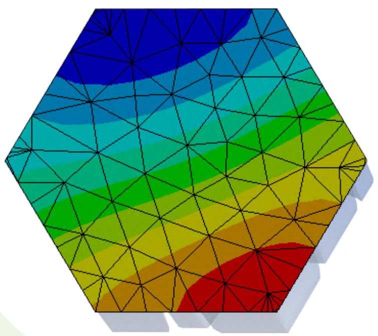


Figure 5 - The temperature performance on the back of the tile with varying shape and size of the bumps. The warmer colors represent greater temperature.

Evaluate - Prototyping & Material Testing

A specific pattern of tiles was 3D printed using PLA and subsequently fabricated in three materials - gypsum, mycelium and clay. Gypsum and mycelium tiles were fabricated at Prof Hortense Le Ferrand's laboratory in Nanyang Technological University, Singapore where they underwent rigorous thermal performance testing. This work has been jointly submitted under a technical disclosure.

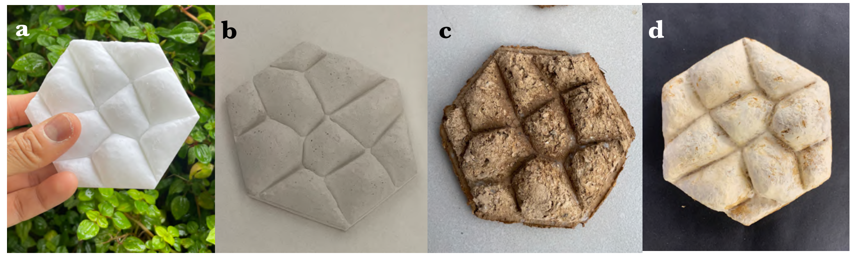


Figure 6 - (a) 3D printed tile in PLA, (b) tile casted in Gypsum, (c) fabricated using FertiClay and (d) grown using mycelium.

Figure 7 - Mycelium tiles have been prototyped on a wall at the Nanyang Technological University, Singapore and are undergoing field testing.

Evaluate - Additional sustainability wins
How would nature use materials?

Clay tiles were fabricated with Ferticlay - a Singapore based company that uses recycled clay (typically discarded at construction sites) and combines it with food waste, thereby providing additional sustainability benefits to the design.

The mycelium tiles are grown using readily available fungal strains and combined with wood waste materials such as saw dust - another sustainability win!

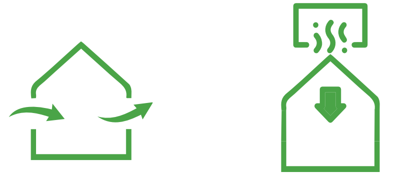
To learn more, watch our video on biomimicry toolkit elephant skin feature https://vimeo.com/818110466

Termite Mounds

Summary

Inspired by the ventilation system of termite mounds, this section showcases the bioSEA team's design of modular façade wall panels. The breathable panels use Murray's law based branching structure to improve ventilation and thereby, better dissipate heat.

Functions addressed



Improve Ventilation

Heat Dissipation

Define & Biologize

Our goal is to develop a passive ventilation system that works across a range of wind speeds thereby, elevating the user comfort and experience of the space. This can be addressed by the functions below.

Discover - Why Termite Mounds?

Found across tropical and subtropical areas, some fungal-harvesting termite species construct large and porous mound structures that function like a ventilator regulating mound temperature, humidity, and gas levels produced by the large termite colony as it breathes underground. Suprisingly, much of the mound remains uninhabited and is used by termites to construct or repair egress tunnels and passageways to the fungal nest they maintain underground.

The beauty of the mounds is that they work not only at steady state wind speeds (as in most human ventilation systems) but also tap onto dynamic wind flows sensing tiny perturbations much like the vibrations of a tuning fork, thereby utilizing small breeze that passes through. This leads to better gas exchange inside and outside the mounds. Wouldn't it be cool if tropical buildings had fresher air and fluctuating but gradually modulated wind flow? See Patterned Flow case study in Horizon Scan (chapter 2) for how this can be beneficial.

Abstract - How do Termite Mounds work?

It is a complex system. The first principle is of a convection system based on natural ventilation and stack effects added with a porous skin. This is manifested through the mound's central chimney and different channels or conduits that are designed to utilize fluctuations in day and night temperatures (Figure 1). During the day, the channels close to the surface of the mound heat up, and warm air flows up these channels, pushing down cooler air through the chimney towards the underground nest. The flow reverses at night. The surface of the mound is also porous with holes all over it which further helps dissipate heat to the environment. Combined, these bulk flows and porosity help cool termite homes without the need for external energy inputs.

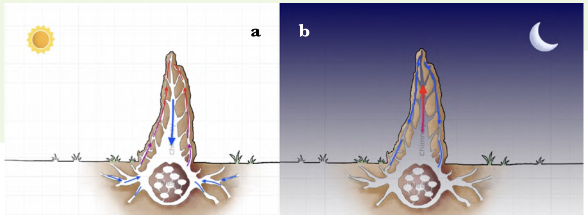


Figure 1 - Bulk flow in termite mounds during (a) day & (b) night particularly under dry conditions. Photo adapted from Channel News Asia.

Figure 2 - A 1m-tall mound constructed by the native black termite species *Macrotermes carbonarius* under wet conditions in Bedok Reservoir Park, Singapore. Photos by Anuj Jain.

Precedent - Eastgate Centre & Council House2

The Eastgate Centre in Zimbabwe and Council House 2 in Australia (both covered in chapter 4 - 'Horizon Scan') utilize these principles by making highly porous buildings.

The Eastgate Centre for example uses 35% less total energy than the average consumption of other conventional buildings with full HVAC.

However, the building still relies, in part, on fans, and therefore, cannot achieve the passive cooling ideal of termite mounds.

The other parameter at play in termite mounds includes diffusive flows that make the mound function much more like a respiratory organ (see Soar, R. (2015) Part 1[32] and Part 2[33]). Termite workers use humidity as cue to construct or repair the mound by sensing the moisture content of the soil, and humidity level in the air.

This motivated us to try to master ventilation at smaller wall-panel scales (see Scale of Application visual in chapter 2) tapping onto convective and diffusive flows. If designed well, such wall panels can connect modularly to produce a stack system that can run through a building's walls and at least in theory, be closer to the ventilation efficiency of termite mounds.

Think Global, Act Local

The mound operation differs with seasons and locations. In dry conditions (such as those found in Zimbabwe) internal mound ventilation is driven by natural convection which switches direction between day and night and where gas exchange takes place through a thin porous mound skin. In wet conditions (typical of Singapore) the mound skin could potentially suffocate the termites. Here workers actively modify the mound skin to create channels and ducts through

which air mixes between the inside and outside of the mound. This modification of the mound skin also drive evaporation of excess moisture from the mound.

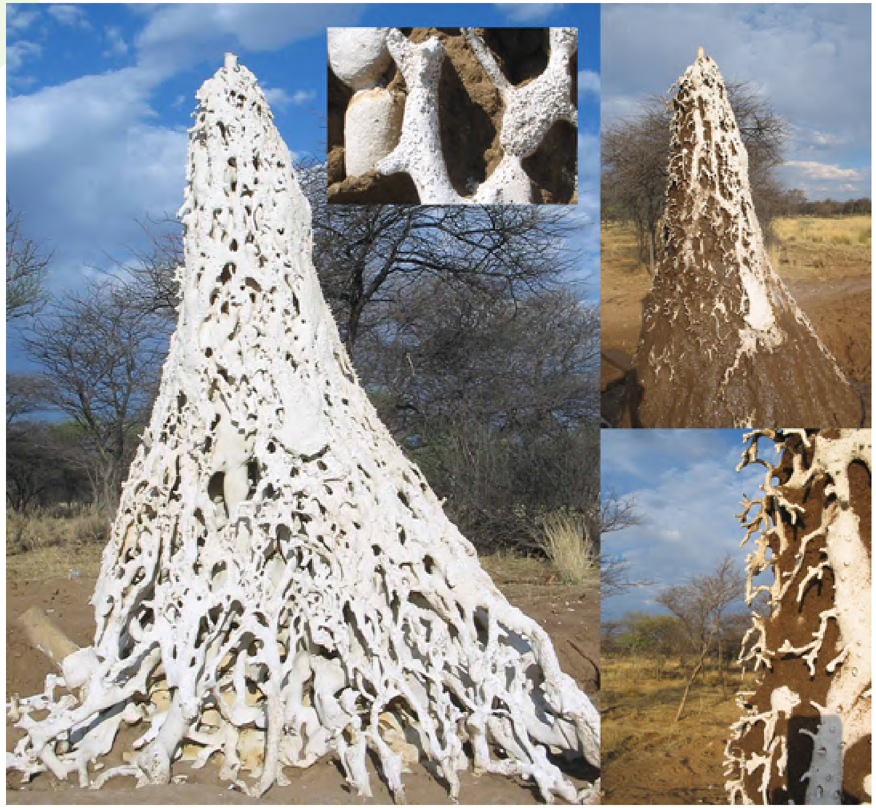


Figure 3 - The internal structure of a *Macrotermes michaelseni* mound using plaster cast showing egress tunnels and surface conduits. The mound surface has been partially washed away. Photos by Rupert Soar.

Emulate & Evaluate - An iterative process

We created a perforated wall panel with efficient 3D branching inspired by Murray's Law as found in termite mounds (see Appendix for details) to allow for improved ventilation between the indoor and outdoor environment. The rationale is that such branching may be effective especially at dynamic and low wind speeds.

Constraints and variables that determine the branching size, shape and orientation were set for the development of design iterations through a parametric approach as each of them produce difference effects on induced air flow. Computational Fluid Dynamics simulations were run in ANSYS Fluent software, one for each iteration to study how the various parameters such as aspect ratio, tubing diameter and branching complexity would affect the induced air flow through the panels.

Using standard brick sizing and by stacking 5 bricks (each brick has standard dimensions of H = 65mm, L = 102.5 mm, W = 215 mm), the designed panels are imagined to be easily integrated with traditional construction methods allowing for the upgrading of existing structures. The detachable hemispherical cups attached to both ends of the central tube allow for an easy to manufacture perforated brick block with Murray's law branching present only in the cup (Figure 4).

Evaluate

Simulations at Singapore's climatic conditions are performed at three different wind speeds (0.5m/s, 2.5 m/s and 5 m/s) to study how different wind speeds are affected by the panel designs. 2.5 m/s is considered as the average wind speed in Singapore. Portland cement was used as the panel material.

When compared with the control panel (similar area of openings but no Murray's Law branching), we found that the designed wall panel has higher induced air flow in the low speed interval bands. The designed panel also demonstrated more balanced spatial mixing of wind within the space.

The designed panel reduces strong wind speeds entering at 2.5 m/s and conditions them to lower speeds such as at 0.5 - 0.75 m/s. A similar conditioning of input wind speed was observed at inputs of 5 m/s.

Overall, the designed panel has stronger air flow compared to the control. It also better "conditions" the wind speeds of the air entering into the interior spaces and maintains greater interior air flow within the favourable range regardless of the external wind speed.

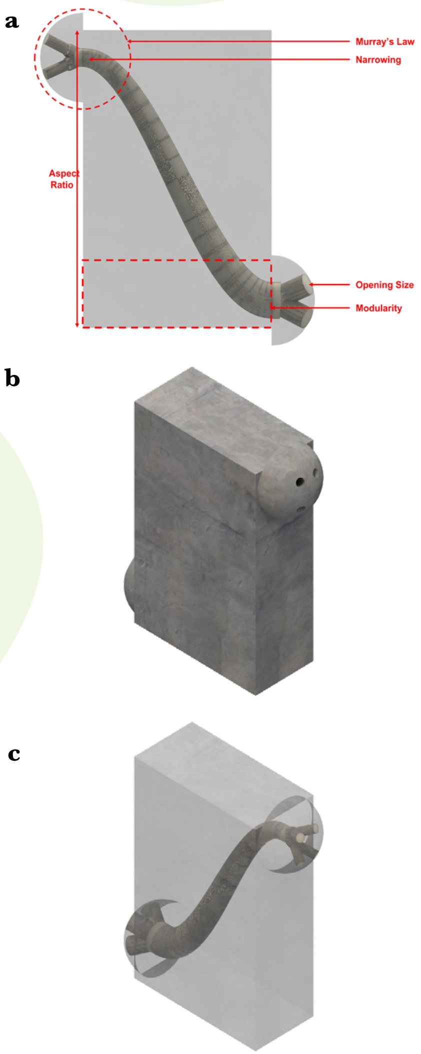


Figure 4 - [a] The wall panel design with branching that narrows towards the centre optimized using CFD simulations. [b & c] A perspective view of the wall panels. A hemispherical cup with Murray's Law branching inside is attached to both ends of the central tube. It has 4 inlets and outlets each with diameter ranging from 12 - 24 mm . Visual by Munshi Mukhtar Toh.

At 0.5 m/s incoming wind speed, the designed panel performs 28% better in terms of average air flow than the control panel. Air flow greater than 0.3 m/s qualifies for Innovation points under the Singapore's Building & Construction Authority (BCA)'s Green Mark. Additional points can be achived by designing for induced air flow > 0.6 m/s.

Application

Applications of such wall panels include breezeways that can take advantage of dynamic wind flow. Complement windows to add porosity to walled areas, increasing their wind potential while maintain privacy and enclosure. This may include data center applications where windows may be undesirable due to security considerations.

Challenges

We are studying how to mitigate any undesirable effects due to porous walls such as noise, smell and insects that may be perceived as undesirable by some people. Solutions include attaching a fine mesh netting inside the panel.

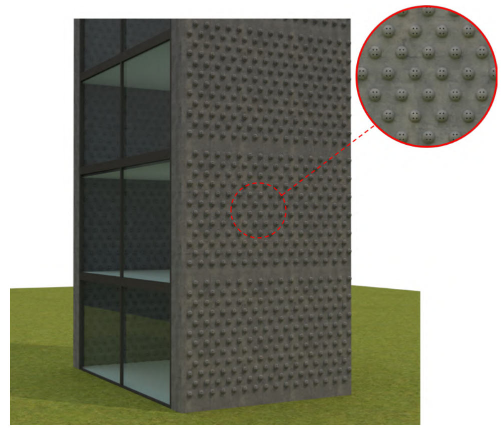


Figure 12 - A potential scale up of the breathable/ perforated wall panel on a building facade. Visual by Munshi Mukhtar Toh.

Will this design cause termite infestations on buildings?

Not from the fungus harvesting termite mounds that inspired our design. This type of termites cannot directly digest wood, and for this reason they establish symbiotic relationships with the fungus in their nests at the first place. They are also unlikely to be found in homes on wooden furniture or on trees.

As a future step, a more dynamic and ephemeral panel is imagined that can open and close in response to humidity levels (see examples of materials in Horizon Scan) and provide better ventilation much like the termite mound themselves.

Image credit: Shutterstock

Namib Desert Beetle

Summary

This design exploration is based on the bioSEA team's investigation of the geometry of a darkling beetle native to the Namibian Desert as a guide towards innovative solutions for humidity control and water capture in tropical climates.

Define & Biologize

In a hot and humid tropical climate, our primary goal (particularly indoors) is to improve humidity control (represented by the functions below). What if such a system could also be applied outdoors to slow down stormwater run-offs from vertical building surfaces? What about water capture applications in colder tropical climates such as cloud forests where fog is abundant but are under climate stress? We start this investigation with such questions and an open mind.

Functions addressed

Humidity Control

Water Capture

We also imagine that our proposed design is likely to be applied in real-life as part of or with a larger humidity control/water capture & purification system that will utilize a combination of strategies such as detention, filtration and retention.

Discover - beetle's fog basking behaviour

In the harsh climate of the Namibian Desert, water is a precious resource. The darkling beetle's elytra (the hard casings that cover its wings) is covered with tiny bumps. The elytra's black color helps it radiate heat to the night sky, making the surface cold and able to condense water. The beetle assumes a 'fog basking' position on top of sand mounds in which they tilt the elytra to an angle that disrupts the morning breeze near the surface just enough to increase the rate of condensation (see Figure 1).

