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BIOMIMETIC BUILDING SKIN:

A PHENOMENOLOGICAL APPROACH USING TREE BARK AS MODEL

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BIOMIMETIC BUILDING SKIN:
A PHENOMENOLOGICAL APPROACH USING TREE BARK AS MODEL

A THESIS APPROVED FOR THE
DEPARTMENT OF ARCHITECTURE

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Abstract

The architectural profession is at a critical point in history with regards to reducing its impact on the natural environment. To truly minimize a building's impact it needs to interact more holistically with its surroundings instead of just singular fixes that focus on one issue like less waste. The lessons learned from natural systems can be applied to architecture to lessen its environmental impact, and this is a critical point to ask: Will architects utilize construction technology as well as advanced scientific knowledge to create an architecture that behaves like nature? To achieve a more efficient building skin and one that is appropriate to its place, architects should look to tree bark as a model because it is efficient with resources and is adapted to its local climate.

Keywords: Biomimicry, genius loci, place, efficiency, architecture, skin

1.0 Introduction

1.1 Aim & Thesis

The architectural profession is at a critical point in history with regards to reducing its impact on the natural environment. Modern technology reveals this impact. A heightened awareness made possible by satellite imagery, sophisticated measuring equipment and powerful microscopes is issuing a challenge that architects must meet. The world can see and measure the negative impact buildings have in areas like air pollution, water contamination, natural material extraction and waste accumulation. Yet, there is hope. Whether it is called green, eco-, enviro-, sustainable or common sense design; architects are seeing this challenge as a great opportunity. Product manufacturers are also responding. Recycled materials, low-e glazing, water conserving fixtures, energy-efficient lighting and reflective roofing are becoming common in the architectural industry.



Figure 1. 20 Watt LED Downlight



Figure 2. Low-e glass

The aim of this research is to show how architects have an opportunity to design better building skins by emulating the very natural system they are attempting to reduce their impact on.

Current innovations like those shown in Figures 1 and 2 are a step in the right direction. However, to truly minimize a building's impact it needs to interact more holistically with its surroundings instead of just singular fixes that focus on one problem like less waste. While technology is allowing designers to solve these problems, it is also revealing mankind's impact on the planet. Additionally, scientific discoveries reveal how nature solves these problems. The lessons learned from natural systems can be applied to architecture to lessen its environmental impact, and this is a critical point to ask: Will designers utilize construction technology as well as advanced scientific knowledge to create an architecture that behaves like nature?

To answer this question, the paper starts by looking at current problems with architecture and focusing on building skins. It continues by looking at reasons why architects should utilize biomimicry as source of inspiration. From there, the paper moves on to discuss architectural advancements from past to present. Following is a section on using the tree as a metaphor and studying its skin, bark. These explorations conclude with a discussion section on the differences, challenges and conclusions of this research. All of which will support the thesis statement that to achieve a more efficient building skin, and one that is appropriate to its place, architects should look to tree bark as a model because it is efficient with resources and is adapted to its local climate.

1.2 Methodology

This research examines biomimetic building skins through a survey of academic and professional literature as well as interviews with scientists and engineers. Moreover, I used the Biomimicry Institute's Design Spiral methodology seen in Figure 3. The Biomimicry Institute (2009) stated it 'can serve as a guide to help innovators use biomimicry to biologize a challenge, query the natural world for inspiration, then evaluate to ensure that the final design mimics nature at all levels—form, process, and ecosystem.' The first four phases: Identify, Interpret, Discover and Abstract, were focused on in the paper. To identify the function of their design, this methodology asks, "What do you want your design to do?" Next was the interpret phase, which causes designers to ask, "What would nature do here?" Seeking answers leads to discovering natural models. The final step was to abstract their functions for architecture.

Future work can build upon research here and develop a project through the next steps: Emulate and Evaluate.



Figure 3. Biomimicry Institute's Design Spiral methodology

2.0 Architecture

2.1 Current problems with architecture

Working with this methodology, it was essential to identify the real challenges in architecture today, which are inefficiency and loss of place.

inefficiency. Energy consumption is a growing global concern.

According to the Environmental Protection Agency (2009), 'Buildings accounted for 72 percent of total U.S. electricity consumption in 2006... 51 percent of that total was attributed to residential building use, while 49 percent was attributed to commercial building usage' (p. 2). Since buildings contribute significantly to energy usage, architects have a responsibility to search for ways to reduce consumption.

By seeking solutions, designers are returning to basic passive design principles while also utilizing sophisticated high-tech systems. One specific area that needs further investigation because it determines so much of the efficiency of a structure is the building envelope, or skin, as it is often referred to.

A building skin makes up the entire exterior of the building that separates between the exterior and the interior environments, and '... with proper management, the building envelope can significantly slash a building's energy demand... the envelope system can waste tremendous amounts of energy, if not properly attended' (The Structural Group, 2008).

When asked about the most pressing challenges facing architects today, Peter Busby of Busby Perkins+Will stated that, 'The hard part is coming now, when we really have to improve the energy performance of our buildings. We

have to invest in the envelope, and that's going to be a big challenge over the next three to four years' (Weeks, 2010, para. 7).

The design of the building skin greatly affects the amount of energy required for lighting, mechanical systems, and maintenance. Building skin's connection to these systems is shown in Figure 4.

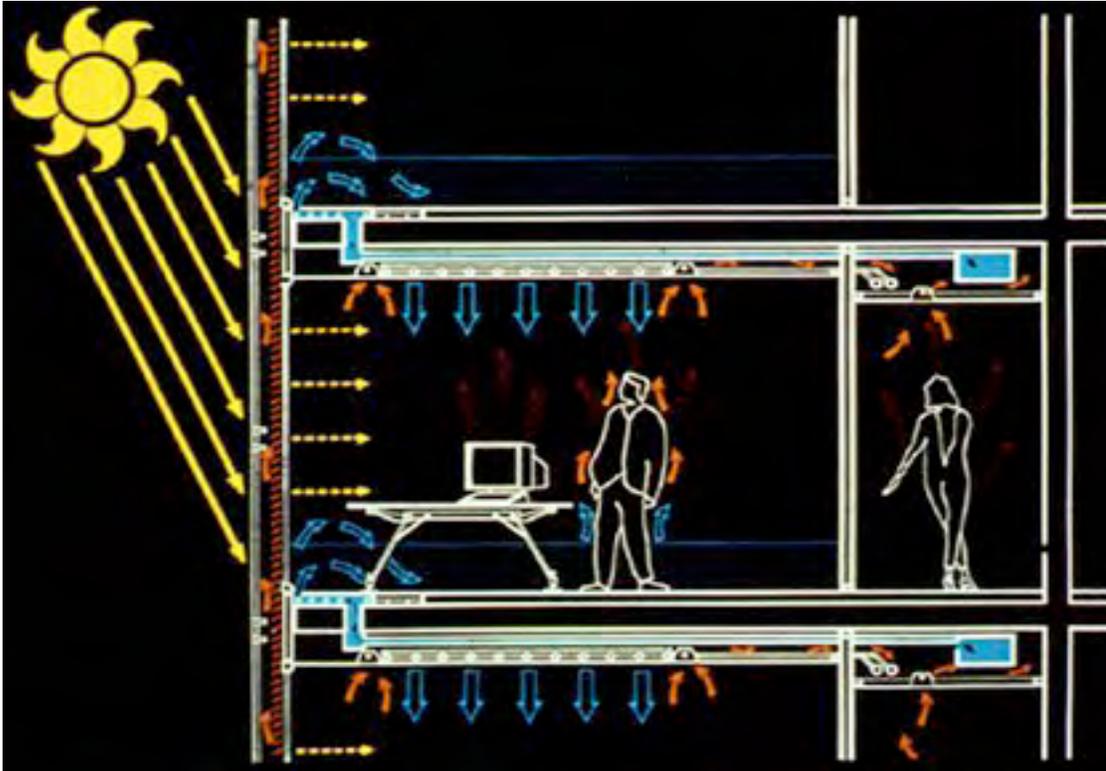


Figure 4. Building Systems Diagram

loss of place. In addition to the problem of energy efficiency, Christopher Alexander (2007) accurately pointed out '...that the biggest problem with architecture is the loss of connection between people and the physical world.' The construction industry has allowed technological advances in buildings, like air conditioning, to separate people from their physical environment, thus losing our *genus loci*, or "spirit of place." People go from a sealed, air conditioned home to a sealed, air conditioned car, then spend the day

in a sealed, air conditioned office or school and then reverse the process at the end of the day. By relying on tightly sealed buildings pushing out the right air temperature for comfort, mankind has forgotten that human beings are connected to the outdoor environment, as are the buildings humans inhabit.