Tiny bumps on the beetles' backs (on the elytra) actually increase the speed of droplet formation. There is debate in the scientific literature about the material properties of the bumps - whether they are hydrophilic (water-attracting) and the valleys (non-bump areas) are hydrophobic (water repelling) or the entire surface of the elytra is hydrophobic. In this project, we focused primarily on geometry. The tiny bumps on the elytra surface give the surface curvature at the scale of tiny droplets, making droplets more likely to form more quickly.

But why mimic a Desert Beetle for the tropics?

Are you still wondering what's a desert beetle doing in a toolkit on tropical climates?

It is because the beetle lives in the dry desert of Namibia which is coastal and one of the foggiest deserts in the world. This makes the beetle's fog basking strategy in cold and foggy desert nights particularly relevant to mountainous tropical climates. There may also be hidden lessons to improve wider water capture strategies including air conditioned tropical indoor climates too.

Precedent - The Warka Tower (covered in chapter 4, Horizon scan) utilizes the fog catching behaviour of the beetles but doesn't fully mimics its surface geometry. This example further motivated us to develop a wall-panel scale solution that can be used across multiple typologies and scaled to buildings. Our designs could potentially also improve water capture efficiency in projects similar to the Warka Tower.

Abstract & Emulate - The Design Approach

For effective water collection, droplet formation is important since, once in droplet form, water will roll, leaving the surface area bare and ready to condense more water. This means more water can be condensed in less time and more water can be captured overall. The diameter of the bumps, and the spacing between them, vary—usually between 0.5 -1.5 mm.

Mimicking the beetle's "fog basking" behaviour, we selected an angle for our surfaces from research by Chakrabarti et al. (2019)[34] which reports that an angle between 35° and 45° maximizes condensation on the beetles back.

We built digital models of bumpy tiles, with different bump sizes, shapes, and spacings, to see if geometry is actually playing as much of a role as we hypothesized; and to see if we could determine which combination of size, shape, and spacing captures the most water. ANSYS Fluent was used for CFD simulations.

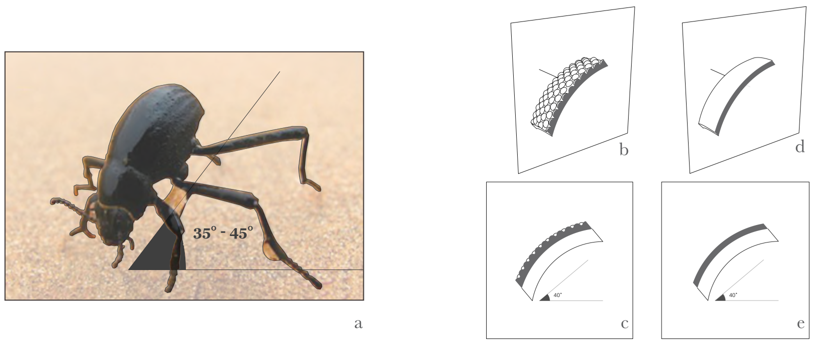


Figure 1 - The Namib beetle engages in "fog basking" behaviour [a]. Our design exploration measures and compares the amount of water condensed on surfaces covered with bumps ([b] and [c]) to a flat surface ([d] and [e]), all of which are tilted to 40°, mimicking this behaviour. Image used in [a] credit to: Domen, J. K., Stringfellow, W. T., Camarillo, M. K., & Gulati, S. (2014). *Clean Technologies and Environmental Policy.*

Research by Park et al. (2016) [35] published in the journal *Nature* combined features from other organisms that capture water from the air, including the directionality of cactus spines, to arrive at a slightly different bump shape. We looked at shapes similar to theirs to see if this directionality, and the capillary action associated with the canyon-like character to the bumps, would increase the rate of condensation. Simulations involved sending a slight breeze of humid air across the surfaces (to match the conditions the beetle is in as it assumes a "fog basking" position). Water condenses on the surface and rolls off into a cistern. We rank the tiles by both the total volume of water condensed and by the total volume divided by their surface areas (to understand the influence purely from geometry—without a bias toward surfaces with larger surface areas).

Evaluation

Our results suggest that bumps can increase the rate of condensation, even when we correct for the increased surface area they represent. But this is not always the case. The specific size and spacing matters a great deal. Our results also suggest that asymmetric bumps perform better (relative to rate of condensation; Figure 2) when compared to spherical bumps.

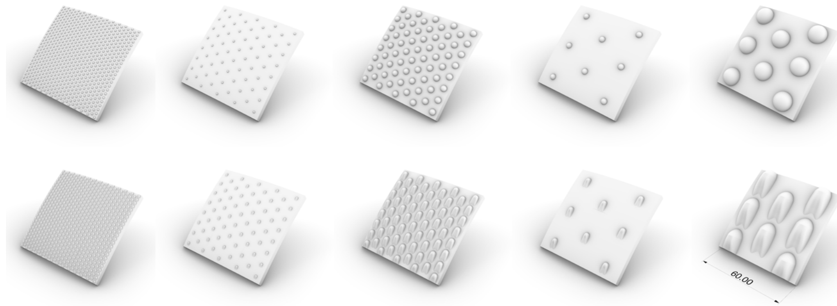


Figure 2 - We explored 24 different surfaces in this study - some of which are shown above. The surfaces span an order of magnitude, from just smaller than the bumps on the Namib beetle's back, to about 8 times larger. The surfaces with larger bumps are shown here arranged on tiles that are 60 mm square. Half of the tiles have spherical bumps (left page) and half have asymmetric bumps (right page).

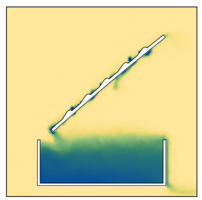


Figure 3 - Volume fraction of liquid water from surface. Areas with deeper blues have higher concentrations of water.

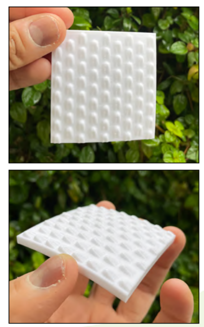


Figure 4 - 3D printed beetle inspired tiles

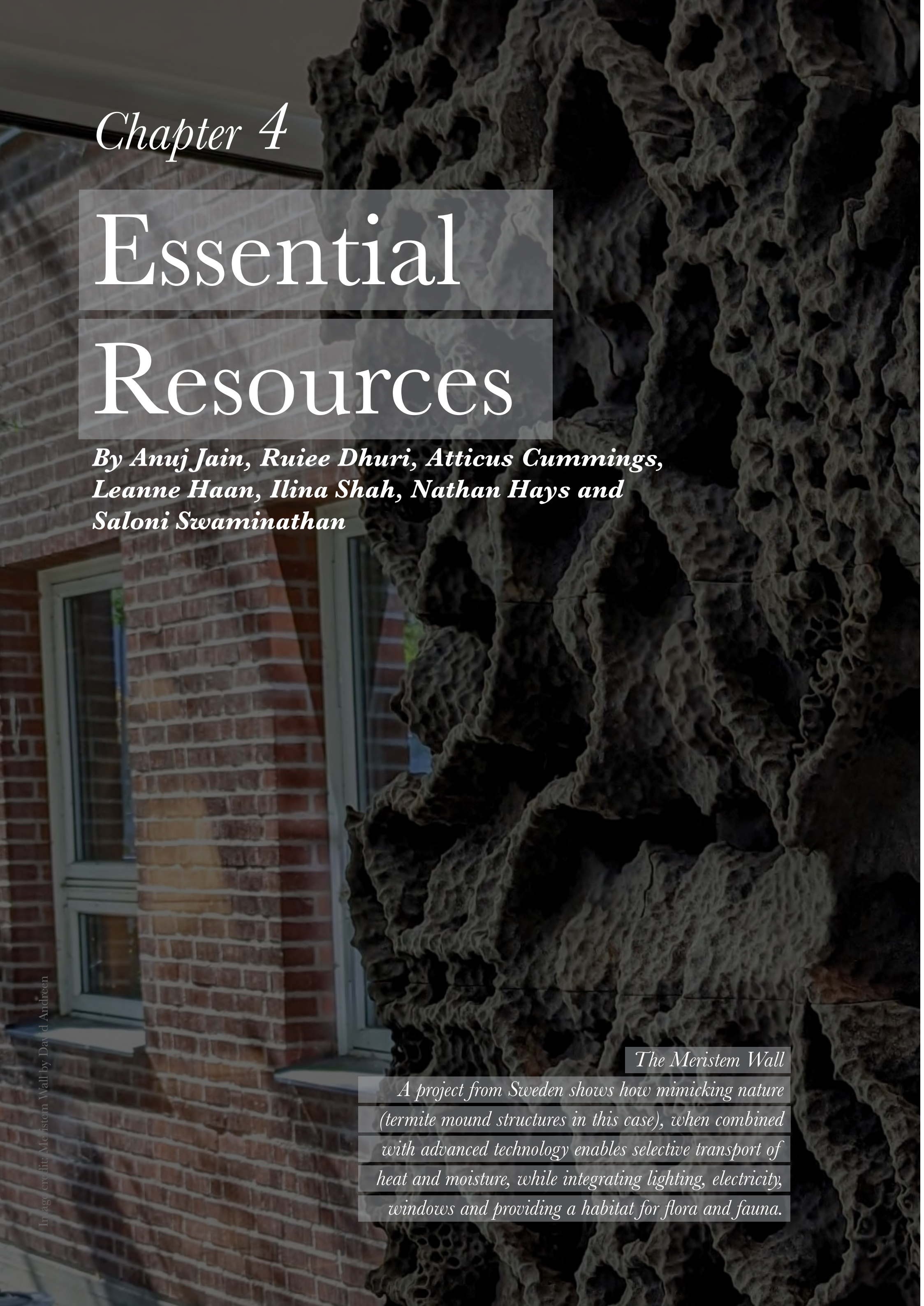
Prototyping

The best performing tiles have been 3D printed (Figure 4) and they are undergoing testing. This is a work in progress. There's so much more we'd like to explore and understand related to evolved geometries that specialize in water capture.

Chapter 4

Essential Resources

By Anuj Jain, Ruiee Dhuri, Atticus Cummings, Leanne Haan, Ilina Shah, Nathan Hays and Saloni Swaminathan



The Meristem Wall

A project from Sweden shows how mimicking nature (termite mound structures in this case), when combined with advanced technology enables selective transport of heat and moisture, while integrating lighting, electricity, windows and providing a habitat for flora and fauna.

Image credit: Meristem Wall by David Andreen

Contents

Horizon Scan

150+
journal papers on biomimicry, architecture, facades reviewed

100+
architectural websites, blogs, magazines consulted

25+
international experts consulted

The Horizon Scan section comprises of a curated collection of 30 biomimetic projects from around the world that utilize natural organisms to solve the primary function of thermoregulation, e.g., heat dissipation, or tackle secondary functions such as water harvesting and carbon capture. The projects are relevant to the hot and humid tropical climate. For each example featured in the horizon scan the corresponding functions are provided. Each project description summarizes the inspiration organism, creator/inventor, year, status of construction/development and scale of application. The description also explains the organism strategy briefly and how it is applied to the project.

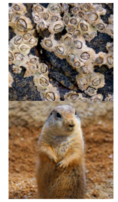
Case Studies

Key Strategies:
Optimize layout of ventilation vents using Voronoi diagram and burrow-like openings.

Project images retrieved from Paar, M.J. & Petutschnigg, A. (2016). *Journal of facade design and engineering.*

Click or scan to find out more

BARNACLE FACADE

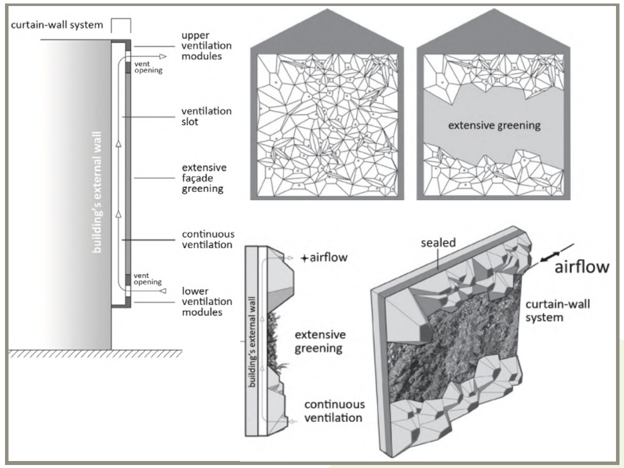


Inspiration: **Barnacles, Prairie dogs**
Creator: **Paar, M.J. & Petutschnigg, A.**[36]
Year: **2016**
Status: **Conceptual**
Application Scale: **Wall panel**

Barnacle colonies cement themselves in a closely packed and flow-optimized pattern on hard surfaces, such as sea rocks and on the sea floor. This helps them direct food towards their mouths and optimize collective feeding efficiency. Their growth pattern follows the Voronoi diagram pattern that optimizes spatial layout by placing each barnacle closer to its neighbour than to any other.

Additionally, the design draws inspiration from prairie dogs burrows. These burrows have a system of passages with inlets & outlets at different heights that generates low- and high-pressure areas. This establishes continuous air circulation and keeps burrows cool during summer.

The façade design has ventilation vents shaped like barnacle openings placed in a Voronoi diagram pattern. This enhances natural wind flow through the ventilation vents, reducing the wall surface temperature more efficiently. The design is padded on the building's external wall like a curtain. The upper and lower ventilation modules mimic prairie dog burrow openings.



Improve Ventilation

Heat Dissipation

Key Strategies:
Porous building with vents and chimneys that utilize stack effect and circulates air using fans.

EAST GATE CENTRE

Location: **Harare, Zimbabwe**
Inspiration: **Termite mounds**
Creator: **Pearce, M. & ARUP**[37]
Year: **1996**
Status: **Built**
Application Scale: **Building**

The Eastgate centre mimics termite mound functionality by deploying chimneys and increasing building porosity with multiple holes that form air passages. These enable a passive airflow driven by outdoor wind flows and tapping onto stack effects.

The tower's "skin" takes heat from outside air during the day and absorbs it into the structure's body. The cooler air in the middle of the building gets circulated using mechanical fans and out of the chimney. At night, the stored heat that was absorbed during the day, is emptied out by large fans. This makes the building ready to receive a new load of heat the next day. Unlike termite mounds however, fans are required for operations, particularly to bring in cool air during the night.

Click or scan to find out more

Improve Ventilation

Heat Dissipation

Key Strategies:
Porous building with vents and chimneys that utilize stack effect, uses recycled water for evaporative cooling benefits.

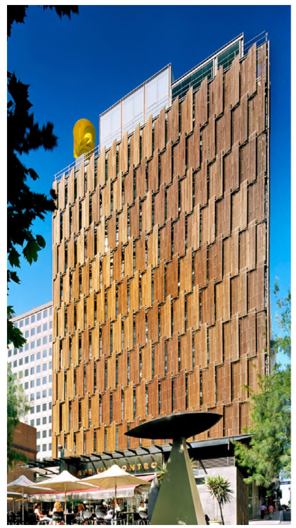
COUNCIL HOUSE 2

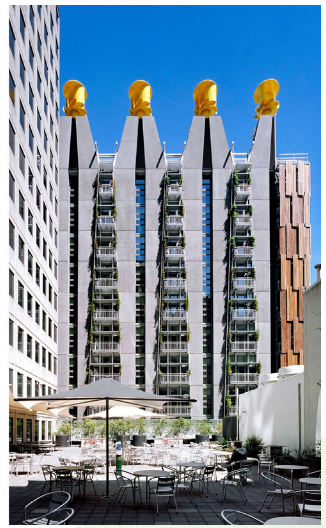
Location: **Melbourne, Australia**
Inspiration: **Termite Mounds**
Creator: **Pearce, M. & DesignInc.**[38]
Year: **2006**
Status: **Built**
Application Scale: **Building**

The Council House 2 uses the same set of termite mound principles as the East Gate Center albeit slightly differently.

Six large wind turbines on the roof allow for natural ventilation of the buildings and release hot air produced by the building's occupants during the day. At night time, vertical timber slats covering an entire part of the facade open up, generating an airflow into the building and creating 'night purge'. This creates a reservoir of fresh cool air twice per day. In addition, the slats open and close in response to the angle of the sun, providing shade when necessary.

Other design strategies include the vertical tubes on the longitudinal facade. These tubes establish evaporative cooling, as excess (recycled) water from the air conditioning drops down and evaporates along its way.





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Improve Ventilation

Surface for Flora & Fauna

Acoustics

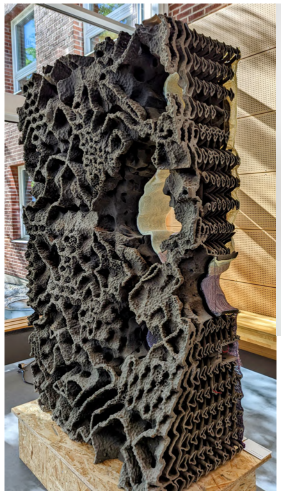
Key Strategies:
Binder-jet sand 3D-printed façade with knitted textile interior and deploying dynamic computer-controlled air channels inspired by termite mounds.

MERISTEM WALL

Location: **Lund, Sweden**
Inspiration: **Termite Mounds**
Creator: **Goidea A., Popescu, M. & Andreen, D.**[39]
Year: **2021**
Status: **Prototyped**
Application Scale: **Wall panel**

Inspired by the vent structure and reticulated branching network in termite mounds, Meristem Wall is a prototype for a 3D printed building envelope. Made out of sand and fabricated through binder-jet sand 3d printing, it features a dynamically controllable network of integrated air channels that allow a fluid relationship between inside and outside. The channels can be controlled through an embedded system of sensors and actuators to enable selective transport of heat and moisture. The wall integrates functional lighting and electricity, windows, and a custom computer controlled knitted textile interior. The extensive channels in the wall created intertwined surfaces, envisioned to provide a habitat for flora and fauna.

The design views the wall as a membrane rather than a barrier, mediating inside/outside environments for multi-species cohabitation.



Project Image retrieved from Goidea, Popescu & David (2021). *Association for Computer Aided Design in Architecture Annual Conference.*

Click or scan to find out more

Improve Ventilation

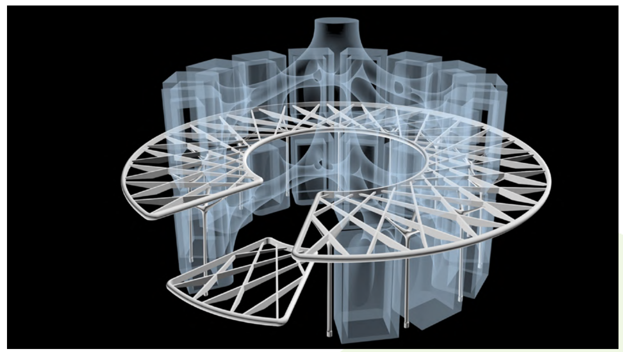
Key Strategies:
Murray's Law inspired air flow system.

MOUNTAIN DATA CENTRE

Location: **Norway**
Inspiration: **Murray's law**
Creator: **Pawlyn, M., Exploration Architecture**[40]
Year: **2014**
Status: **Conceptual**
Application Scale: **Building**

Murray's law is a mathematical principle that shows how branching systems in biology are optimized for fluid transport. The characterising angles of branching observed through Murray's law are seen everywhere in nature, including in the respiratory and vascular structures of animals.

This conceptual data centre uses two principles found in nature, first is the natural occurrence of cooler areas where animals find refuge, such as mountains. The second is Murray's law guiding the branching of flow in natural systems. In this design, data blocks are clustered in circles allowing air to be circulated towards the middle. This design requires less bands and ductwork than conventional data centers.



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Improve Ventilation

Heat Dissipation

Limited Heat Gain

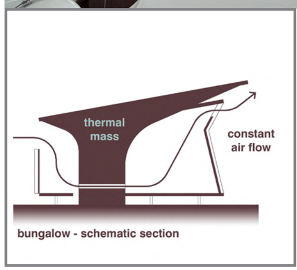
Key Strategies:
Ventilation enhanced by modifying bungalow shape and vents thereby creating pressure gradients. Self-shading provided by folds on slats.

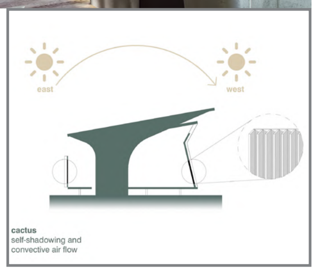
VOTU HOTEL

Location: **Bahia, Brazil**
Inspiration: **Prairie dogs, Saguaro Cactus**
Creator: **GCP Arquitectura & Urbanismo**[41]
Year: **2016**
Status: **Simulated**
Application Scale: **Building**

Prairie dogs design their burrows in such a way that a continuous air circulation is established by creating a system of passages with inlets & outlets at different heights. This generates low- and high pressure areas, keeping a cooling air flow through their burrows during summer. The Saguaro cactus grows with long spines and accordion-like folds. These folds offer partial shade and cool the air on the shaded side. Such a form creates circulation around the cactus that minimizes heat absorption.

The bungalows at Votu have a design similar strategy to that of the prairie dog burrows. Using computer modeling, each bungalow is strategically placed at its location to allow for optimal natural ventilation. In addition, a semi-permeable guardrail is placed in front of the prevailing winds. These slow down the airflow and draws air into ventilation ducts below the modified roof. In addition, the bungalows have many self-shading slats inspired by the cactus that provide further cooling benefits.





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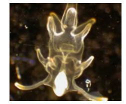
Improve Ventilation

Key Strategies:
Optimize texture on building surfaces to create undulating patterns of air velocity that can create a higher cooling effect than constant speed.

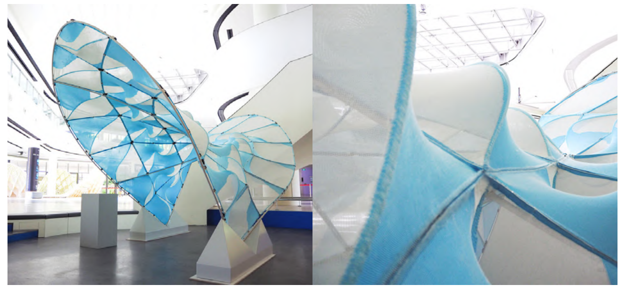
PATTERNED FLOW



Location: **Singapore**
Inspiration: **Starfish Larvae**
Year: **2021**
Creator: **Singapore University of Technology & Design (Tan, Y. Y., Yogiaman C., Tracy K., Alvardo P. V. Y)**[42]
Status: **Prototype**
Application Scale: **Building**

Patterned Flow is a surface strategy that increases the performance and capabilities of low energy design in hot and humid climates by manipulating airflow. Referencing starfish larvae's ability to swim by controlling fluid vortices through altering the direction of cilia (hair) movements along the perimeter of its body, specific textures are applied onto the prototype pavilion canopy to form and release vortices in intervals that patterns airflow. Its overall parabolic hyperboloid geometry funnels wind through its interior while its scallop-shaped panels create textured undulations that deflect and hasten wind flows.

Particle Image Velocimetry is used to study the most effective texture that produces the undulating patterns of air velocity that can create a significantly more cooling effect than the same mean velocity at a constant speed. This implies that by texturing building surfaces, warm urban environments could be made to feel cooler without using energy to increase the overall airflow.



Click or scan to find out more

Improve Ventilation

Structural Efficiency

Material Optimization

Surface for Flora & Fauna

Key Strategies:
Use gyroid and lonsdaleite microstructures and Voronoi patterns to create up to 3 times stronger yet lightweight concrete blocks.

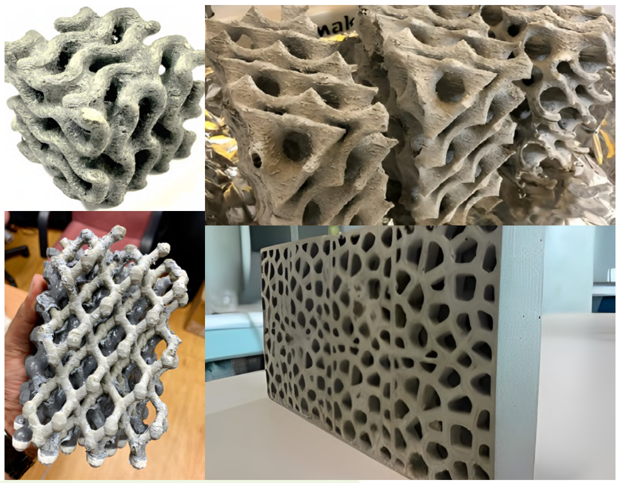
Click or scan to find out more

MICROSTRUCTURE BUILDING BLOCKS

Location: **Singapore**
Inspiration: **Microstructures, butterfly wings**
Creator: **Goel, A. and DBE Team, National University of Singapore.**
Year: **2020 - 2022**
Status: **Prototyped**
Application Scale: **Wall Panel**

The team studied molecular structures in nature, such as Gyroids and Lonsdaleites and Voronoi patterns. Gyroid is a stable, strong and triply periodic minimal surface that occurs naturally in polymers, also on butterfly wing scales. Lonsdaleite is a crystal structure believed to be stronger than diamond and is currently known from meteorites. They are popular in 3D printing as lightweight and easily printable internal structures.

By casting concrete in 3D-printed bio-polymer molds, the components with different microstructure designs were fabricated. The optimized shape of these microstructures effectively reduces the overall building component weight and provides sufficient strength and stiffness for non-structural purposes. Results suggest such structures to have thrice the specific strength (strength vs. density) of typical block concrete i.e. they can 3 times the strength for the same density of concrete material used. They also pack multiple benefits by creating porous walls that can aid ventilation and dissipate heat.



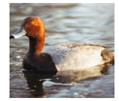
Heat Dissipation

Humidity Control

Key Strategies:
Evaporative-cooling based system that uses a specially coated ceramic to cool air without adding humidity.

Click or scan to find out more

ColdSNAP

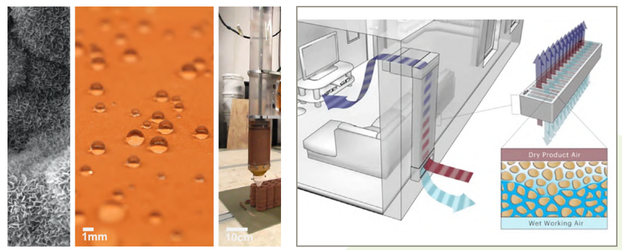


Location: **Massachusetts, USA**
Inspiration: **Duck Feathers**
Creator: **Harvard University's Wyss Institute[43]**
Year: **2022**
Status: **Prototyped**
Application Scale: **Wall Panel**

Traditional air-conditioners use vapor compression but are inefficient. Natural evaporative cooling is energy efficient but works typically in dry climates. It becomes less effective in humid climates as this technique adds moisture to the cooled air.

This new evaporative cooling technology uses a 3D-printed ceramic coated with a nanoscale hydrophobic material. The novel coating material mimics the water repellent qualities of duck feathers made possible due on their surface properties.

The coating is selectively applied to the ceramic on the inner walls of the cooler, such that it isolates water vapour from the air that is released into a building. The coating helps prevent the air from becoming humid while promoting heat transfer to maximize cooling. The cooler uses less electricity and no harmful chemicals found in standard air conditioners, it also requires less water than other evaporation based air conditioning units.



Heat Dissipation

Limited Heat Gain

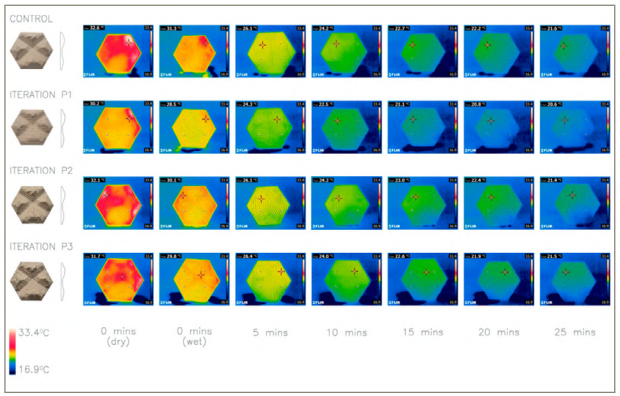
Key Strategies:
Textured tiles optimize evaporative cooling and self shading properties with increased surface-to-volume ratio.

ELEPHANT SKIN TILES

Location: **Bristol, UK**
Inspiration: **Elephant Skin**
Creator: **Peeks, M. & Badarnah, L.[44]**
Year: **2021**
Status: **Prototype**
Application Scale: **Wall Panel**

Elephant skin helps them stay cool even in very high temperatures. The cracked texture of the skin provides an excellent surface-to-volume ratio for evaporative cooling. It also provides a measure of self-shading as layers of dead skin shade the living skin beneath.

Researchers mimicked this process, creating ridged concrete tiles. The tiles provide superior cooling capability when misted with water. Hexagonal tiles proved to be more efficient at cooling compared to other shapes. White concrete gave the best cooling performance compared to other colors due to its high albedo.



Project images retrieved from Peeks & Badarnah (2021). *Biomimetics.* Bottom image - thernal imaging comparison of four patterns. Average heat loss after 30 mins: Temperature at Control > P1 > P2 > P3.

Click or scan to find out more

Heat Dissipation

Humidity Control

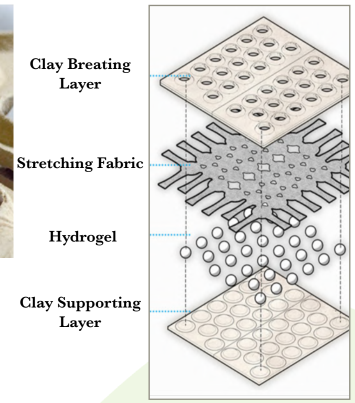
Key Strategies:
A composite material façade system that uses hydrogels to absorb water (via evaporation) while controlling humidity through clay ceramic and fabric-based water channels.

HYDROCERAMIC FACADE

Location: **Catalonia, Spain**
Inspiration: **Perspiration in humans**
Creator: **Institute for Advanced Architecture of Catalonia[45]**
Year: **2013**
Status: **Prototype**
Application Scale: **Material**

Like biological tissues, hydrogels can maintain their structure while being predominantly composed of water. When enriched with other molecules, hydrogels can respond to external stimuli in a similar manner as biological tissues. Evaporation of water from hydrogels and tissues can have a cooling effect, much like the pores of our skin, and the rate of evaporation is based on the surrounding temperature.

This facade design uses a composite material that combines the evaporation property of hydrogels, humidity control property of clay ceramic and fabric as the water channel. This hydroceramic system works due to the cooling effect provided by evaporating water. Hydrogel pellets absorb large quantities of water, this exposes a large surface area for evaporation. This both decreases the temperature and increases the humidity of the surrounding air. In turn, the material is responsive: the cooling effect is greatest when the surrounding environment is warm, but when the surrounding is cool little evaporation occurs. This design can create energy savings of 28% and is made from low-cost materials.



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Limited Heat Gain

Light Optimization

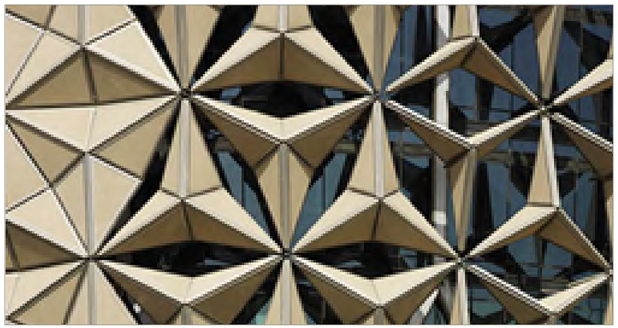
Key Strategies:
Fold and unfold shading screen in response to sun movement

AL BAHR TOWERS

Location: **Abu Dhabi, UAE**
Inspiration: **Adaptive flowers**
Creator: **AHR Architects**[46]
Year: **2012**
Status: **Built**
Application Scale: **Wall Panel**

In nature, many flowers open and close their petals according to the circadian clock. More specifically, plants precisely time the onset of flowering to ensure reproductive success.