Figure 5. Japanese Vernacular Architecture

Not only does designing with this mentality require immense amounts of energy to operate buildings that are constantly at odds with the outdoor environment, it also makes our communities look indistinguishable. With large amounts of heating or cooling, a building can look the same whether it is in Phoenix or in Boston. Contrast this with the building shown in Figure 5. Almost immediately one knows its location. Its style was crafted over time in response to sun control and dealing with rain, along with local building traditions. By ignoring the building's response to its locale, mankind is losing our cultural identity and the natural world's place in human society.

So what does it look like to have the natural world's place in human

society? If architects follow the vernacular examples, they see that they looked no further than their immediate surroundings. Or simply put they emulated the place they were in. Vernacular architecture did not rely on materials found in a catalog that could be shipped from anywhere in the world. They used what was available locally. More importantly, the buildings did not rely on heating and air-conditioning systems to provide comfort. Instead, the building's orientation, form and details created comfortable places to live and work. These historical examples evoke a spirit of place; also known as 'genus loci.'

In looking to nature for inspiration, one sees that it has no option but to be connected to place. Organisms don't just survive, but thrive if they are in the right place. While a cactus is resourceful of water and a great example of toughness in a harsh climate, if it is put in the Everglade swamps, it dies.

Some critics feel that a return to vernacular architecture is not appropriate in today's modern world and that designers should fully utilize technology. By looking at vernacular architecture I am not saying humanity needs to return to living in huts or in only historical styles, but there is a need to understand the principles of these early designs. One example is that designers actually have to be reminded that different facades require different exterior solar treatments. The heavy reliance on heating and air conditioning makes it apparent architects have forgotten the basic solar path as shown in Figure 6.

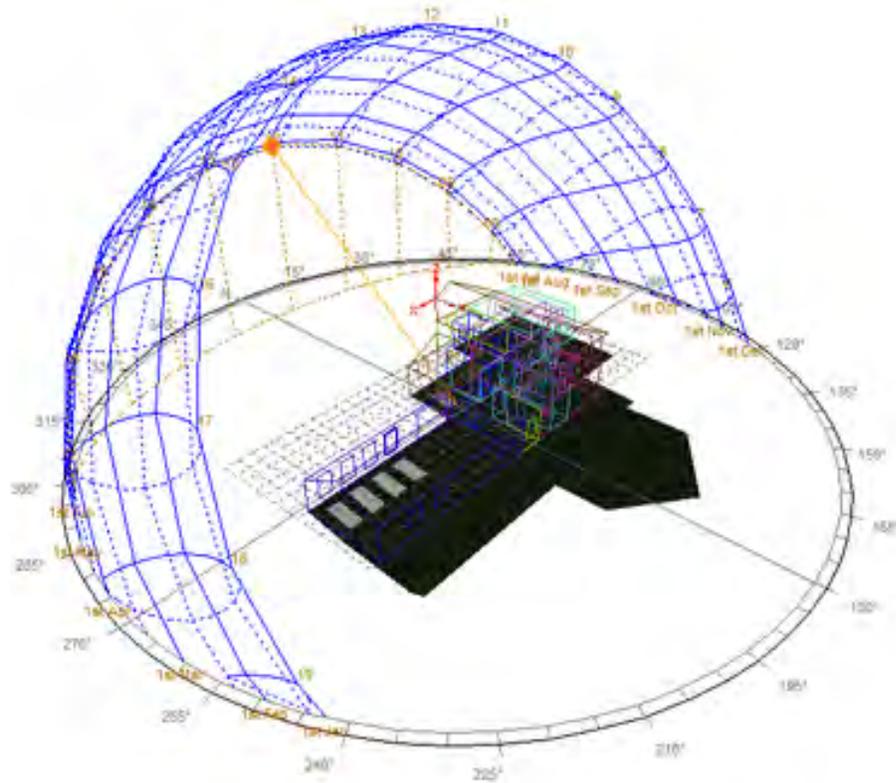


Figure 6. Sun-path diagram

It is no surprise where the sun will be everyday in relation to this planet. Nature's beautiful order gives us a known condition designers can accurately predict and utilize. Remembering and implementing simple, but often forgotten, principles not only make a building more efficient, but also more comfortable for the users. If the construction industry is to imitate nature, the understanding that buildings and people are connected to place may be the most important principle to understand. If architects solve the place issue, they can also solve the energy efficiency problem.

Furthermore, instead of just relying on technology to provide humanity's well being, science is showing us that our health and welfare are based on mankind's connection to the natural world. Perhaps this is most evident in

Edward O. Wilson's work in biophilia. 'Biophilic design is the deliberate attempt to translate an understanding of the inherent human affinity to affiliate with natural systems and processes—known as biophilia—into the design of the built environment' (Kellert, 2005, p.3).

Designers are applying biophilia to building design. Guy & Farmer (2001) offer a detailed biophilic approach, 'The eco-cultural logic draws inspiration from a phenomenological account of the environment and revives Heidegger's concept of dwelling with an emphasis on reinhabiting or relearning a sense of place' (p. 144). The Eco-cultural Logic gives architecture an environmental and cultural connection to the place in which it is designed for.

2.2 Envelope as skin

To connect to place, architects should start by making the interface of our buildings better suited to its environment. This interface occurs in a building's first line of defense to the environment, the building envelope, which includes the exterior walls, roof, and exterior openings. Interestingly enough, the building envelope is commonly referred to as "building skin."

In *Biophilic Design*, architect Stephen Kieran (2005) noted that, 'Skin is appropriate here for its biological reference. Skin acts as a filter, not an envelope, which selectively admits and rejects the environment based upon the needs of the body across time' (p.247).

skin focus? Why concentrate on skins? For one thing, this is where the action is on the building and as a relatively thin layer, it is constantly working to

protect the interior inhabitants. Additionally, the building skin is the typically the first impression people get about the design of a project. Even though it is a thin membrane covering the skeleton (structure), regulating the organs (mechanical, plumbing and electrical) defining the interior space, it, like a natural skin, plays a vital role. Figure 7 shows how indigenous people used animal skins to create their building skins; so the reference is steeped in tradition.

Modern buildings have the opportunity to employ technology and create new skins that further this tradition. Natural skins are good models for how building skins should behave. However, current envelopes are seen as barriers from the outside world, instead of filters like a natural skin.



Figure 7. A Prairie Camp

Akin to building skins, natural skins are an organism's first line of defense to protect its interior from the exterior environment. But, a natural skin can regulate temperature and humidity, is often waterproof, yet permeable when needed, integrates systems in a very thin membrane, protects from sunlight, can repair itself and is beautiful. Plus it does all this with environmentally friendly manufacturing, done at the local level and will not be harmful to the environment at the ends of its life. Can the same be said of building skins?

2.3 Problems with current skin design

Looking at how natural skins protect the interior from the exterior environment, architectural skins pale in comparison. What if our building envelopes interacted better with the outdoor environment? What if they could be manufactured in a way to use fewer components and actually integrate the building's systems into it? What if they required less energy to manufacture while using no harsh chemicals? Imagine a building envelope that was better suited for its local climate and could actually produce energy for the building. Our current building skins do not interact with nature and are harmful to the environment due to their manufacturing, installation and maintenance.

Besides energy inefficiency, another problem with current building skins is that they are constructed from multiple dissimilar components. Which creates too many opportunities for material failure and leads to condensation, thermal bridging and wasteful material use.

In an attempt to solve these potential failures, the envelope is designed as a closed, sealed system. This type of system causes the skin to act as a barrier to the exterior, not as a filter like natural skins do.

2.4 What should building skins do?

To make improvements in the building skin's efficiency and construction it is necessary to ask how should a sustainable building skin function? Searching for answers, I arrived at seven functions. These are as follows:

1. Protection from the natural elements.
2. Environmentally-friendly manufacturing.
3. Not be harmful to the natural environment at the end of its life.
4. Integrate multiple systems within thin membrane.
5. Regulate transfer of heat, air and water efficiently.
6. Be adaptable to its local environment and respond accordingly.
7. Be beautiful.

In order to meet these functions a building façade will be required to perform multiple tasks. Designers are focusing their efforts to meeting these challenges. The architectural firm KieranTimberlake is working on solutions that answer the question they asked: 'Can a façade system provide not only thermal resistance, but also a high degree of transparency?' (Gerfen, 2007, p. 75). Projects like their Loblolly House are advancing technology in innovative facades. Seeking examples that achieve the seven requirements above, I discovered that they are not often found in our high-tech building skins. However, examples can be found in natural skins.