The principle of adaptive flowers was translated to the Al Bahr towers to reduce glare and solar gain entering the building. The shading screens fold and unfold in response to the movement of the sun, reducing solar gain by up to 50%.



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Limited Heat Gain

Energy Capture

Key Strategies:
Use live algae to create a living shelter that provides shade. The algae can be harvested from time to time.

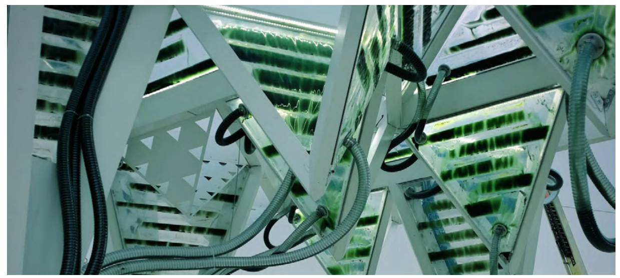
URBAN ALGAE CANOPY

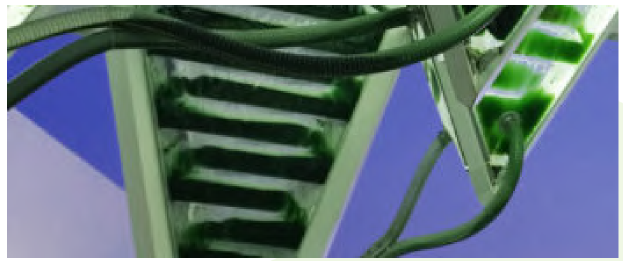
Location: **Milan, Italy**
Inspiration: **Tree canopy**
Creator: **ecoLogicStudio**[47]
Year: **2015**
Status: **Prototype**
Application Scale: **Building**

Trees depend on sunlight to generate energy and grow. The leaves absorb CO2, which is converted into energy sources and oxygen under the influence of sunlight.

In the algae-tower, micro-algae are used to simulate this process. Under specific conditions, the microalgae generate biomass when exposed to sunlight. This biomass can then be converted into a biofuel, providing a renewable energy source. In addition, the production of biomass creates a green cover on the building's facade, providing shade and increasing thermal comfort. In times of little sunlight, the transparency allows the sunrays to naturally heat the interiors.

The design uses live algae to produce shade. The structural design creates a green canopy that functions as a living shelter. The design co-evolves with the seasons and with the environment. In addition, the algae can be harvested and processed into a dietary supplement such as spirulina.





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Limited Heat Gain

Light Optimization

Key Strategies:
Use a combination of mirrors - convex mirrors to direct light, concave mirrors to reflect light to desired parts of the building.

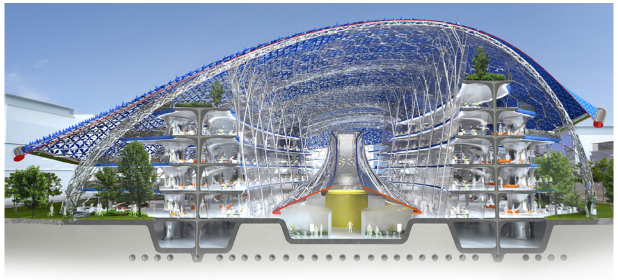
Click or scan to find out more

BIOMIMETIC OFFICE BUILDING

Location: **Switzerland**
Inspiration: **Spookfish**
Creator: **Pawlyn, M. and Exploration Architecture**[48]
Year: **2016**
Status: **Conceptual**
Application Scale: **Building**

Spookfish is a deep-sea creature with a unique optical system to enhance vision in the dimly lit sea. It has two eyes, each of which is split in 2 connected parts, one pointing up and another pointing down. The part pointing up uses regular convex lens to direct the sky light from above to the retina of the fish eye. The unusual downward pointing eye-part uses tiny crystals that acts as a concave mirror (instead of lenses) to reflect faint light coming from the sea below on the retina.

The building mimics the structure of the Spookfish eyes, using convex mirrors on top of the building to bring incoming sunlight and concave mirrors that reflect incoming sunlight to the lower darker floors of the building. This enhances natural light diffusion and reduces the need for artificial light sources.



Limited Heat Gain

Light Optimization

Material Optimization

Structural Efficiency

Key Strategies:
Spherical shaped interlocked domes provide stability made up of hexagonal cells to optimize light, heat and material usage.

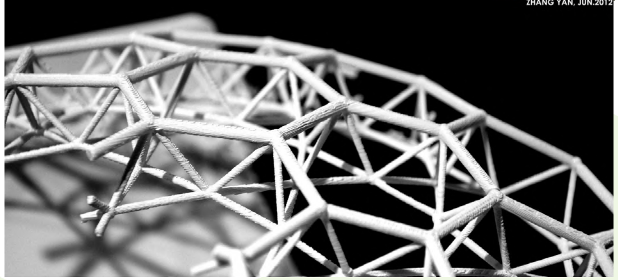
Click or scan to find out more

THE EDEN PROJECT

Location: **Cornwall, UK**
Inspiration: **Honeycombs & soap bubble**
Year: **2001**
Creator: **Grimshaw Architects**[49]
Status: **Built**
Application Scale: **Building**

Hexagons are commonly found in nature as hexagon shapes pack an area with the least amount of material, equal sized units and no wasted space. For such shapes, the surface tension pull in each direction is also most mechanically stable. When used on facades, these shapes provide several benefits, including optimal sunlight exposure, spatial distribution, material optimization and structural strength. Soap bubbles can merge with each other driven by surface tension and grow without collapse.

The Eden project is the world's largest greenhouse, located in Cornwall, UK. At the time of construction, the site was a clay quarry that had unstable ground conditions. The design response was to create a series of connected spherical domes, inspired by soap bubbles, that can interlock across a constantly shifting landscape. The dome elements are made of a light, transparent ETFE polymer, installed on a frame with hexagon shaped cells, enabling optimal amount of sunlight to enter the space and reducing heating costs in winter.



Limited Heat Gain

Light Optimization

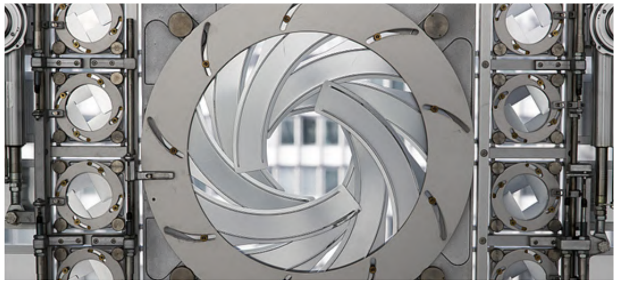
Key Strategies:
Iris inspired features with openings use photoelectric cells to open and close and control light and heat entering the building.

INSTITUT DU MONDE ARABE

Location: **Paris, France**
Inspiration: **Human eye**
Creator: **Architecture Studio**[50]
Year: **1987**
Status: **Built**
Application Scale: **Wall Panel**

The colored part of the eye, the iris, helps regulate the amount of light entering the eye. When there is bright light, the iris contracts the pupil to let in less light. When there is little light available, the iris will dilate the pupil so more light can enter the eye, enabling better vision.

The facade of the Institute du Monde consists of several hundred light-sensitive elements installed on traditional mashrabiya features. The photoelectric cells and mobile parts open and close based on the amount of sunlight. This helps regulate the amount of light and heat entering the building.



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Limited Heat Gain

Light Optimization

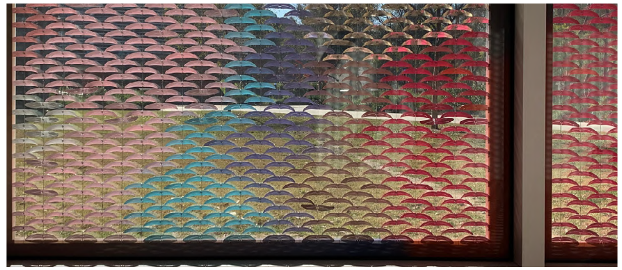
Key Strategies:
Use of thermobimetal to vary its shape with light exposure, thus varying the light and heat in building interiors.

INVERT

Location: **California, USA**
Inspiration: **Phototropic Plants**
Creator: **DO | SU Studio Architecture**[51]
Year: **-**
Status: **Prototyped**
Application Scale: **Material**

Phototropism is the ability of a plant to reorient its shoot growth. Reorientation can either be directed towards or away from the light source, in this case, sunlight.

The InVert shutter system makes use of thermo-bimetal, essentially two different metals laminated together with different heating and expansion coefficients. When sunlight reaches the metal, the bimetal will curl and constrict light from passing. The angle of the opening in which each thermo-bimetal piece sits controls the degree to which the piece can invert. This allows bespoke tuning for varying sun exposures. When applied to a large surface, this system can help reduce heat gain and thus the need for air conditioning without the need for manual controls.



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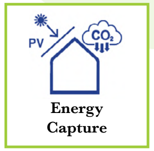
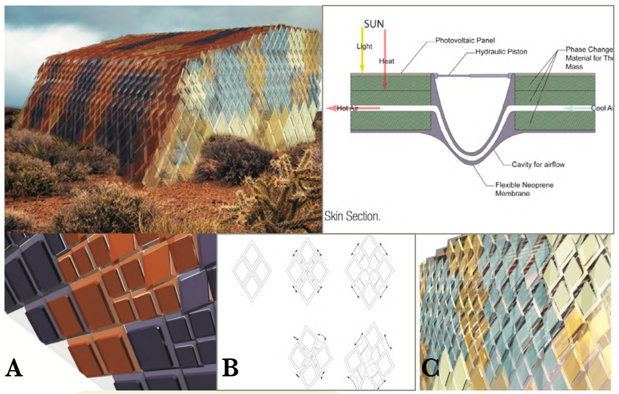


Key Strategies:
Wall panel having coloured Photovoltaic cells with layers of phase change material and an air passage between them that allows rotation and expansion of panels and modulation of air temperature.

LIZARD ENVELOPE

Location: **California, USA**
Inspiration: **Side-blotched Lizard**
Creator: **Mazzoleni, I., Pedro, J.M.S., Nahmgoong, A., Yuan Y. - Southern California Institute of Architecture**[52]
Year: **2010**
Status: **Conceptual**
Application Scale: **Wall panel**

The lizard skin in deserts is typically darker on its back to absorb sunlight and lighter on the abdomen to reflect heat from the ground. The lizard adjusts its body and positions itself parallel to the sunlight with toes curled to avoid heat gain. It hides in the cool when overheated. The scales on the surface of the lizard's skin also vary in shape according to the animal's physiology and needed degree of movement. The physiological adaptions of the lizard skin inform the wall design of the building whereas the lizard's behaviour informs sun tracking technique. The wall envelope is comprised of coloured photovoltaic (PV) panel surfaces that have hydraulic pistons and a flexible neoprene membrane between each panel. The membrane permits the expansion and rotation of wall panels to allow for air flow and heat management. The individual panels contain two layers of phase change material and a flexible air passage between them. This allows air to flow between the thermal mass and absorb heat or be cooled down depending on the time of the day. The PV panels are colored according to the sun path. The roof and south side have darker PV cells to absorb an abundant amount of heat and light. The east and west sides have lighter colors to reflect heat and light preventing the building from overheating.



Project images retrieved from Mazzoleni, I. (2010). *Disegnarecon*. A - Roof and south facade dark colour for heat gain, B - Skin panel movement diagram, C - East and west facades light colour for sunlight reflection.

An expanded version of this project can be retrieved from

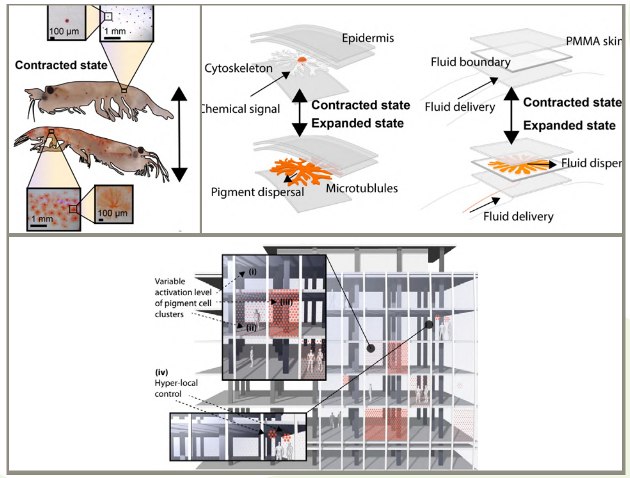
Click or scan to find out more

Key Strategies:
Multicell arrays on building façade inject or withdraw photo-sensitive pigmented fluids to tune light levels

PIGMENTED FLUIDS

Inspiration: **Antarctic Krill**
Creator: **Kay, R. et al.**[53]
Year: **2022**
Status: **Simulated**
Application Scale: **Material & Building**

Decapods such as Antarctic Krill and Crabs can actively change colour depending on sunlight intensity by moving pigments within their skin, for ultraviolet protection, to thermoregulate and dynamically shade against the sun. Under intense light exposure, the pigments spread across each cell, which changes the optical appearance of the skin. In building applications, pigmented fluids are reversibly injected and withdrawn from confined layers of the building facade to dynamically tune light levels at the façade. This allows for shading to be adjusted locally, and for interior solar exposure. The pigmented fluid is comprised of PMMA (Polymethyl Methacrylate) sheets – a bio-compatible thermoplastic resin that is used as a strong, light weight alternative to glass, common fluids (castor oil, water) and carbon suspension (ethanol, carbon black) ingredients. The fluid is delivered through multicell arrays across large areas of the building interface that are fitted with photosensors and thermocouples and controlled by a basic pump and controller to manage dynamic fluid flow. Simulations suggest a reduction in cooling or lighting energy loads by over 30% compared to conventional techniques.



Project images retrieved from Kay et al. (2022). *Nature Communications.*

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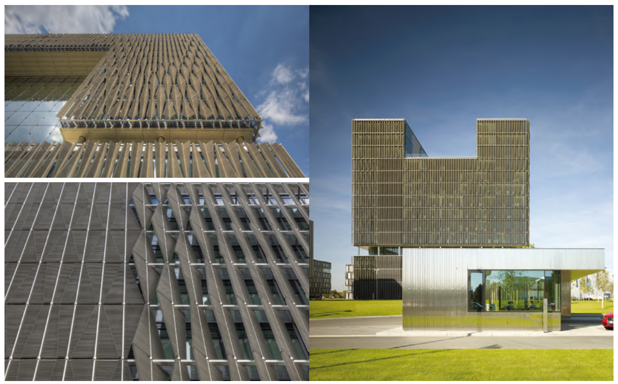
Key Strategies:
Mechanically controlled louvers open or close depending on solar exposure. Louver shape and orientation vary learning from feather arrangements on bird bodies.

Q1 BUILDING THYSSENKRUPP QUART

Location: **Essen, Germany**
Inspiration: **Bird feathers**
Year: **2010**
Creator: **JSWD Architekten Köln and Chaix & Morel et Associés, Paris**[54,55,56]
Status: **Built**
Application Scale: **Wall Panel**

Bird feathers have multiple functions depending on their position on the bird's body. Outer feathers are straight and flat, great for flying. Down feathers are short, soft and flexible, great for retaining body heat. Also, colors on birds feathers vary by position. White feathers are present on the root of wing where it attaches to body and black feathers are at the wing tips. The latter heat up and provide better lift while flying.

The shading system of the Q1 building consists of approximately 400,000 metal "feathers" (i.e. louvers) that are anchored into 3,150 stainless steel moveable stalks, which can be mechanically controlled to transform the façade to allow more or less heat and light into the building. The motorized elements can be closed to create a more solid enclosure, follow the position of the sun, or be entirely open to allow maximum solar exposure. The individual louvres vary in shape, creating optimal shading performance just like the feathers. The louver system keeps the glazed areas cool and minimizes the use of an air conditioning system. It also directs natural light into interior spaces, reducing the need for electric lighting.



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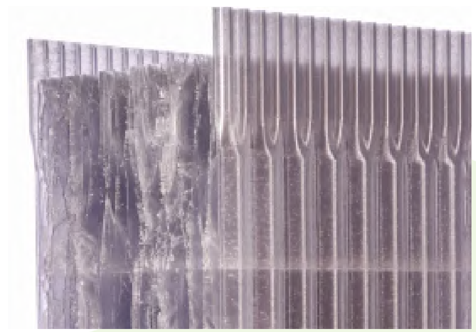
Key Strategies:
An intra-wall façade system with an inner layer that has air cavities and two outer layers that have moveable liquid to allow for adaptive heat storage.

SPONG3D

Inspiration: **Blood Vessels**
Creator: **University of Delft, University of Eindhoven**[57]
Year: **2017**
Status: **Prototyped**
Application Scale: **Wall Panel**

Our blood vessels display a dense network of interconnected loops. This system allows for optimal flow and rapid responses to external environment.

Spong3D is a 3D printed facade system made out of PETG (a thermoplastic polyester) that can be used installed inside a wall, to control the heat exchange between building interior and exteriors and thereby maintain the building's internal climate. It has a porous inner layer, which incorporates air cavities for thermal insulation. It also has two outer layers that contain a moveable liquid (water with additives) and provides adaptive heat storage as a moveable thermal mass. The liquid can be transferred from one side of the façade to the other to absorb and release the heat as required using channels that allow minimal pressure drop and uniform flow.



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Limited Heat Gain

Humidity Control

Key Strategies:
Use of high albedo surface to reduce heat gain; hydrogel to passively and reversibly absorb water (like frogs); and Bio-PCM to store/release energy with varying temperature (like beetles).

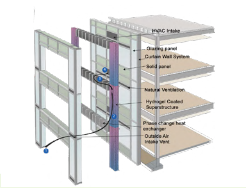
BIOMIMETIC BUILDING ENVELOPE

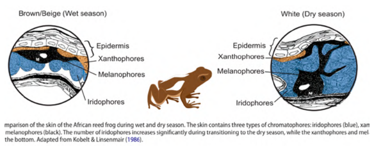
Location: **USA**
Inspiration: **African Reed Frog, Hercules Beetle**
Creator: **Fecheyr-Lippens D., Bhiwapurkar, P.**[58]
Year: **2017**
Status: **Conceptual**
Application Scale: **Building**

The African Reed Frog copes with the hot/dry season by changing its coloration to a reflective white and uses its nitrogenous waste to induce naturally reflective purine crystals to grow on its skin. It also optimizes its position to minimize direct sun exposure. The Hercules Beetle also changes color with rain/moisture – olive green when dry and black under wet conditions. These changes allow it to blend in and manage heat. The beetle has a spongy layer of chitin filaments that have a photonic crystal structure below the transparent epicuticle. These layers create open pores that fill up with air (dry environment) or water (wet environment) giving the skin a resulting colour.

A facade system was developed to mimic these systems for improved building energy efficiency. The frog inspired the application of a high albedo surface alongside standard glazing to reflect a high proportion of light to decrease heat gain and to use indoor temperature to trigger adaptive thermal comfort. The build-up of internal heat gain was delayed just like in frogs by embedding the Bio-PCM (Phase Change Material) heat exchanger – a material that can store or release large amounts of energy as it melts or solidifies at a certain temperature.

The beetle inspired the use of hydrogel - superabsorbent polymers for passive and reversible absorption of water to manage humidity. Air entering the building passes through layers of hydrogel and Bio-PCM to be cooled and dehumidified. The cooling element can transfer heat to the building water heater system. Finally, a small HVAC unit does the final conditioning and distribution of air within the building. Results show a 66% reduction in energy use intensity of the space condition system.





Project images retrieved from Fecheyr-Lippens, D. & Bhiwapurkar, P. (2017). *Architectural Science Review.*

Click or scan to find out more

Humidity Control

Key Strategies:
Veneer wood combined with fibre or chemicals creates a bilayer material that can change shape based on humidity levels.

WATER REACTING PANELS

Location: **London, UK**
Creator: **Royal College of Art (Chao Chen)** [59]
Year: **2015**
Status: **Prototyped**
Inspiration: **Pine Cone**
Application Scale: **Material**

Pine cones have slender scales that open up in dry conditions to disperse seeds via the wind. When humidity rises, the scales curl up to prevent ineffective seed dispersal.

Veneer wood combined with nylon or polyester fibre or styrene creates a bilayer material that mimics the outer- and inner layers of pine cones. This material detects humidity levels and changes its shape automatically and has practical applications as a façade material.

Click or scan to find out more

Water Capture

Material Optimization

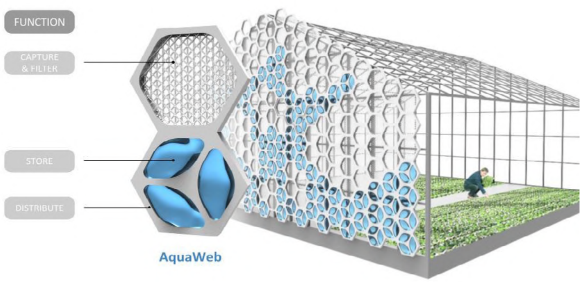
Key Strategies:
Water modules packed in a honeycomb shaped structure with each module having meshing to capture & store water.

AQUAWEB

Location: **USA**
Inspiration: **Epiphytes, Spiders, Honeycombs**
Creator: **NexLoop**[60]
Year: **- 2016-2021**
Status: **Prototyped**
Application Scale: **Wall Panel**

Epiphytes take moisture from the air and make it accessible to neighbouring organisms. Spider webs can collect water from humid air due to alternating threads that differ in thickness. Ice plant leaves are covered in bladder cells, which act like small water reservoirs. Honeycombs are considered the most space-efficient structures and provide optimal structural strength.

Deriving inspiration from multiple organisms, AquaWeb consists of modular, hexagon-shaped structures with fine spider-web like meshing to optimize water collection and condensation. It also deploys ice-plant like bladder cells to optimize water collection. Once assembled, the design captures and stores natural sources of water (rain, fog and dew) that can be used locally.



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Water Capture

Key Strategies:
Using façade surface to purify wastewater via micro-algae. Optimal flow achieved by modular tiles with leaf-venation inspired channels

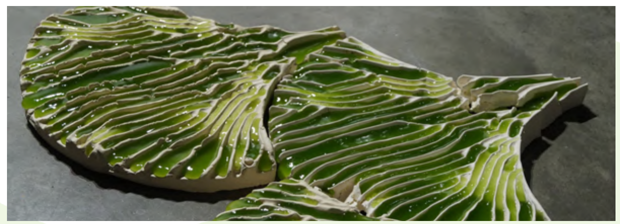
INDUS TILES

Location: **London, UK & Delhi, India**
Inspiration: **Vein system of leaves**
Creator: **UCL team (Malik, S., Parker, B., Cruz, M.) & Miller, R.**[61]
Year: **2019**
Status: **Prototyped**
Application Scale: **Wall Panel**

Similar to our blood vessels and branched trees, vein systems in leaves display a dense network of interconnected loops. This system allows for optimal flow and rapid responses to acute damage.

Indus tiles are envisaged as a lost cost wastewater purification system for home-based textile artisans in India. Traditionally, the artisans discharge heavy metal laden water that is created during the textile dying process into the public drains.

Indus tiles consist of two complementary systems: (1) the hydrogel containing micro-algae that purify wastewater, and (2) the hydrogel sits on a surface where flow channels are inspired by veins on a leaf, allowing for optimal wastewater distribution. As wastewater flows down the wall it is purified by the micro-algae that isolate heavy metals and contaminants. Each modular tile unit is attached to the next through half-lap joints, and so can be individually removed without taking apart the entire system. The saturated algae can be scraped away from the tiles and sent for chemical extraction of heavy metals via a standard industrial process and subsequently re-used. The system saves heavy metal laden water discharge into public drains.



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Water Capture

Material Optimization

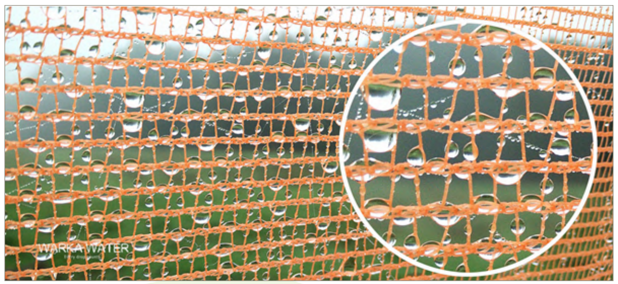
Key Strategies:
Condense water from cold humid air by increasing surface area.

WARKA TOWER

Location: **Cameroon**
Inspiration: **Namib Desert Beetle**
Creator: **Vittori, A.**[62]
Year: **2015**
Status: **Built**
Application Scale: **Building**

Micro-sized grooves or bumps on the beetle's hardened forewings help accumulate and direct water toward the beetle's mouth. To enhance this process, hydrophilic and hydrophobic areas are present on its forewings, ensuring great water-harvesting efficiency.
Warka Tower was designed to harvest water from the atmosphere, providing an alternative water source for rural populations that face challenges accessing drinkable water.
The passive structure functions solely by the presence of natural phenomena such as gravity, condensation & evaporation.

Note that the Warka Tower uses biomimicry in its simplest form – the idea of capturing water from fog. However, it does not yet apply the shape of optimized micro-sized bumps and hydrophilic and hydrophobic surfaces found on the beetle's back.



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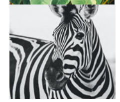
Energy Capture

Structural Efficiency

Key Strategies:
Zebra stripe pattern hypothesized to improve air flow of cooling exhaust; circular system with algae from farms used to generate energy; algae panel placement and space frame design inspired by taro leaf skin.

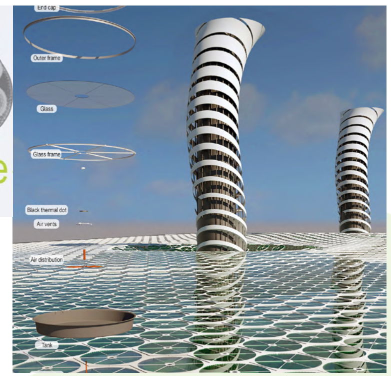
HSINTA ECOLOGICAL POWER PLANT



Location: **Taiwan**
Inspiration: **Taro leaf, Zebra**
Year: **2018**
Creator: **Ambi Design Studio and Regenerative Earth and Anthropocene Design (READ) Lab, Tunghai University**
Status: **Conceptual**
Application Scale: **Building**

Located on the western coast of Taiwan, the power plant design re-knits the surrounding landscape of fish farms by using their algae waste as a resource. The response was to create a giant space frame – a rigid, lightweight, truss-like structure with interlocking struts arranged in a geometric pattern that can easily transmit the tension and compression loads, thereby needing few interior supports. The space frame design was inspired by how taro leaf skin (epidermis) is held with channels supporting the transportation of resources between the epicuticle and the inner leaf.

Algae panels dot the skin of the space frame where they sequester CO2 and generate energy. The algae-biofuel system doubles up as an air filtration system drawing in polluted air from vents and pumping out clean air. A zebra stripes pattern on the cooling towers is hypothesized to create greater airflow leading to cooling effects on the exhaust. With algae acting as a filter, the power plant effectively pumps the "exhaust" through its algae skin. Additionally, the landscape created diverse wetlands around the built structures to restore the ecology of the coastal flats.



Surface for Flora & Fauna

Material Optimization

Key Strategies:
Use essential structures such as walls to integrate natural cavities to enhance pollinator (solitary and stingless bees) diversity around buildings.

BEE BRICKS

Location: **UK**
Inspiration: **Natural bee cavities in wood**
Year: **2020**
Creator: **Green&BlueUK[63]**
Status: **Built**
Application Scale: **Wall Panel**

Solitary bees make up over 90% of the bee population diversity in the UK and tropical areas like Singapore. The bees are essential for pollinating many species of plants and are a key facilitator of biodiversity. They nest in small holes or crevasses.

Designed to encourage biodiversity, this bee brick helps encourage pollinators. It provides a safe nesting place for non-swarming, solitary, and non-aggressive bees like resin bees and leaf-cutter bees. The bee bricks are interchangeable with other standard bricks facilitating easy integration.

While bee bricks are new to Singapore, standalone bee hotels made of wooden blocks with holes of varying sizes have been successfully implemented in several public projects here.

Click or scan to find out more

Limited Heat Gain

Water Capture

Surface for Flora & Fauna

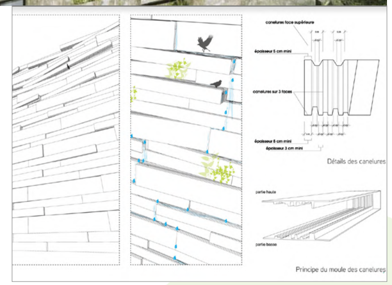
Key Strategies:
Integrate soil medium on concrete façade much like rock cliffs instead of externally clad green walls.

BIODIVERSE WALLS

Location: **Paris, France**
Inspiration: **Natural rock cliffs**
Creator: **ChartierDalix, Museum of Natural History of Paris, FAIRE Paris and Pavilion de L'Arsenal[64]**
Year: **2021**
Status: **Built**
Application Scale: **Wall Panel**

Plants grow naturally on many vertical rock faces in the wild. Plant growth is facilitated by sediment deposits in cracks in the rock face. Cracks can form and grow in the presence of water. As soil begins to accumulate in the cracks plants of increasing size can find a successful foothold.

This new vertical planting system allows plants to settle durably. Brick, stone and monomer are arranged in a way that an interior void is provided between an inner and outer layer to accommodate the substrate of the plants. This operation is made possible by the presence of lateral chaining that hold the two parts of the wall together.



Click or scan to find out more

Limited Heat Gain

Surface for Flora & Fauna

Water Capture

Key Strategies:
Integrate soil medium on concrete façade much like rock cliffs instead of externally clad plastic green walls.

INTEGRATED GREEN WALL TILES

Location: **Singapore**
Inspiration: **Natural rock cliffs**
Creator: **Goel, Abhimanyu**
Year: **2021**
Status: **Prototyped**
Application Scale: **Wall panel**

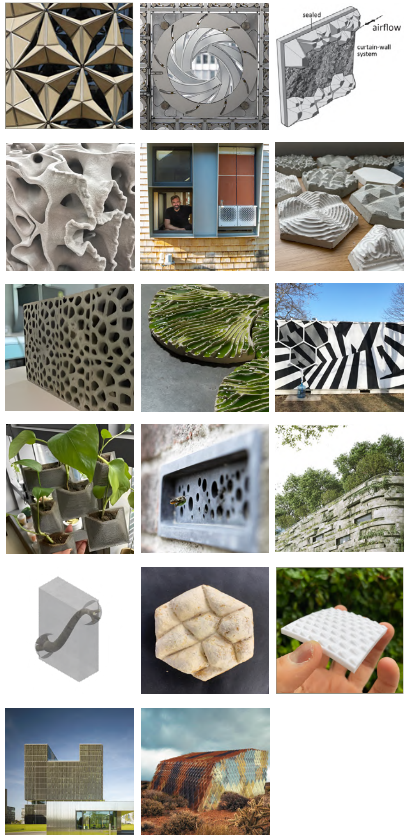
Plants grow naturally on many vertical rock faces in the wild. Plant growth is facilitated by sediment deposits in cracks in the rock face. Cracks can form and grow in the presence of water. As soil begins to accumulate in the cracks plants of increasing size can find a successful foothold.