3.0 Biology + Architecture

3.1 Why biology?

'If architecture is to please through imitation, it must imitate nature.' -- Laugier

These natural skins, whether on flora or fauna, in wet, dry, hot or cold climates, or above ground or under water, all have to be efficient in terms of energy to survive. The organism cannot afford to waste energy because of its skin. Dr. Petra Gruber (2008) is an architect and professor at the Vienna University of Technology and she expanded this idea: 'Organisms use what is available in their environment, concerning availability of energy source, material, cooperation etc.' (p. 111). Architects would be wise to learn how organisms do so. Gruber (2008) agreed: 'The study of the overlapping fields of biology and architecture shows innovative potential for architectural solutions. Approaches that have been taken to transfer nature's principles to architecture have provided successful developments' (p. 5). Furthermore, architect Frei Otto (1971) declared, 'Not only has biology become indispensable for building but building for biology' (p.12).

A strategy of this paper is to learn how indispensable biology is for buildings. And there are various strategies that can be utilized. Biomimicry, biomimetics, and bionic are used synonymously throughout the paper. And since they each have only a slight variation in their definition, it will not affect the strategy. However, it is necessary to define these terms.

Author Janine Benyus (1997) defined biomimicry as being from the Greek *bios*, *life*, and *mimesis*, *imitation*. And that 'Biomimicry is a new science that

studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems...' (Introduction).

The term Biomimetics is mainly used in England and according to Webster's dictionary (2010) it is defined as 'The study of formation, structure, or function of biologically produced substances and materials... and biological mechanisms and processes... especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones.' Julian Vincent is a professor of Biomimetics at the University of Bath in the U.K. and is a world-renowned expert in the field.

Germans are leaders in bio-based design and they typically use the term Bionik (or Bionic). For a simple definition, it is, 'The interdisciplinary field of bionics is about scrutinizing and transferring 'natural inventions' into technical applications' (Biokon, para. 2). It is derived from the word 'Bionics' derived from the Greek bios (life) and ikos (unit).

Those who work in these fields all stress that each one is a science that does not attempt to trace or copy, but should provide ideas for new designs that can improve current ones.

3.2 Reasons for architects to study biomimicry

To improve our current designs, architects need to begin looking to nature for ideas. 'Benyus believes that architecture and design on the critical, cutting edge of environmental sustainability. [Benyus says] 'When I look at where biomimicry could make the most impact, the built world is it' (Walstrom, 2006, p.10).

To solve the inefficiency and loss of place problems, designers need a new solution, not more of the same. Architects should remember the words of Albert Einstein, 'You can never solve a problem on the level on which it was created.' Simply revising current building technology will not get to the goal of creating a sustainable structure. The construction industry needs to look beyond itself and look to nature.

Why should designers interested in sustainable design look to nature for inspiration? One reason is that nature already has many solutions to our problems. For example, the leaves on every tree convert sunlight into energy better than any photovoltaic panel ever created. And it does so without harming the earth it is growing in. Also, nature works best in the region it is in which means it utilizes the appropriate systems for survival. Vernacular architecture was based on the concept of regional appropriateness and looking to nature for inspiration. Indigenous people knew the meaning of, 'Speak to the earth, and let it teach you;' (Job 12:8a, New American Standard Bible). And architects would do well to remember this in modern times.

Again, relearning a sense of place does not mean designers should abandon technology and live exactly like our ancestors in primitive huts. Embracing modern technology actually helps us to understand the natural world more than ever before. Scientists from various fields are learning how nature operates with the use of high-speed computers and precision microscopes. And what these scientists are seeing can be applied to solving human problems.

In fact, the Biomimicry Institute set up an online database of biological

information to aid designers in this endeavor called *AskNature*. It is described as 'a free, open source project, built by the community and for the community. Our goal is to connect innovative minds with life's best ideas, and in the process, inspire technologies that create conditions conducive to life' (Biomimicry Institute, para. 5). The amazing taxonomy created here provides a valuable resource for the construction industry to utilize.

why imitate nature? Before going further, it is important to ask why should architects look to nature for inspiration and imitate it? To imitate something means to hold it in high esteem. And it is crucial to see if what you are imitating is worth this esteem? The answer is connected to one's view of nature. Why do designers study and esteem the Anasazi ruins in the Chaco Canyon in New Mexico? Or why observers show respect to a Van Gogh painting in a museum by standing a certain distance from it? People don't necessarily respect everything found dug up or just any random painting. No, these items are held in high esteem because they were well designed and designed with purpose. They give us an insight into the designer's mind and their order and beauty surpasses any accidental occurrence.

Ancient civilizations, from the Aboriginals to the Greeks to the Celtic tribes to the Plains Indians, had a reverence for nature. They knew it was not chaotic, but that it had order and purpose. And it is not just thousand-year-old cultures; recent history shows that philosophers, scientists, writers and architects also held nature in high esteem. Heidegger's view of the natural world's "mysteriousness" has given rise to an environmental ethos of the conservation of the nature.

In the book *Biophilic Design*, Benyus (2005) explained her view on why architects should aspire to imitate nature, 'Like all good design, it [nature] never fails to inspire wonder, and, eventually, imitation. Everywhere we looked, we saw beautiful forms and systems – designs that made life possible' (p. 27). Nature has been the inspiration of designers for millennia, and our advanced knowledge of nature today continually reveals what British astrophysicist Paul Davies (1988) said: 'There is for me powerful evidence that there is something going on behind it all... It seems as though somebody has fine-tuned nature's numbers to make the Universe... The impression of design is overwhelming' (p.203).

3.3 Beyond Form

Establishing that nature is worth imitating, understanding its design means more than just copying its forms. Innovative architect Buckminster Fuller stated the direction designers should take, 'We do not seek to imitate nature, but rather to find the principles she uses.'

For architecture to connect to place and make significant strides towards energy conservation, it must move beyond what Kellert (2005) described as, 'The first basic dimension of biophilic design is an organic or naturalistic dimension, defined as shapes and forms in the built environment that directly, indirectly, or symbolically reflect the inherent human affinity for nature' (p.5).

To make a deeper impact, architects need to focus on another area Kellert (2005) defined as, 'The second basic dimension of biophilic design is a place-based or vernacular dimension, defined as buildings and landscapes that

connect to the culture and ecology of a locality or geographic area' (p.6). By working on this second dimension, architects can begin finding solutions that help in solving the loss of place problem.

Much harm is done in the architectural profession when forms are copied without understanding the principles that lead up to those forms. Of course it is interesting that the examples found in nature are beautiful. Their beauty is secondary though; the real beauty lies in their functionality.

It is not just other architectural forms that are copied, but there are many examples of nature's forms applied to buildings. Birds look the way they do because they are designed to fly, buildings do not fly. Fish have fins and are aerodynamic so that they can quickly move through water; buildings do not have to move through water at high speeds. Some buildings were created that looked like animals, but they do not actually function like the organism they are imitating. The natural form is usually just a shell for the standard functioning building. The book *Zoomorphic*, Aldersey-Williams (2003) showcases an exhibition by the same title that highlights the trend of buildings that look like animals. A few of these structures are shown in Figures 8 - 10.



Figure 8. Beached Houses by Michael Sorkin Studio



Figure 9. Vila Olimpica by Gehry Partner



Figure 10. Milwaukee Art Museum by Santiago Calatrava

Despite the fact that these examples are generally considered good architecture, they are imitating nature in form only. For biomimicry to be a truly successful methodology and have meaning in architecture, it needs to be applied to more than just forms. Author Peter Forbes (2005) noted that:

Julian Vincent, Professor of Biomimetics at Bath University, was scathing about what he sees as an often superficial appropriation of the outward forms of living structures without learning from the way that nature actually functions. At its worst, he says, the architect's approach comes down to: 'I'll say I got the structure from an animal. Everyone will buy one because of the romance of it.' (p. 230).

Buildings that follow this logic may look like nature, but unlike natural organisms, they are not necessarily connected to the region they were designed for. An eco-aesthetic logic is based on a romantic view of nature and results in iconic elements that give priority to form above performance and efficiency.

It is not just in the natural forms people can see with their naked eyes, but also what is seen on a smaller scale that is captivating. Images drawn by Ernst Haeckel, were made possible through improved microscopes in the mid-1800's. In looking at these images in Figures 11 and 12, it is easy to see why designers want their buildings to reflect the beauty they see in nature.