A novel approach to use concrete planters integrated as wall tiles was adopted. It is hoped that this design can replace the need for using plastic planter boxes on vertical green walls. The green wall was prototyped by 3D Printed formwork

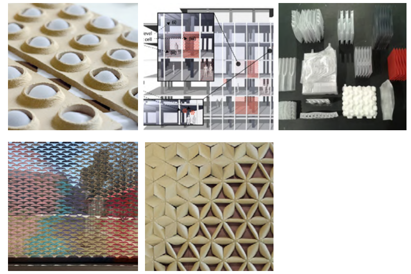
Case Study Scale, Taxonomy, Type

Scale of application for case studies

WALL PANEL

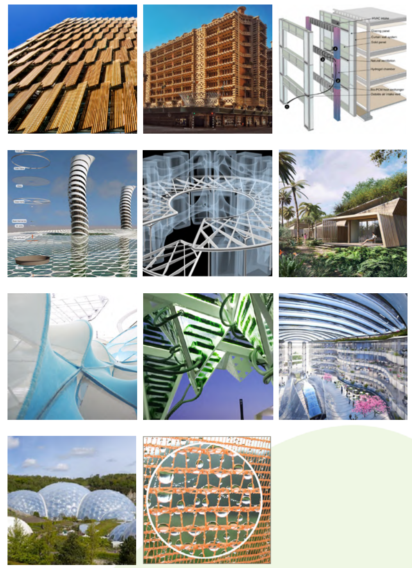


MATERIAL*



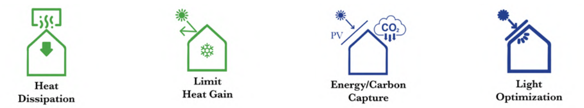
* Please refer to the 'Biomimetic & Bio-inspired materials synopsis' section in this chapter for additional material examples. The examples listed here are those that operate at a material scale but the solution is integrated with the facade.

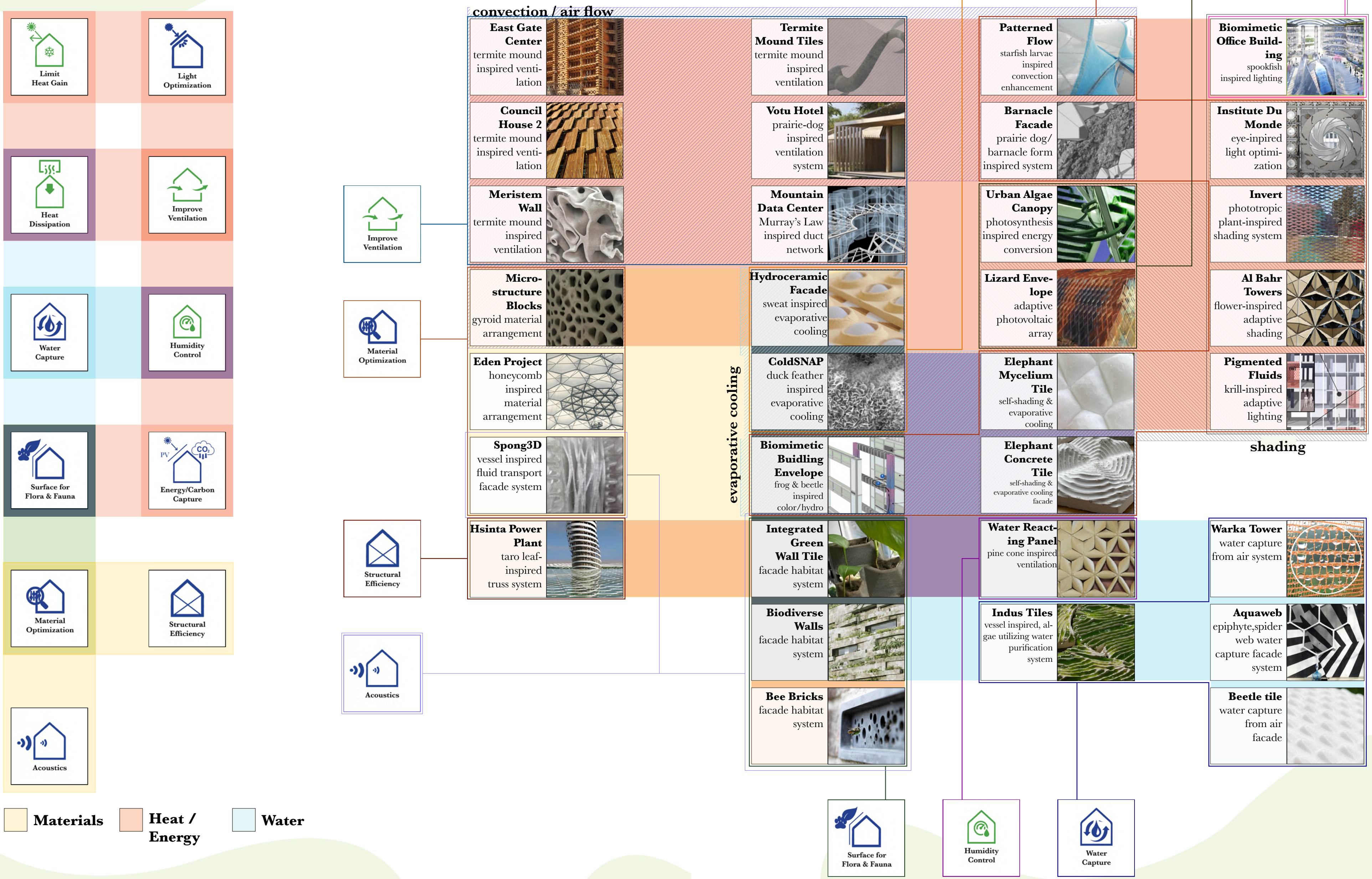
BUILDING



Taxonomy of case studies

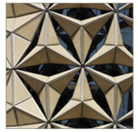
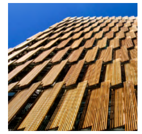
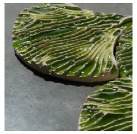
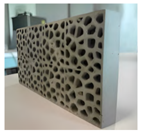
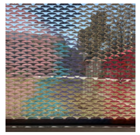
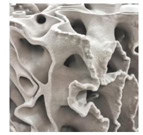
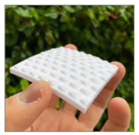
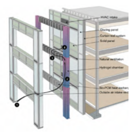
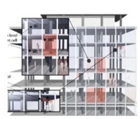
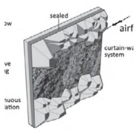
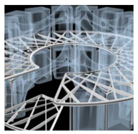
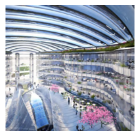
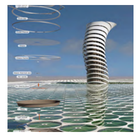
This diagram shows how some basic concerns (materials, heat/energy, and water) relate to our functions and to the case studies. Many of these examples include many strategies. We have highlighted just one key aspect of each to get a simpler picture of how these functions exist in designs and how they connect to each other.





Status of development & Type of biomimicry used

Refer to Chapter 2 for definition of Form, Process & System biomimicry

	FORM	PROCESS	SYSTEM
4 Built A full scale deployment of the concept has been made in its physical form.	   	  	 
3 Prototyped A physical prototype has been developed but not applied to a long-term full-scale deployment yet.	    	     	  
2 Simulated/ Abstracted Performance Known Performance data is available or published for the concepts.	 	  	
1 Conceptual Only drawings/schematics available as a concept.	 		

Novel Materials

Biomimetic & Bio-inspired Materials Synopsis
This section features a curation of biomimetic and bioinspired projects that do not always solve for thermal comfort but can be important in providing a suitable material **in implementing the case study ideas presented in the Horizon Scan or generally in improving the sustainability of building facades**.

The synopsis is non-exhaustive but feature a range of materials - organic & inorganic, composites, substrates as well as coatings and paints that support functions such as flexibility in shape, or sustainability principles such as incorporating the use of natural materials and more. Some of these materials have already been comercialised or used in built projects while others are in the prototype or research stage. All of them have a range of applications in building facade design.

Materials

Inorganic materials

BIOLITH

Location: **USA**
Inspiration: **Coral reefs**
Creator: **BioMASON[65]**
Function: **Grow hard substrate**

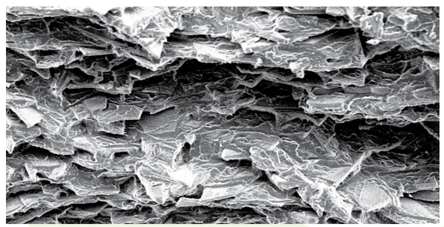
The process use natural microorganisms to "grow" biocement bricks, using a zero carbon emission process similar to the way coral reefs are formed. It contains 85% recycled aggregate and 15% biocement.

Click or scan to find out more

DEFORMABLE GLASS

Location: **Canada**
Inspiration: **Nacre**
Creator: **McGill University[66]**
Status: **Prototyped**
Function: **Anti-break glass**

Nacre is a composite material produced by molluscs as an inner sea shell layer. It is also the material of which pearls are composed of. Nacre is made up of calcium carbonate layered with highly elastic soft proteins that gives it exceptional strength. By replicating layers of glass flakes and acrylic, researchers found that the glass will strengthen and become 200 times tougher than standard glass. The nacreous glass deforms without shattering, making it ideal for windows.



Project image retrieved from Amini, A., Khavari, A., Barthelat, F., & Ehrlicher, A. J. (2021). *Science.*

Click or scan to find out more

CON-FLEX-PAVE

Location: **Singapore**
Creator: **Yang, E.H., & NTU Team**[67]
Status: **Prototyped**
Function: **Bendable substrate**

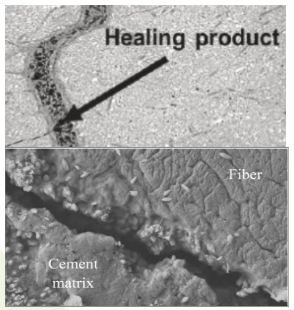
This bendable concrete is able to flex and bend under tension, making it at least twice as strong as conventional concrete. This allows for the creation of slim precast slabs for quick installation, with less maintenance required.

Click or scan to find out more

SELF-HEALING CONCRETE

Location: **Singapore**
Creator: **Qui, J., & Yang, E.H. (NTU)**[68]
Status: **Prototyped**
Function: **Self-heal on a hard substrate**

Limestone producing bacteria (*Bacillus halodurans*) is embedded into Engineered Cementitious Composites (ECCs). When exposed to favourable conditions, due to the porous nature of the cracks, the bacteria becomes active. This triggers limestone production, which repairs the cracks.



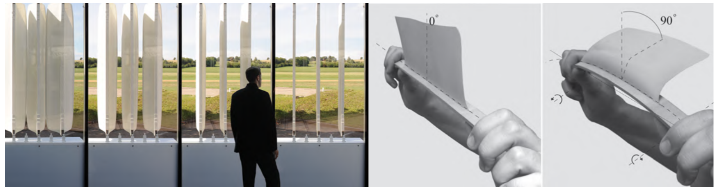
Project image retrieved from Qiu, J., He, S., & Yang, E. H. (2019). *Cement and Concrete Research.*

Click or scan to find out more

FLECTOFIN

Location: **Germany**
Inspiration: **Bird of Paradise Flower** (*Strelitzia reginae*)
Creator: **University of Stuttgart, University of Freiburg, BIOKON e.V.**[69]
Status: **Commercialized**
Function: **Low-energy reversible deformation**

The Bird of Paradise flower has three reinforcing lateral ribs, that allow its bottom petals to be unsealed by insects during pollination. A constricted zone is present between the upper ribs and wings (two lateral petals) with no fibrous tissue that provides flexibility and elastic bending of the wings. Inspired by these principles, the Flectofin was developed as a hingeless flapping mechanism. It utilizes fibre-reinforced polymers that combine high tensile strength with low bending stiffness, thus offering a large range of calibrated deformations and eliminating the need for local hinges. This folding mechanism has been used to develop low-cost convertible shading systems.



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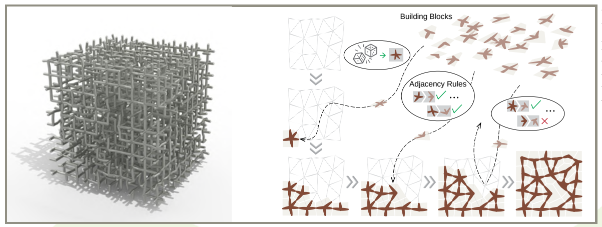
IRREGULAR ARCHITECTED MATERIALS

Inspiration: **Termite Mounds**
Creator: **Liu, K., Sun, R., & Daraio, C.**[70]
Status: **Prototyped**
Function: **Mimic nature's structural stability and ventilation**

Termites mounds are geometrically irregular but optimized for structural stability and ventilation. The gas exchange of oxygen and carbon dioxide is established through temperature gradients between the mound periphery and centre. Based on such biological systems, the Virtual Growth Program has been developed to engineer irregular architected materials with superior functionality. The program identifies basic rules to control mechanical properties by varying the microstructure's topology and geometry.



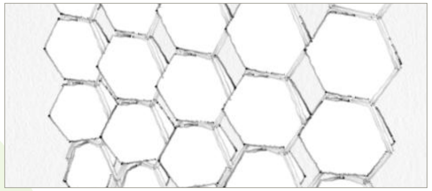
Project images retrieved from Liu, K., Sun, R., & Daraio, C. (2022). *Science.*

Click or scan to find out more

KAOLIN FACADE

Inspiration: **Ticks, Earthworms**
Creator: **Eleftheriadis S.& Yannan, S.** [71]
Status: **Conceptual**
Function: **Humidity Control**

Brown ticks can detect high humidity, and in response, they release a hydrophilic solution, namely a hygroscopic salt released from the tick's mouth. This solution absorbs humid air, allowing the tick to swallow the collected water. Inspired by the salty solution secreted by ticks, researchers have developed a material made of Kaolin and Calcium Chloride that absorbs water vapor from the air, providing an alternative dehumidification system.Earthworm bodies consist of a semipermeable membrane. Due to osmotic pressure, its body will attract water molecules from the soil, functioning as a dehumidification system. Using a dehumidification chamber and rotating panels that contain the tick-inspired material, this system forms the 'membrane'' as seen in Earthworms. In future applications, this system can be integrated into a building's skin to control the humid inlet air.



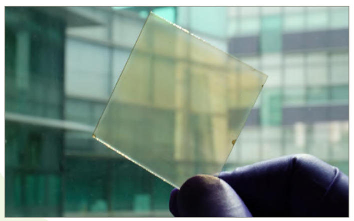
Project image retrieved from Eleftheriadis S.& Yannan, S. (2012). *Sustainability through Biomimicry Conference. At: Dammam, Saudi Arabia.*

Click or scan to find out more

SELF-ADAPTING GLASS

Location: **Singapore**
Inspiration: **Tetra Fish**
Creator: **Ke, Y. et al.** [72]
Status: **Prototyped**
Function: **Heat dissipation, Limit Heat Gain**

Tetra Fish have chromatophores in their skin, which contain arrayed guanine (basic building block of DNA/RNA) platelets that can selectively reflect light of a certain wavelength and thereby act as a photonic crystal. The selective reflection property generates direction-dependent vivid colours, similar to butterfly wing colours. The glass is coated with layers of a Vanadium Dioxide (VO2) nanoparticles composite - a reliable smart thermochromic window material due to its optical stability during transition in the visible range. The coating can also regulate solar heating and radiative cooling.



Project image retrieved from Ke et al. (2022). *Applied Energy.*

Click or scan to find out more

Organic materials

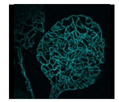
MYCELIUM BRICKS

Location: **UK**
Inspiration: **Mushrooms**
Creator: **BIOHM**[73]
Status: **Commercialized**
Function: **Build lightweight substrate using natural materials**

Mushrooms produce thin white filaments known as mycelium. Mycelium's roots and fibres will bond to surrounding organic matter, allowing it to grow. Mycelium is naturally durable, and provides the mushroom with support and anchorage. A substrate (usually a biowaste residue) and fungi are combined in a solution, and inserted into molds with chopped substrate. After several days of growth, the material is shaped and solidified. It is placed in an oven to deactivate microorganisms, allowing it to be used to make bricks.

Click or scan to find out more

FUNGAL-LIKE ADHESIVE MATERIAL (FLAM)



Location: **Singapore**
Inspiration: **Fungus-Like Oomecytes**
Creator: **Fermant Lab & SUTD Team**[74]
Status: **Prototyped**
Function: **Build lightweight substrate using natural materials**

FLAM is inspired from the walls of fungus-like oomycetes (a type of parasite) that is reproduced by introducing small amounts of chitin between cellulose fibres. The resulting FLAM is a strong, lightweight and inexpensive composite material. The raw materials - cellulose and chitin are common natural polymers and industrial byproducts that provide strength and structural integrity. The material can be molded to form 3D structures, using woodworking techniques.