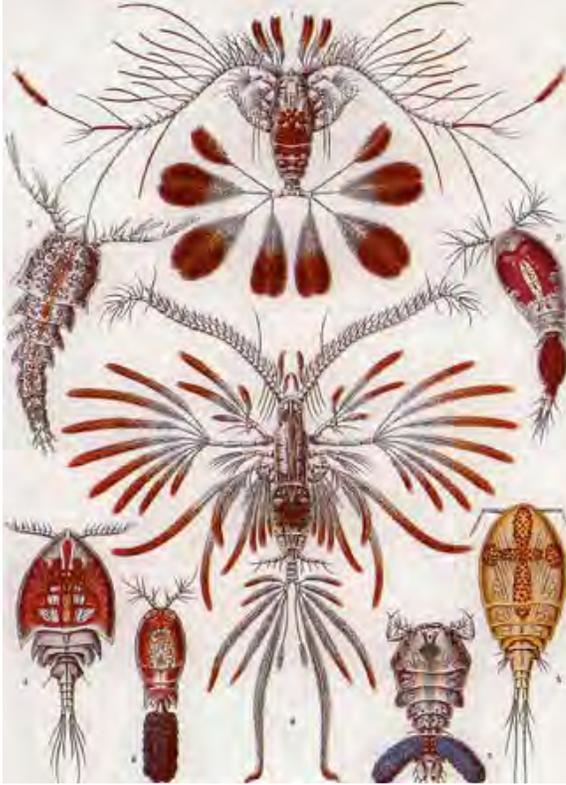


Figure 11. Small crustaceans
Drawing by Ernst Haeckel

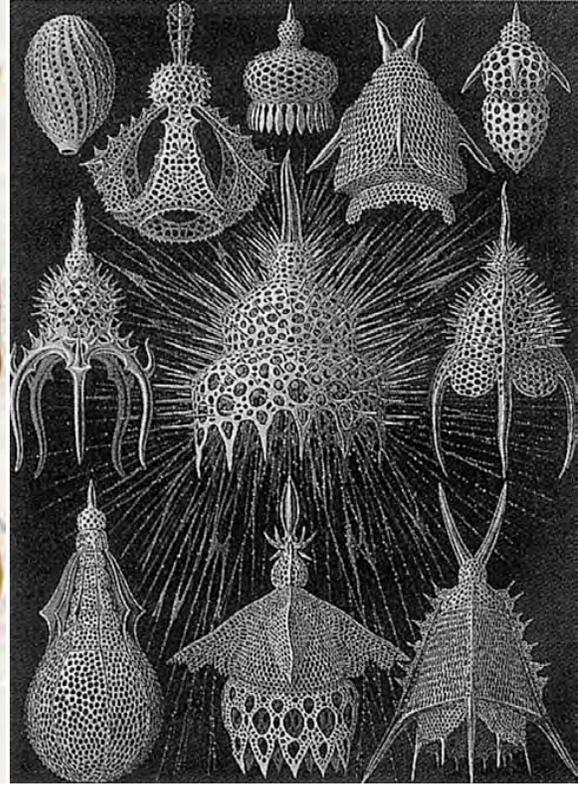


Figure 12. Cyrtoida
Drawing by Ernst Haeckel

However, it is more important to seek the principles behind natural forms. An example of a deeper method of finding form is illustrated here: 'Frei Otto coined the term 'Selbstbildung', the process of self-forming that underlies most of his experiments... This design method of form finding... is profoundly different from the still prevalent form definition' (Hensel, Menges & Weinstock, 2010, pp. 48, 49).

So to avoid looking at form only and understanding the principles of nature's skins, the challenge needs to be looked at more specifically. Which means that architects should first understand the common elements between building and natural skins.

3.4 Commonalities between building and natural skins

As an architect, I was able to analyze the basic elements of building skins, but needed to seek out the expertise of scientists to understand the common elements of natural skins. I created the diagrams in Figure 13 representing four basic functions of architectural skins to share with the scientists I interviewed.

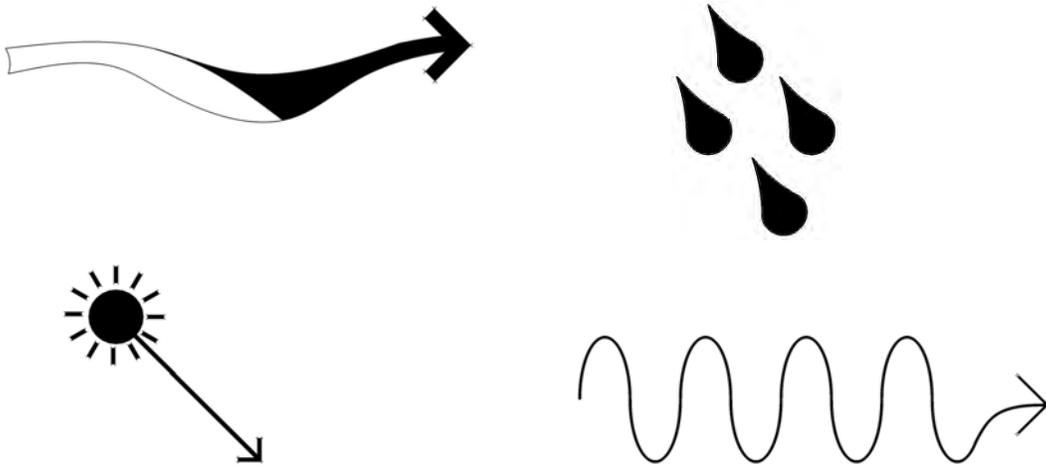


Figure 13. Clockwise: Regulate Transfer of Air, Regulate Transfer of Moisture, Regulate Transfer of Heat, and Regulate Exchange of Light.

Thanks to these scientists and the literature review, I was able to confirm that natural skins deal with the same four functions.

4.0 Advancements

4.1 Other industries utilizing biomimicry

Looking outside architecture helps us to find other sources of inspiration and also learn from how they are applying biomimicry within their industry. KieranTimberlake (2004), like Le Corbusier, were inspired by what other industries are doing as evident in their statement,

Relatively few of these materials have yet made their way into architecture, but many are now used in other industries... We must overcome an industry wide aversion to research and experimentation in order to speed the integration of these new materials into architect (p. 23).

second skin. Many industries (i.e. automobile, aeronautical) are seeking solutions deeper than just form. One is most closely related to this study on skins, the clothing industry. Clothing is often referred to as our 'second skin', with our natural skin being the first. The clothing industry provides architects with applications that achieve what building skins also attempt to achieve. Clothing must protect us from the elements, is capable of thermoregulation, and should be comfortable for its user. It must integrate these 'systems' in a thin membrane efficiently.

A new clothing product called Stomatex derives its inspiration from nature. The company stated that their fabric 'replicates the way that the leaves of plants transpire' (Stomatex, para. 1). Stomata is a pore that plants utilize for exchange of gases through its epidermis or skin.

The researchers at Stomatex were inspired by how plants' skins are

designed to be weatherproof and yet highly breathable. They did not simply create a textile that looked like a leaf, but took it further and actually studied the principles of this system and eventually applied it to create a new clothing line shown in Figures 14 and 15.



Figure 14. Stomatex Clothing

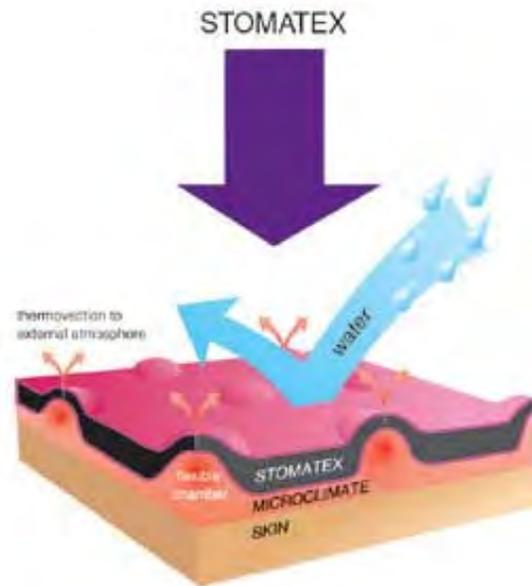


Figure 15. Stomatex Diagram

While looking at the automobile, shipping or aeronautical industries bring designers many good solutions, looking even further outside man-made technology will provide even more solutions. Nature has been the inspiration for designers for millennia, and with our advanced knowledge of nature today, like other industries, it is time architects return to this source of inspiration to solve our challenges.

4.2 Architects inspired by nature

With other industries like clothing already applying biomimicry to the 'second skin', I researched what the architectural industry is doing to advance the building envelope, or 'third skin.' On the surface, it appears, very little. Yet, upon further inspection, architects have been, and currently are, being inspired by nature. 'Researchers and scholars, who have used biological role models for their work, can be found very early in history' (Gruber, 2008, p. 22).

historical. The quintessential Renaissance Man, Leonardo Da Vinci said, 'Those who are inspired by a model other than Nature, a mistress above all masters, are laboring in vain.' Many of his designs, manned flight for example, drew inspiration from nature. Additionally, the 19th century architect Antonio Gaudi studied the structural forces in natural structures. Looking at his projects, like the one in Figure 16, it is easy to see that Gaudí was inspired by what he discovered in nature.



Figure 16. Detail of Gaudí's Sagrada Família.

Moving from the sculptural Spanish designs of Gaudi in the 1800s, the United States in the 1950s saw a more engineering-based approach to bio-inspired design. 'There is another approach to structures which has strong roots in nature: it began with Buckminster Fuller. His geodesic domes, created from complex webs of triangular or hexagonal and pentagonal units, have found many echoes in natural structures' (Forbes, 2005, p. 216). Richard Buckminster Fuller was an American engineer, author, inventor and futurist and is best known for his geodesic domes seen in Figure 17.



Figure 17. Buckminster Fuller's patented geodesic dome.

This modern approach towards bio-inspired architecture continued in 1960s Germany. Gruber (2008) explains the importance of the German architect Frei Otto by saying that, 'The structural functioning of natural role models is the most important feature investigated. The so-called "Sonderforschungsbereich

230 Biologie und Bauen", which was the frame for many efforts, partly laid the base for the active bionics community in Germany today' (p. 56). Otto and his biological research unit drew inspiration from soap bubbles and plant cells along with other natural forms seen in Figure 18. But he looked deeper than just the forms themselves. Gruber (2008) described this approach, 'Frei Otto's group used an experimental approach aiming at the understanding of the natural structures and processes, and finally making use of the physical laws, which were discovered, to design new structures...' (p. 58).

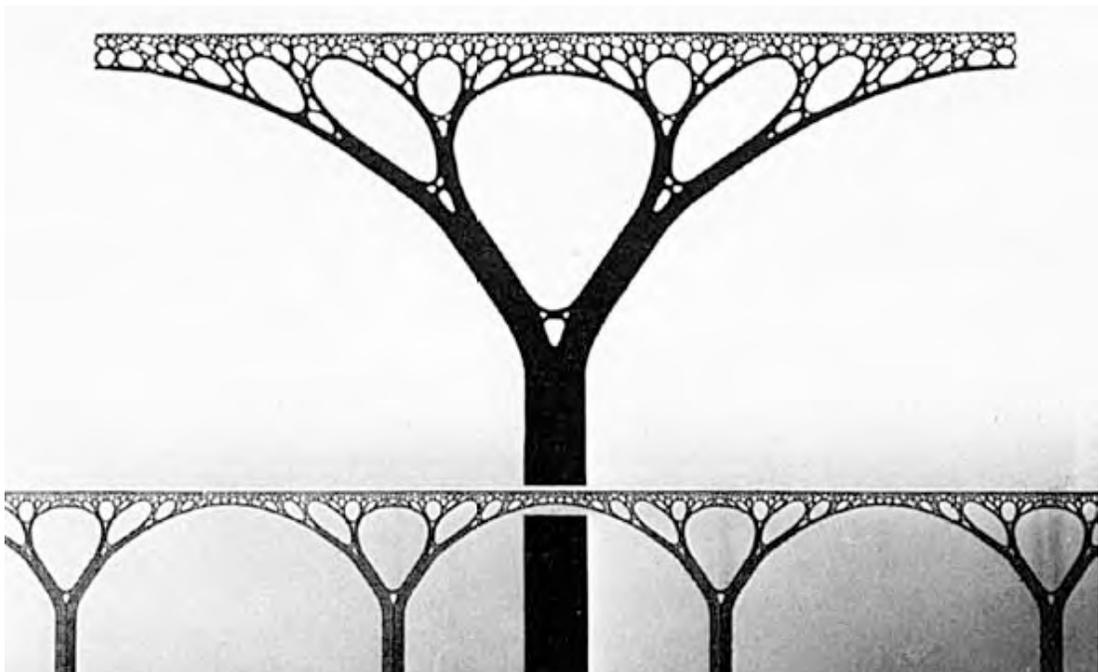


Figure 18. Frei Otto's soap film models

To conclude, 'In biology, Otto found a fertile field of research for seeking resistant and rational structure' (Lee, n.d., p. 5). If innovative historical designers like Leonardo da Vinci, Antonio Gaudi, Buckminster Fuller, and Frei Otto looked to nature for inspiration shouldn't today's architects do the same?

contemporary. Research reveals there are some currently following in the footsteps of those who used nature for inspiration. One such innovator is Cecil Balmond. ‘Over the past decade, Balmond - designer, musician, university teacher and author as well as engineer - has been working with some of the world's most daring architects to create radical new buildings’ (Glancey, 2007, para. 3). Many of today’s cutting-edge buildings were only possible through Balmond’s ingenuity. His designs, as shown in Figure 19, utilize higher geometry as well as his analysis of biology’s principles.



Figure 19. Seattle Public Library - Cecil Balmond & Rem Koolhaas.

Nature’s influence is expressed by Balmond’s statement, ‘... that architecture is very interested in biology, it always has been. Biology is intricate at many levels: it’s highly structural, highly dynamic and has all sorts of

architectures in it. Nature has always been the paradigm for architecture.’
(Abruzzo, Ellingsen, & Solomon, 2007, p. xlv).

Another engineer, Santiago Calatrava, uses nature to inspire forms for his designs as seen in Figure 20. Calatrava is also an architect and artist who is ‘Following the tradition of civil engineering of Nervi, Candela and others, Calatrava's main works are bridges, buildings for traffic, which unite ventured constructions with distinct architectonic forms.’ (Gruber, 2008, p. 74).

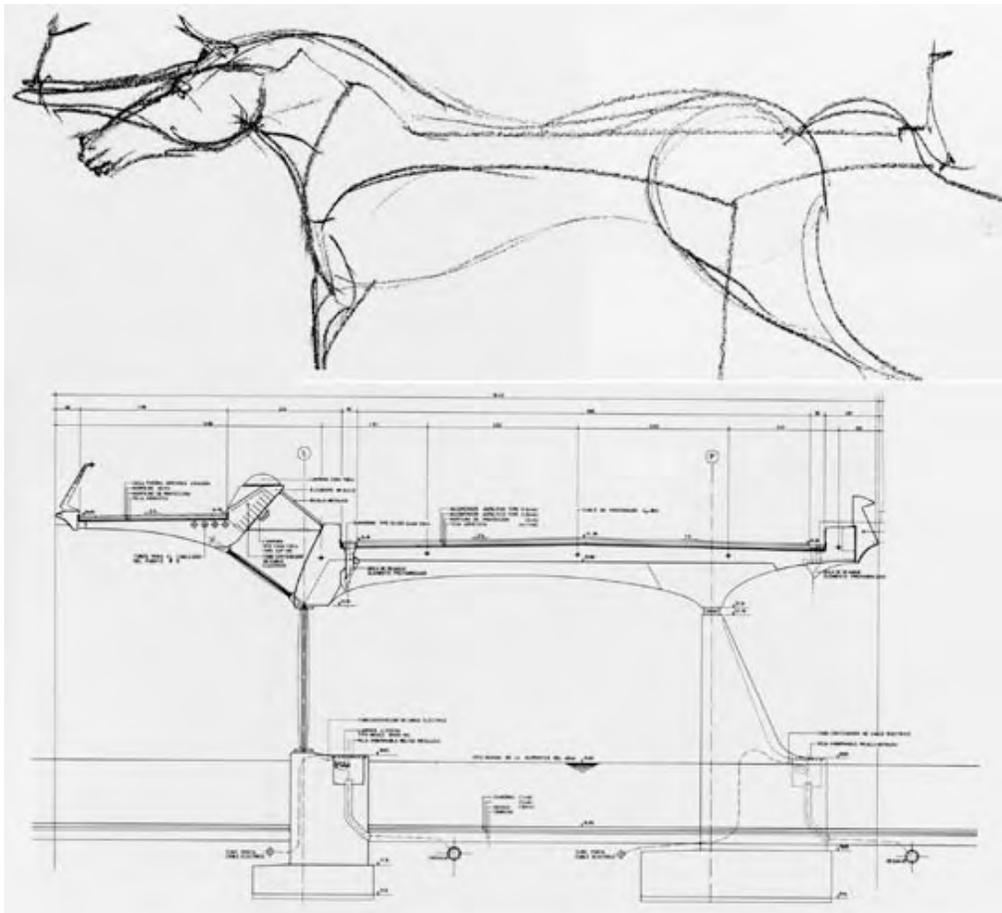


Figure 20. Sketch for the Bridge of 9th of October

However, he does not go deeper like Otto did to understand natural principles as Gruber (2008) highlighted: ‘Movement and locomotion as an interesting aspect of Calatrava's work is mostly expressed only through form’ (p. 74).