Click or scan to find out more

PULP FACTION

Location: **Sweden**
Inspiration: **Fungal combs in Termite Mounds**
Creator: **Goidea, A., Floudas, D., & Andreen, D.**[75]
Status: **Prototyped**
Function: **Build lightweight substrate using natural materials**

Pulp Faction uses a design system called Protomycokion in which fibrous by products (such as waste wood) are inoculated with a fungus that transforms the waste into a resilient construction material. The resulting pulp material is self-supporting, has good thermal and acoustics insulation, and simultaneously hydrophobic and hygroscopic. Live pulp material is 3d printed into a column that is algorithmically designed to incorporate the requirements of the fungus and human users.

Click or scan to find out more

ALGAE PANELS

Location: **Germany**
Inspiration: **Algae**
Creator: **Splitterwerk Architects**[76]
Status: **Built/Commercialized**
Function: **Energy generation using natural materials**

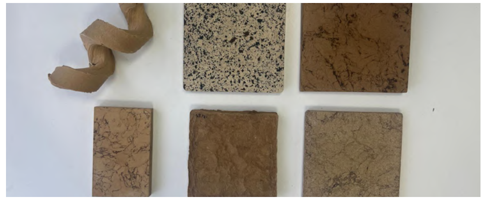
Algae photosynthesise more efficiently than most plants due to a wide range of antenna pigments that harvest more solar energy. This ensures that they can produce more biomass per hectare faster than the majority of alternate crops. The Algae Bioreactor Facade on the BIQ building has algae filled in glass panels. The algae pulp can be periodically harvested and fermented in an external biogas plant to generate energy and provide shade.

Click or scan to find out more

DAIKA WOOD

Location: **Israel**
Inspiration: Jerusalem stone
Creator: **Layani, M., Magdassi, S., & Shosayov, O.**[77]
Status: **Commercialized**
Function: **Chemistry oriented texture**

DAIKA wood developed an all-natural based materials processes combined with a unique water based chemistry (much like nature) to turn wood waste into natural, strong and hazard free products. By enabling the right chemistry, it is able to mimic the creation of a natural mineral. This is a sustainable, natural process that uses relatively low temperatures and water, without thermoplastics. The unique appearance is combined with exceptional industrial properties of high mechanical strength, fire retardancy and water resistance. The company pays homage to the "Jerusalem stone" where it was founded in the old stone buildings of the Hebrew university campus.



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SELF-SHAPING CLAY COMPOSITE

Location: **Singapore**
Inspiration: **Celery (cellulose) fibers**
Creator: **Zhang, Y., & Le Ferrand, H.**[78]
Status: **Prototyped**
Function: **Bendable substrate**

Plants morph due to the presence of cellulose fibres in their internal structure. These provide direction dependent mechanical properties and can lead to reversible deformation, when swelling and drying occur. The composites made of clay and starch, mimic this process by using celery fibres that can respond to external triggers such as temperature or humidity and thereby, transformed into 3D shapes.

Project image retrieved from Zhang, Y., & Le Ferrand, H. (2022). *Biomimetics.*

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Coatings & Paints

ORNILUX BIRD PROTECTION GLASS

Location: **Germany**
Inspiration: **Spider Web**
Creator: **Arnold GLAS**[79]
Status: **Commercialized**
Function: **Prevent bird collisions on glass**

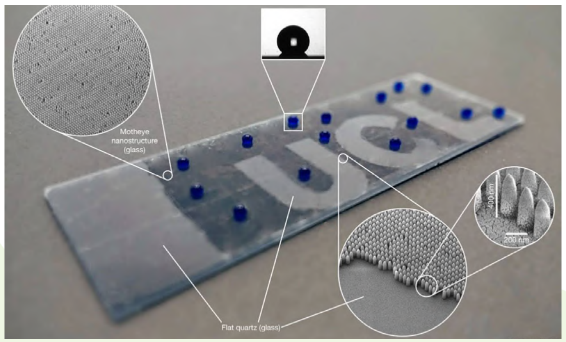
Every year, millions of birds die because they are unable to recognize glass panels and fly into the facades of buildings. Some species of spiders incorporate UV reflective silk strands into their webs. This distracts or warns away birds that can see in the UV spectrum and reduces the incidence of large birds crashing into the webs. Using a patterned UV reflective glass coating, Ornilux glass is visible to birds whilst appearing transparent to humans.

Click or scan to find out more

SELF-CLEANING WINDOW

Location: **UK**
Inspiration: **Moth eyes**
Creator: **University College London**[80]
Status: **Prototyped**
Function: **Self-clean**

Researchers have developed windows that mimic the nanostructures found in the eyes of moths. Due to its anti-reflective properties, the window cuts the amount of light reflected internally in a room to less than 5%. Likely, the window will also result in a decrease of heating energy consumption.

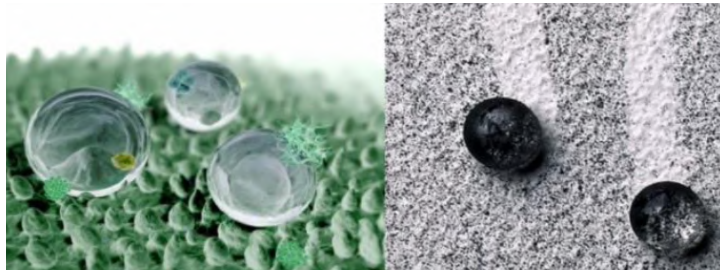


Click or scan to find out more

LOTUSAN - SELF-CLEANING PAINT

Location: **Germany**
Inspiration: **Lotus leaf**
Creator: **Prof. Barthlott, W.**[81]
Status: **Commercialized**
Function: **Self-clean**

Lotusan, a façade paint, mimics the leaf surface of the Lotus that is covered with tiny bumps and waxy hydrophobic surface. This results in dirt particles being simply washed away in times of rainfall. Purchase at Sto Color.



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NANO INKS

Location: **Melbourne, Australia**
Inspiration: -
Creator: **Taha, M. et al. 2023** [82]
Status: **Prototyped**
Function: **Limit heat gain**
Function: **Air purification & self-clean**

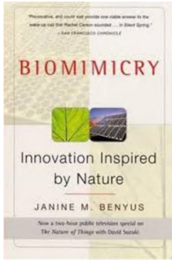
This phase-change ink can help with passive temperature control by adjusting the amount of radiation that can pass through it. This is achieved by developing a technique through which Vanadium Oxide can be enabled to transition from an insulator to metal phase at near-room temperatures (~ 40°C), thereby increasing the ease, scalability and efficacy of application. The ink can be laminated, sprayed or added to paints and building materials

Click or scan to find out more

Useful Books & Links

Biomimicry Basics

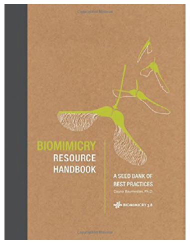
https://www.learnbiomimicry.com/



Innovation Inspired by Nature
by Janine M. Benyus

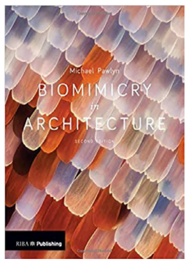
Biomimicry Methodology

https://toolbox.biomimicry.org/

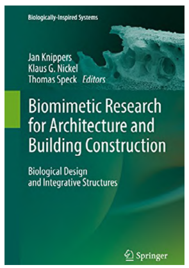


Biomimicry Resources Handbook
by Dayna Baumeister

Biomimicry & Architecture



Biomimicry in Architecture
2nd Edition
by Micheal Pawlyn



Biomimetic Research for
Architecture and Building
Construction
by Knippers Jan, Nickel Klaus
G. and Speck Thomas

Learn about Nature's Strategies

https://asknature.org/

NASA's AI powered biomimicry
toolkit https://petalai.org/

Local Resources (Singapore)

https://www.biomimicrysingapore.net/

ASEAN Resources

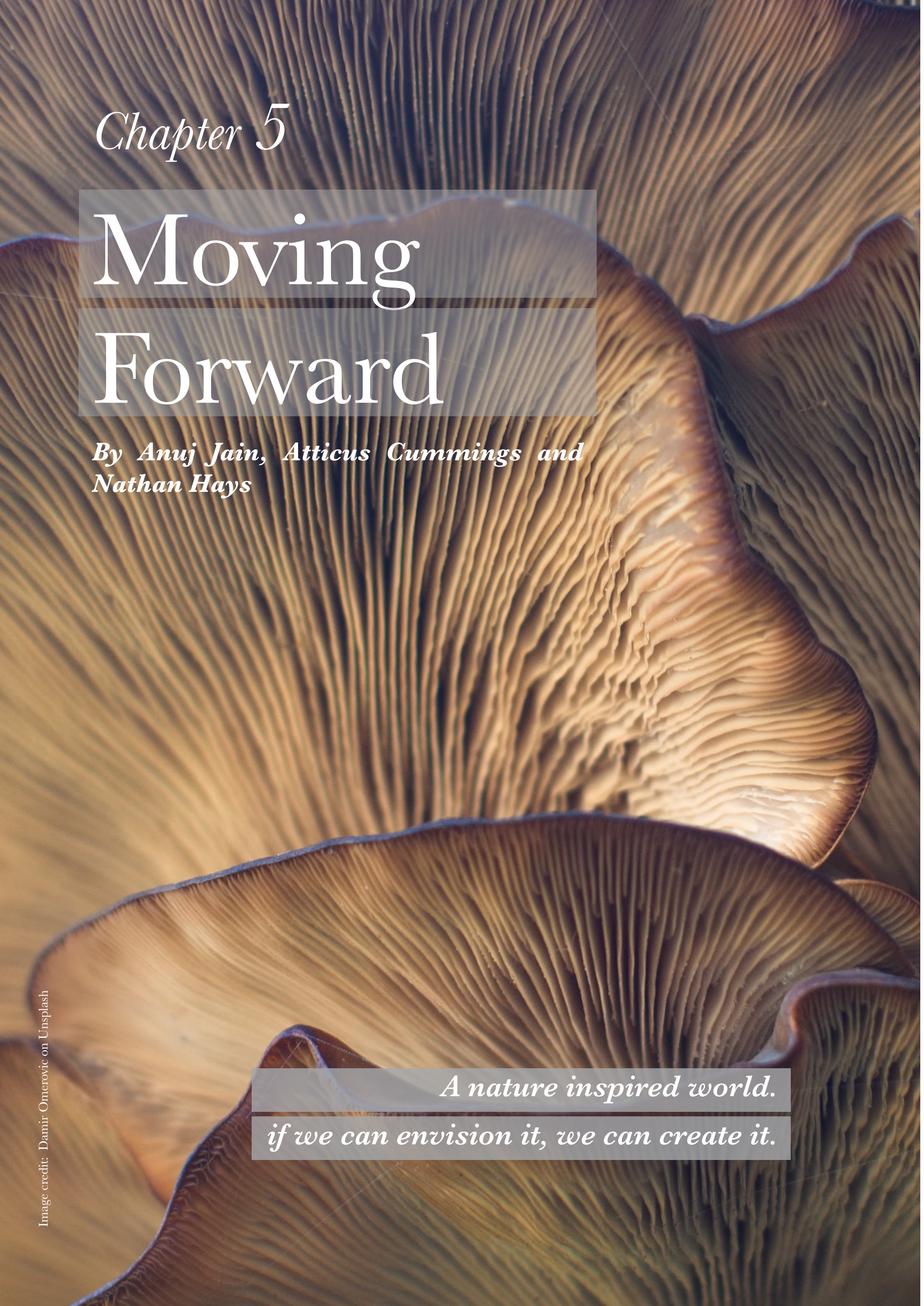
Bali, Indonesia
https://www.biomimicry.works/

Jakarta, Indonesia
https://www.facebook.com/Bio-
mimicryIndonesia

Chapter 5

Moving Forward

By Anuj Jain, Atticus Cummings and Nathan Hays



A nature inspired world.

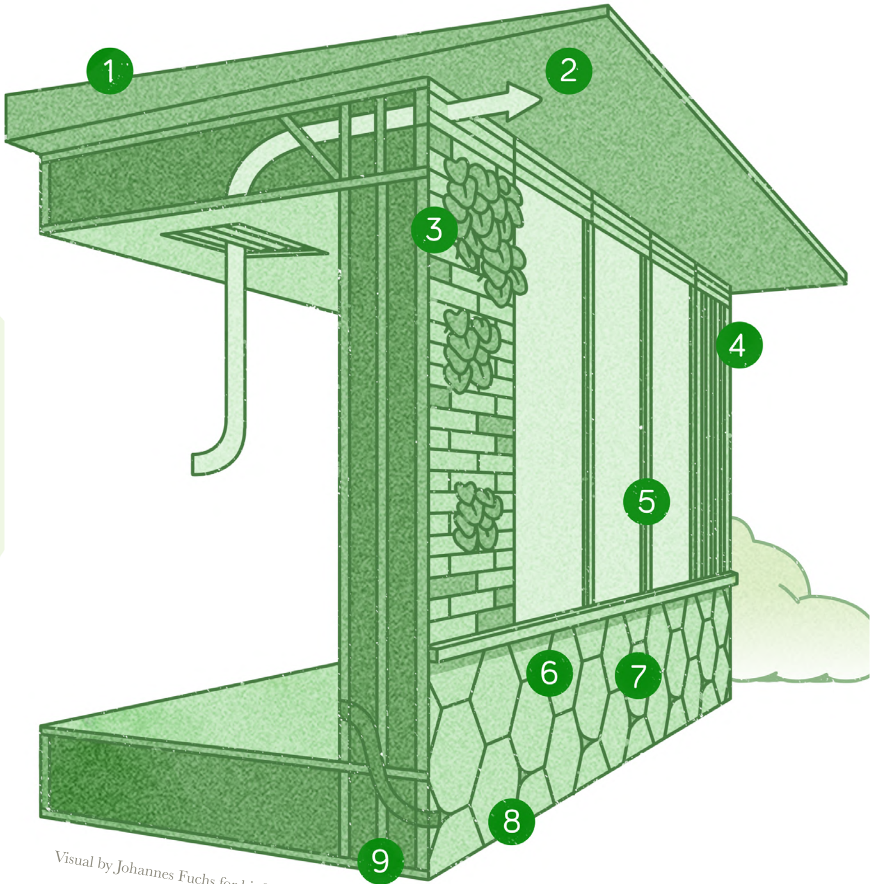
if we can envision it, we can create it.

Image credit: Damir Omerovic on Unsplash

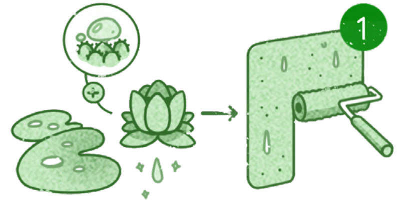
Contents

Biomimetic Hybrid Facade

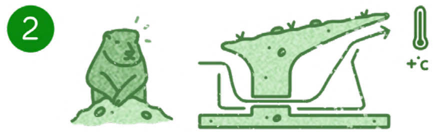
Conventional and biomimetic designs can be integrated to create a multi-functional building facade that is suited for the building context.



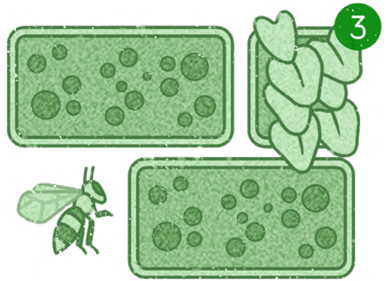
Visual by Johannes Fuchs for bioSEA



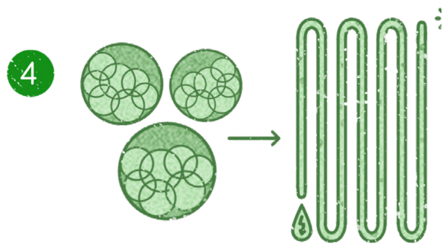
Lotusan paint on the roof prevents the attachment of dirt or microbes.