A unique contemporary architect that does explore these principles is Dennis Dollens. Dollens, an architect, uses what is described as 'biodigital, which takes biological principles, translates them into computer algorithms, and then uses these algorithms as a basis for generating architectural forms' (Brennen, 2010, para. 3). Dollens has written a paper entitled *Digital Botanic Architecture II* (2009) where he illustrated: 'This series of experiments with simulated digital trees, hybridized into architectural elements, illustrates botanic forms and their morphological and mathematical attributes applied to design systems and structures' (p.5). An example is shown in Figure 21.

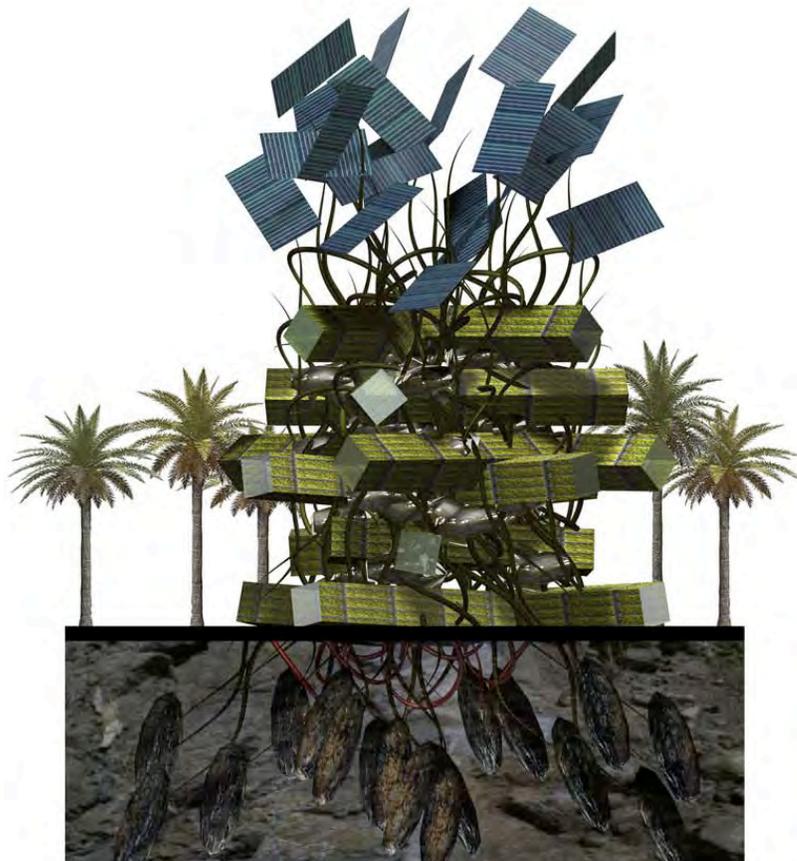


Figure 21. ArizonaTower

This is not an extensive list, but is meant to show that there is an interest in biology in contemporary architecture and engineering.

4.3 Advances in building facades

Finding that other industries and architects are being inspired by nature, I explored what advancements are being made in building skins.

integrating systems. One such advancement is to integrate various systems in a building skin. A firm that is working on systems integration is Philadelphia based KieranTimberlake. This innovative architectural firm has been focusing on high-performance exterior skins, like SmartWrap™. 'It proposes to replace the conventional "bulky" wall with a composite of millimeter scale that integrates climate control, power, lighting, and information display on a single substrate' (KieranTimberlake, 2011, para. 1). Their thin façade provides shelter and climate control as a membrane. By printing solar panels and electronic circuitry on this membrane (Figure 22), it is able to provide lighting, information display and power.



Figure 22. KieranTimberlake's SmartWrap™

Products that integrate systems into thin exterior membranes like SmartWrap™ create building skins that start to behave more like thin, integrated natural skins. And this is a truly exciting frontier for the architectural industry because it is responsible to the environment by minimizing material use and adds to the continuum of technology in the building façade.

responsive building skin. Making building facades behave even more like natural skins is to have them respond and interact with the exterior and interior environments. Skins of local flora and fauna are constantly responding to regulate temperature, humidity, gas exchange and daylight.

For too long our building skins have been seen as inanimate and static barriers between man and the outdoor environment. With new technologies, however, our building skins now have the opportunity to do be dynamic and engaging with the outdoor environment. Chris Wilkinson, of London-based WilkinsonEyre.Architects, (2005) is working on such structures and believes that, 'Buildings should be designed to be more responsive to the environment and to interact with their occupants' (p.1). If a building, like theirs shown in Figure 23, is more in tune with its environment and responds to its temperature, humidity and light, then it also becomes efficient in real-time as opposed to a preprogrammed setting.



Figure 23. Anglia Ruskin University Ashcroft International Business School

phase change. Individual materials also are being used that can respond to environmental factors improving thermal performance. One such technology is known as,

Phase Change Materials (PCMs) ... are "latent" energy storage materials. They use chemical bonds to store and release heat. The thermal energy transfer occurs when a material changes from a solid to a liquid, or from a liquid to a solid. This is called a change in state, or "phase" (Anmol, 2011, para. 1).

A product utilizing PCMs is GlassX. The glazing system by Greenlite Glass Systems is developed in Switzerland. 'The GlassX glazing system incorporates a salt-hydrate phase change material that stores energy from the exterior temperature and reuses it to either heat or cool the building as needed, putting less pressure on the mechanical HVAC system' (Orrell, 2010, p. 55).

self-healing. One more product that changes and acts like a natural system is classified as a self-healing material. BacillaFilla was created by ‘A team of Newcastle University (U.K.) students recently unveiled a proposal for a self-healing concrete powered by bacteria... the students developed a genetically modified microbe designed to reconstruct cracks that form in concrete.’ When a crack forms in the concrete bacteria goes to it and creates a mixture of calcium carbonate and microbial glue that repairs the concrete. ‘This biological patch ultimately cures to the same strength as the surrounding material’ (Brownell, 2011, p. 90).

bio-based. Biological based design is taken even further in the advancement of entire facades that behave like biological organisms. One such design (Figure 24) is expressed as, ‘An evaporative cooling system (Stoma Brick – SB) for building envelopes... was designed based on principles... of several natural systems. These include stoma of a plant... and human skin’ (Badarnah, Farchi & Knaack., 2010, p. 258). The function of this wall is similar to the Stomatex clothing product.

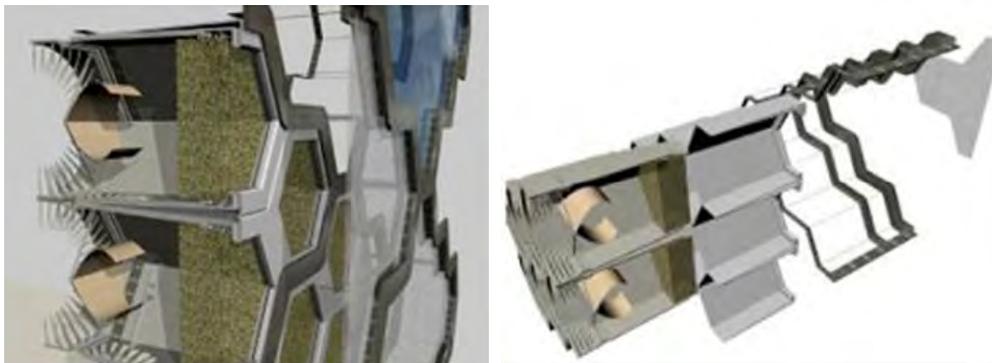


Figure 24. Stoma brick

vegetative facades. Another advancement in architectural skins is not just emulating, but literally utilizing the stomata in plants through the use of vegetative facades. These are façade that have plants growing on the exterior and take a variety of forms, from ivy growing up a trellis to placing a growing medium directly on the exterior where the plants can grow. One such façade was placed on The Musee de Quai Branly shown in Figure 25.



Figure 25. The Musee de Quai Branly exterior wall

Irrigation of these vegetative walls is crucial, ‘Patrick Blanc... put plants in pockets in a felt curtain, and irrigates through hydroponics. The felt holds a substantial amount of water, which allows the roots to remain constantly moist’ (Miflin, 2009, pp. 17-18).

4.4 Algorithmic Software for design technique

While these advancements in building skins show innovation in materials that attempt to solve environmental issues, they can be taken further by designing an entire skin that actually behaves more like natural skins.

Natural systems rely on sophisticated feedback systems for survival and growth. These systems can adapt to the environment and are dependent on a variety of functions. To better model building skin based on these changing natural organisms, parametric and algorithmic software will be needed. Such software will develop the skin based on the local environment therefore making the façade more efficient and appropriate to place. Designers will need to be able to compute the form and function in order to show what D'Arcy Thompson (1961) said, 'The form of living things is a diagram of the forces that have acted on them' (p.16). Fortunately, there are current computer software programs that will allow designers to explore biomimetic solutions to their problems. Both academics and professionals are advancing their designs with the use of these programs.

academics. Many of the advances of this software can be seen in academic programs. Two such schools are the Architectural Association (AA) and the Bartlett School of Architecture, both in London. To clarify, the quotes from these schools below have not been altered from their original spelling.

Dr. Marcos Cruz is the Director of the Bartlett School of Architecture, Director and he explained his work this way: 'Through the analysis and design of a variety of projects, I propose Flesh as a concept that extends the meaning of skin, one of architecture's most fundamental metaphors' (Bartlett, 2008, para.3).

To analyze and design architecture based on a soft tissue like flesh (Figure 26) requires unique software. It was difficult to find what software Dr. Cruz uses, but a search on the Bartlett website states that he uses Realflow and Blender which are both fluid dynamics simulation software packages. They also list Microstation, AutoCad mechanical desktop and FormZ on the Bartlett website under Digital Media. In one of their workshops they used neural network software called Neuro-Solutions.



Figure 26. Marcos Cruz's rendering of architecture as Flesh

Like the Bartlett, the AA is also employing sophisticated software. Three professors have written extensively on their work at the AA in the Emergent Technologies Program. Michael Hensel is an architect, researcher, writer and professor whose PhD thesis focuses on establishing the theoretical framework for 'Performance-oriented Design: A Biological Paradigm for Architectural Design and Sustainability', which he pursues at the Centre of Biomimetics at the University of Reading.' Achim Menges is a professor and an architect whose

institute is part of the German Competence Network for Biomimetics.’ Michael Weinstock is also an architect and professor. ‘His personal research interests lie in exploring the convergence of emergence, natural systems, evolution, computation and material sciences...’ (Hensel et al., 2010, pp. 251-253).

In their book, *Emergent Technologies and Design* (2010), these professors described how the program at the AA ‘utilises computation to recognise and exploit the material system’s *behaviour* rather than merely focusing on its *shape*’ (p.48). This process follows what Fuller and Otto emphasized in their form finding research. Unlike these two great architects, the teaching at the AA utilizes cutting-edge software. Hensel et al. (2010) emphasized the important role that computer software simulations play in these biomimetic models by stating that,

Simulations are essential for designing complex material systems, and for analysing their behaviour over extended periods of time. Once strictly within the domain of engineering practice, they now can and should be used as part of the generative design processes. (p.19).

Hensel et al. (2010) go on to explain how form is achieved through the software, ‘In computational design form is not defined through a sequence of drawing or modelling procedures but generated through algorithmic, rule-based processes’ (p.51).



Figure 27. Biomimetic Study from the AA

Figure 27 reflects the biological forms that can be generated through their work. AAs Biodynamics and Active Systems is a ‘...course [that] examines the ways in which biological organisms achieve complex ‘emergent’ structures and performances from simple components, relating this to an exploration of current architectural and industrial component design, prototyping and production’ (AA Natural Systems, 2010, para. 1).

Work being done at the AA begin with a study of natural organisms before moving on to techniques generated through a digital growth process. Hensel et al. (2010) explained how form is generated, ‘... the organism has a capacity for maintaining its continuity and integrity by changing aspects of its behaviour. The form of an organism affects its behaviour in the environment, and a particular behaviour will produce different results in different environments...’ (p. 13). An example of this analysis is shown in Figure 28.

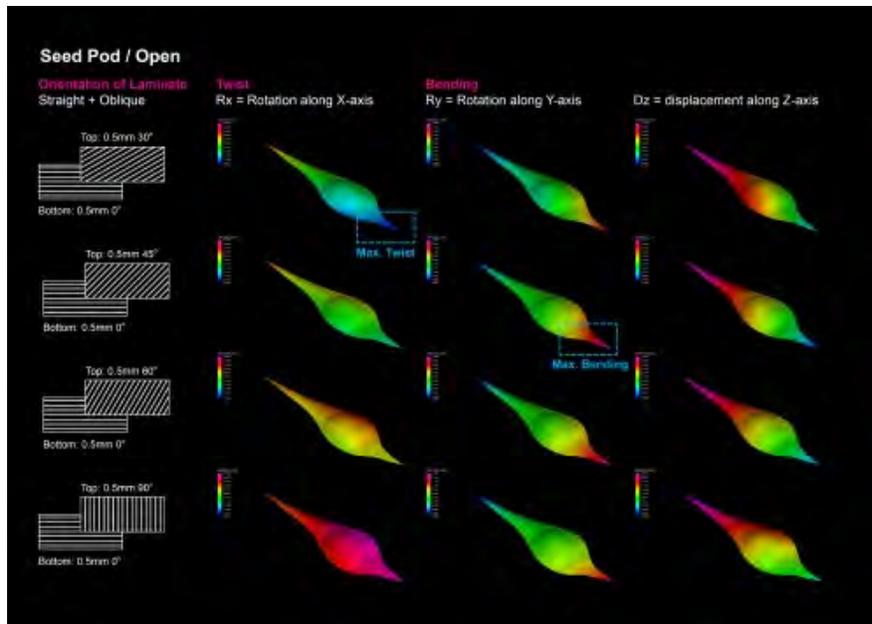


Figure 28. Example of Biodynamics and Active Systems at the AA.

The AA primarily uses two software programs for their analysis, GenerativeComponents and Grasshopper. GenerativeComponents (GC) is from Bentley and is an extension of the MicroStation program. According to Bentley, ‘GenerativeComponents is an associative parametric modeling system used by architects and engineers to automate design processes and accelerate design iterations’ (Bentley, 2011, para. 1). Grasshopper is an add-on through Rhino software and is portrayed as being for, ‘... designers who are exploring new shapes using generative algorithms, Grasshopper® is a graphical algorithm editor tightly integrated with Rhino’s 3-D modeling tools’ (Davidson, 2011, para. 1).

AA explained how Grasshopper is integrated into studio work, specifically, ‘Core Studio I will be supported throughout with weekly sessions on associative modelling in Grasshopper/Rhino, ... for modeling and controlling growth processes’ (AA Core 1, 2010, para. 1). And that they use GC in the

following manner: 'Parametric modelling, developed using Generative Components software, underlined the entire design process... The associate modelling software enabled a significant level of control over an intensely complex structure through a hierarchical build-up of parametric relationships...' (AA Membrane Canopy, 2007, para. 6).

Projects like these at the AA require unique software that is not like other 3D solid modeling programs on the market. The uniqueness of GC is that:

In contrast, building information modeling (BIM) is designed to help users with the predictable requirements of building design... GC can be a valuable addition to the BIM model because it can address the part of the design that is not anticipated or hard wired into the system. (Smith, 2007, para. 9).

The list of academic programs working with GC continues to grow because of this differentiation from other software. Professional architecture firms are also taking advantage of these new unique software programs like GC.

professional. One such firm is Skidmore, Owings & Merrill (SOM) in Chicago. SOM, in collaboration with the Center for Architecture Science and Ecology (CASE), won an *Architect* magazine 2009 R+D Award for its Active Phytoremediation Wall System. The online article by Katie Gerfen (2009) described it as '... a modular wall system of pods housing hydroponic plants. [SOM and CASE]...created a new prototype that would work with a building's existing HVAC system to reduce energy loads and improve indoor air quality' (p. 48). Their innovative wall system is shown in Figure 29.

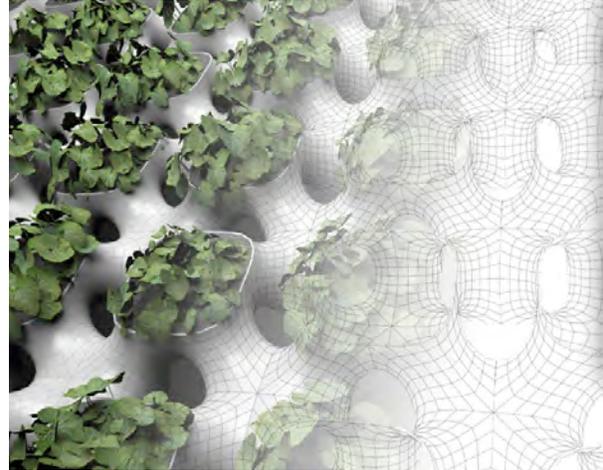
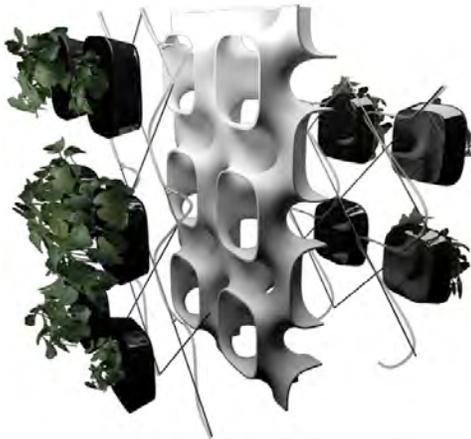


Figure 29. Active Phytoremediation Wall

Designing this new wall required looking at how nature would reduce energy loads and purify the air, using innovative computer programs. And in researching more about CASE, it was apparent they were integral in the software design side because of their expertise in cutting-edge software seen in Figure 30.