Vents at different heights create cross ventilation in a process inspired by prairie dog burrows.



Well textured surfaces can mimic cliff faces to create biodiverse walls with bee bricks. These can be integrated with existing vertical greenery systems to provide habitat for flora and fauna.



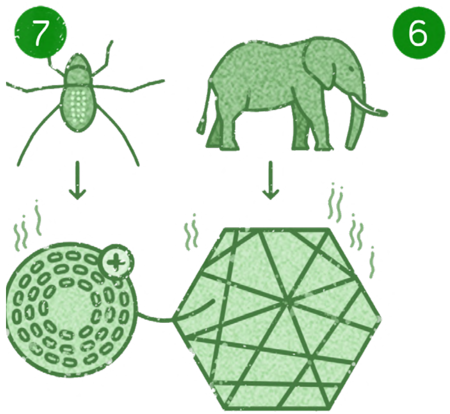
Algae can be grown on various building elements such as columns and walls, the biomass can be used to capture carbon dioxide and make biofuel or other products.

Ornilux glass mimics spiderwebs in a spectrum of light invisible to the human eye to prevent bird collisions.

Elephant skin inspired surface texturing enhances surface area for evaporative cooling.

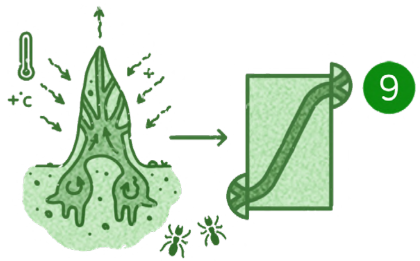
+

Microtexture inspired by the Namib desert beetle condenses water to cool the building.

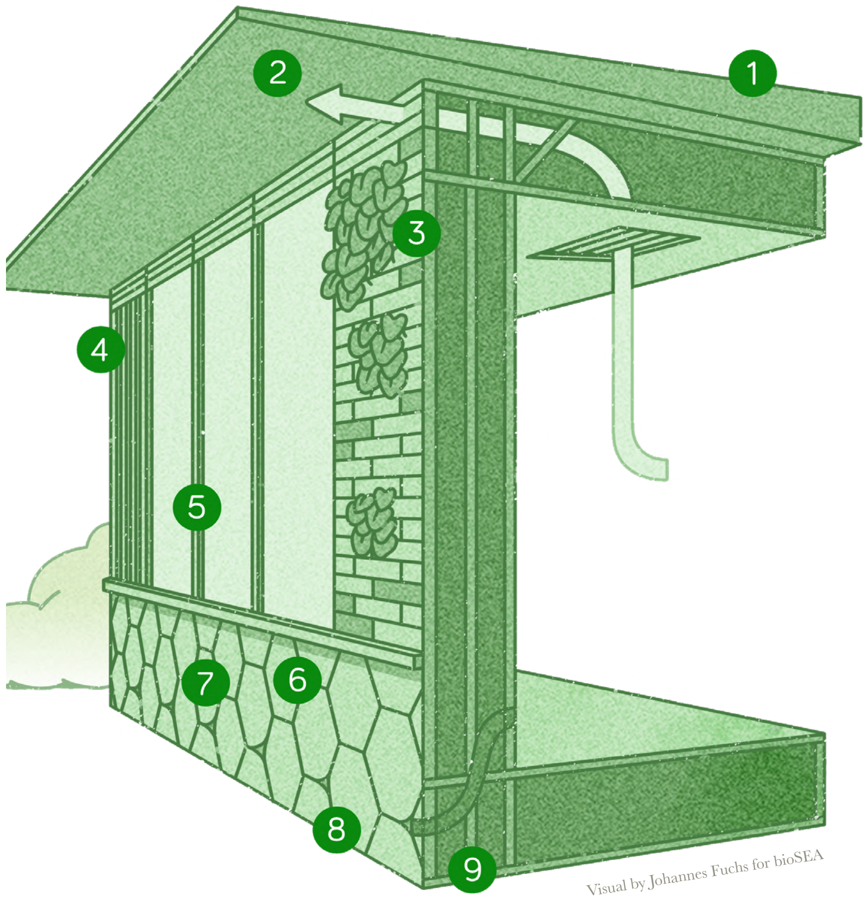


Pinecone inspired flaps open or close ventilation tubes based on humidity and temperature.

Termite mound inspired ventilation tubes create convective airflow reducing the need for airconditioning.



Imagine the benefits and functionality such a living facade would bring to the building and the landscape for humans and non-human species



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Ever Evolving Responsive Design

Nature is indeed remarkable. As we delve deeper into the extraordinary world of living systems, it becomes increasingly apparent that there is so much we can learn from their evolution, growth, and adaptation. Envision a future where building façades harmonize with their surroundings as living organisms, seamlessly integrating with the ecosystems around them, their occupants, and each other. This vision might be closer than we think. This biomimicry toolkit is the first of many to come—each with the goal of moving us toward this future.

"Seeing is believing. Why don't we create an impressive biomimicry building full of different applications of biomimicry designs. This should be an easily accessible public building where visitors can get to see and experience first-hand an array of different biomimicry building design solutions - and hopefully get excited about biomimicry and its wider application in our built environment."

Gregers Reimann
Engineer | Managing Director
IEN Consultants | Malaysia

In the near future, we will possess the tools necessary to design façades in simulated environments, taking into consideration not only information about sun paths, temperature, humidity, precipitation, and wind, but also the life nearby. The communities of organisms, the ecosystem services present or missing, the air and water quality, soil pH, and pollens and other living particulates all contribute to the façade's evolution. By embracing the natural world's inherent adaptivity, multi-functionality, and hierarchical structuring, biomimetic buildings will become integral components of the ecosystem, much like the living systems that inspire them.

The façades of the future will continuously adapt and become visibly kinetic when necessary. Façades will resemble living, dynamic systems that are constantly remodeled to maintain an optimal balance between strength and flexibility. Just as bones heal themselves and move material to areas of highest stress, buildings of the future will be self-healing, with materials that respond to change. Like the tortoise beetle, façades of the future might sometimes vary in color and transparency, maybe for communication or temperature regulation, or to offer views or control glare.

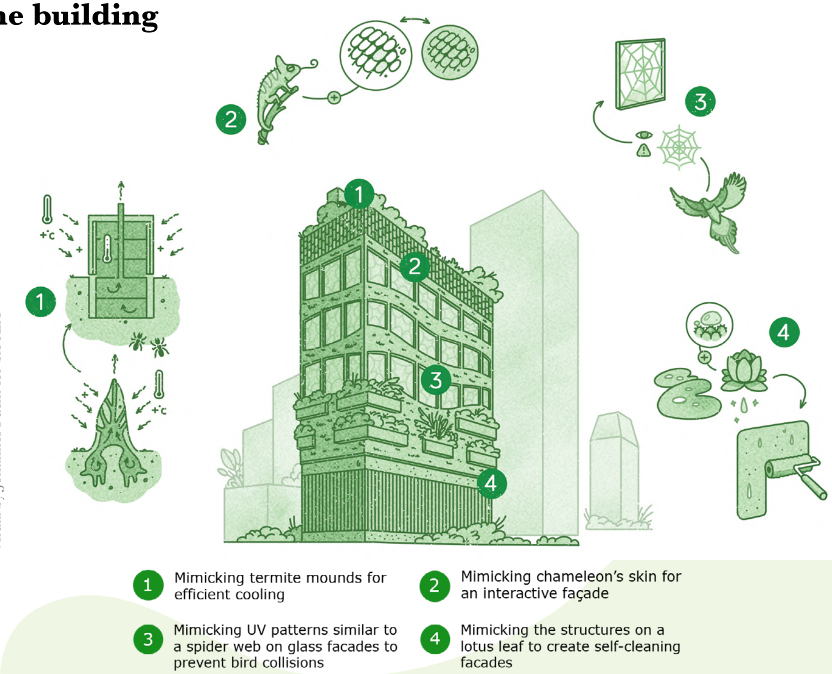
"It will be good to have an incentive scheme, a grant or funding to try out biomimicry ideas in built projects. This will ensure that R&D work can take off to application. Usually, clients and developers may not want to invest in new research and technologies so policies need to tackle this."

Mun Summ Wong
Architect | Co-founding Director
WOHA Architects | Singapore

Façades of the future may be spatially or temporally attuned to sound—in some scenarios projecting sound, in others making it more crisp, or dampening it through material and geometric design, much like the stealth flight of owls. Façades will provide habitats for life, support pollinators, all while being constructed from safe, locally sourced materials. These materials will either be inherently well-suited, or perhaps programmed, as nature programs its tissues, to address a multitude of functions. Façades of the future may be easier to construct as they emulate the material assemblies and fabrication processes in nature which tend toward stability.

Like mycorrhizal networks connecting a forest, façades might be vascularly interconnected—different areas connected at different scales. They may transport shared materials, fluids to assist with temperature regulation at different locations, or bring nutrients to vegetation on the façades. They could transmit information about the state of activity in different areas. Façades will contribute to balanced and harmonious systems, pulling their buildings and environments toward oscillating and ever-adapting homeostatic states, together with their ecosystem. We are excited to explore the specifics of these futures, and with your help, see them come to reality.

Imagine the biomimetic hybrid facade scaled up to the building



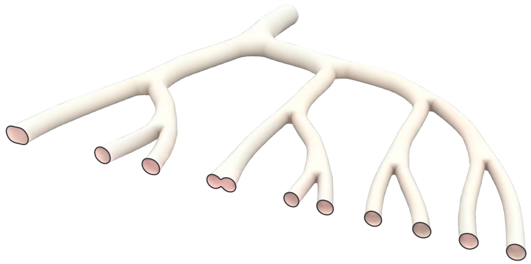
Visual by Johannes Fuchs for bioSEA

Appendix - Design Patterns & Principles

By Nathan Hays & Anuj Jain

This sections features commonly occurring design patterns & principles found in nature. For example, termite mound inspired panels utilize Murray's law. The elephant skin inspired wall panel uses capillary action to pull water and Voronoi patterns to generate the arrangement of bumps. Hexagon packing is used across multiple example in the Horizon Scan (chapter 4) including the Eden Project.

Murray's Law [83]



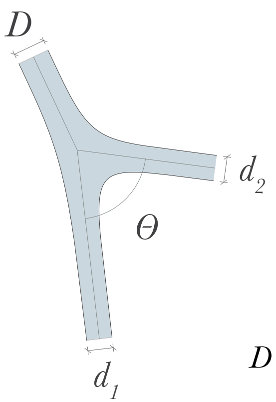
turbulent flow

$$\sum_{in} d^{7/3} = \sum_{out} d^{7/3}$$

laminar flow

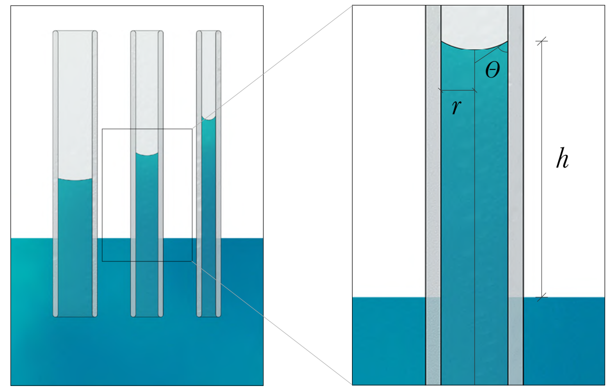
$$\sum_{in} d^{3} = \sum_{out} d^{3}$$

Murray's Law describes the ratio between the diameter of a parent vessel and the daughter vessels that branch from the parent in vessel networks. The equations above show the general relationships of between the diameters of vessels going into a branching event (usually just one, parent vessel) and the diameters of vessels leaving a branching event (usually two or more daughter vessels). The exponents vary depending on the flow type, turbulent (top) or laminar (bottom). The diagram to the left shows the relationship between the diameters of a parent vessel (D) and two daughter vessels (d_1 and d_2) with laminar flow. A typical angle between the vessels (Θ) is between 70° and 80°.



$$D^3 = d_1^3 + d_2^3$$

Capillary Action [84]



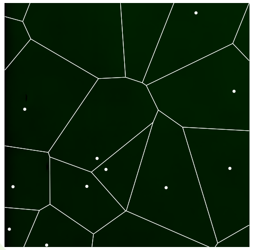
$$h = \frac{2\, \gamma \cos(\Theta)}{\rho\, g\, r}$$

The molecules in any liquid have an attraction toward each other. It's this attraction that hold liquids together in pools or droplets; and it's this attraction that creates surface tension. In many scenarios, the molecules in a liquid also have an attraction toward the molecules that make up the container that holds them or the surface they are on, as with the example above showing water in glass tubes. Because the molecules in the water are attracted to the molecules in the glass, water climbs up the glass tubes, attaching itself to more of the surface of the glass. This force is called capillary action. The height a liquid will travel vertically is related to several variable shown in the equation above, including the surface tension of the liquid (γ), the density of the liquid (ρ), the force of gravity (g), and the radius (r) of the tube or crevice the water is in.

Voronoi Pattern [85]

a

A Voronoi cell describes an area (or volume) of space that is closer to one seed point (out of a list of seed points) than it is to any other seed point (in that list). Voronoi patterns appear frequently in nature, like on the fur of a giraffe, in the clustering of leaf cells, or in the structure of a dragonfly wing (a). If the white points in (b) are the seed points, then the white boundaries surrounding each point outline the area within which any point is closer to that seed than any other seed. In living systems, this is often the result of a reaction, or growth, being triggered at different points. As those points expand, grow, and/or nestle together, the resulting pattern is Voronoi in character. This cellular packing also appears in nonliving systems, as when mud is swollen and packed together, then dries and cracks; and in 3-dimensions in bubbles or foam.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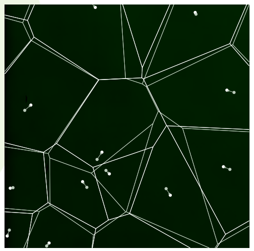
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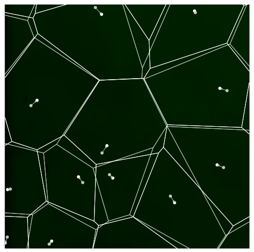
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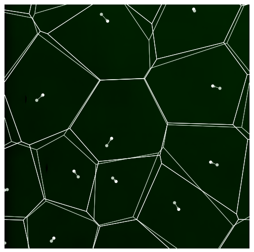
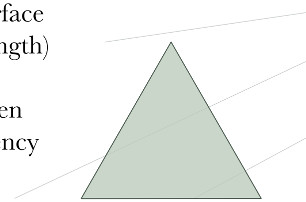
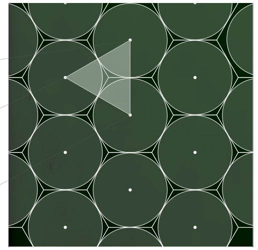

e

Hexagon Packing [85]

Voronoi cells with equidistant seeds form perfect hexagons. As the seeds from (b) push off of each other to pack as tightly as possible, given a certain packing radius the result is a hexagon packing pattern (c - h). Connecting the dots between points in (i) and their nearest neighbors will give you equilateral triangles (i.e. each point is equal distance to its six closest neighbors). A circle is the most efficient way to enclose an area (i.e. the boundary is the shortest relative to the size of the area enclosed). From this we see that the most efficient way to create cells on a surface (shortest total boundary length) is with hexagon packing. This appears in nature when maximizing packing efficiency is of high importance (j).

j

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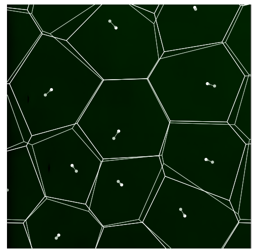
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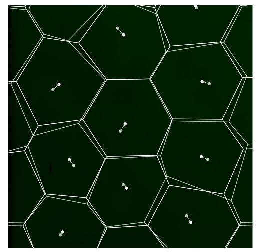
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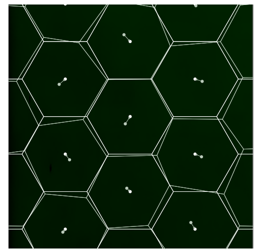
h

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