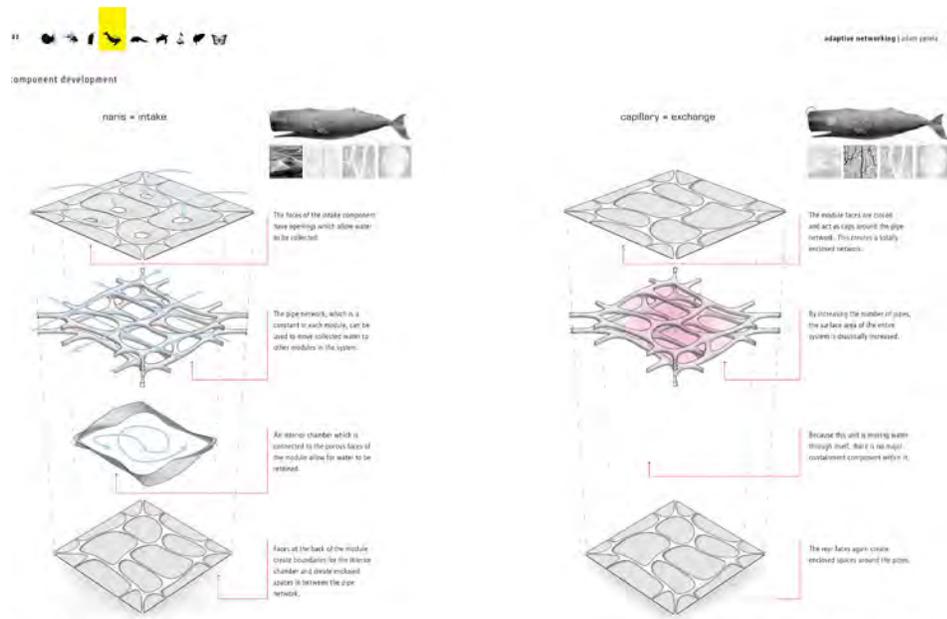


Figure 30. Ted Ngai Illustrative Example

Their work is described as, ‘...addressing the need for accelerated innovation of radically new sustainable built environments through the development of next-generation building systems’ (CASE, 2008, para. 1). And one of the key

individuals at CASE working with parametric modeling is Ted Ngai. Ngai is a Clinical Assistant Professor in the Department of Architecture at Rensselaer Polytechnic Institute. He is also the founder of atelier nGai, which is ‘... an experimental design and research studio specializing in exploring new aesthetics and environmental possibilities through co-evolving design processes with scientific first principles and new technologies in design computation...’ (Pinupspace, 2009, para. 1). Similar to work at the AA, CASE uses new technologies like Grasshopper shown in their project in Figure 31.

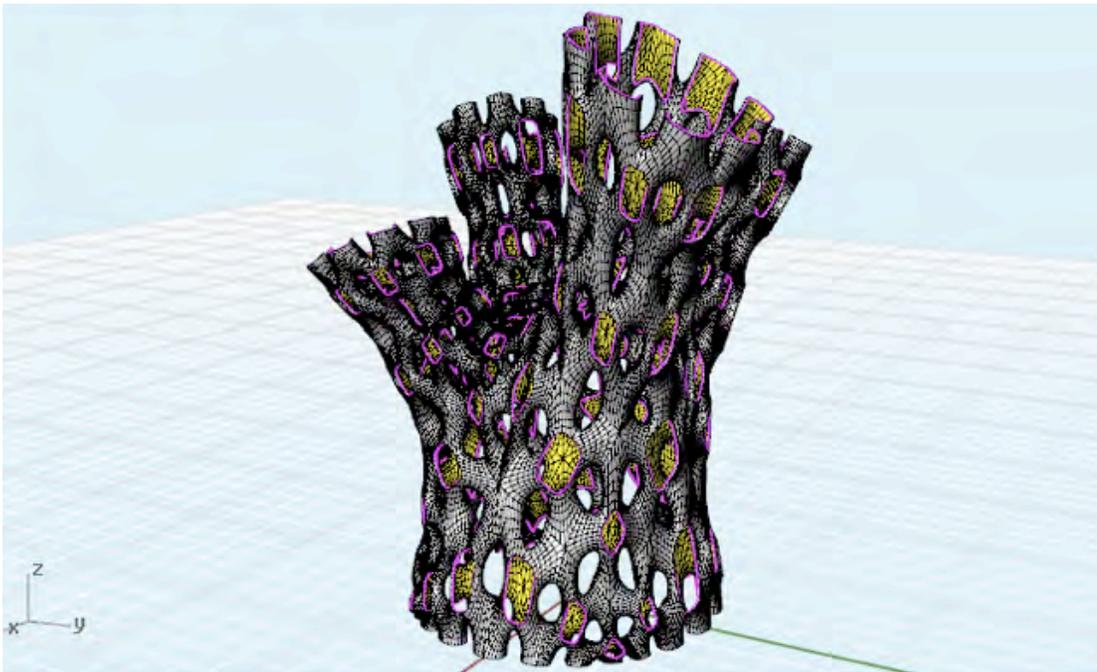


Figure 31. Ted Ngai work in Grasshopper

Another professional using sophisticated software is Dennis Dollens. His projects like the ones in Figure 32 were generated in Xfrog, edited in Rhino, and rendered in 3DS Max.



Figure 32. Dennis Dollens Digital Botanic Architecture

Dollens (2009) uses algorithmic modeling of biological systems and described his work as follows, 'This series of experiments with simulated digital trees, hybridized into architectural elements, illustrates botanic forms and their morphological and mathematical attributes applied to design systems and structures' (p.3). He digitally grows the structures with a program typically used in landscape architecture called Xfrog. Fifteen years in development, the program animates plant growth, which Dollens applies to his building designs to predict how they can grow. Predicting the growth of a building, generating forms based on natural systems and creating architecture that acts like flesh are only possible through these new algorithmic software programs.

5.0 Tree Bark Study

5.1 Tree as Metaphor

In addition to the need for new software, in order to solve the problems of building skin inefficiency and loss of place, architecture is in need of a new metaphor. Mankind communicates and learns through metaphors and is often used in architecture. The influential modernist architect Le Corbusier applied the machine as his metaphor in the 1930's. However, to solve today's problems and design in a manner more appropriate to nature, a new metaphor is needed. Benyus (1997) agreed, 'To emulate nature, our first challenge is to describe her in her terms. The day the metaphors start flowing the right way, I think the machine-based models will begin to lose their grip' (p. 237). The right way is to define a new metaphor that is rooted in place and is efficient with its resources. For a new biomimetic building skin, I propose using a tree as a new metaphor.

Why use a tree? Trees provide shelter for many organisms seeking protection from the natural elements and they are literally rooted in place. In researching trees, I discovered that they:

- are adapted to their local climate
- sequester carbon and produce oxygen
- use only the water they need
- efficiently convert sunlight into energy
- produce waste that is beneficial to the ecosystem
- are beautiful structures.

Trees are able to achieve all of this in an environmentally friendly manner. Imagine a building capable of doing the same and functioning like the list compiled above and being as beautiful as the tree in Figure 33.

Instead of just abandoning the metaphors designers learned to look into, perhaps it is a combining of metaphors that will be a useful transition. After all, the more people discover how nature works, the more it appears to be machine-like. But it is a 'machine' that does not harm the environment it is working in.



Figure 33. Cedar Elm

5.2 Tree Skin = Bark

So using the tree as a metaphor, this study on skin needs to explore how the skin of a tree operates. What is the 'skin' of a tree? While there are multiple layers to a tree's 'skin', for simplicity's sake, it is known as bark. Tree bark serves a variety of functions (details in section 5.3) but it also serves as a way to identify the individual tree species and even its location.

Other natural skins could have been used for research. I explored the skin of humans, reptiles, amphibians and birds as models for building skins. However, each of these organisms need shelter, because their skin is not sufficient enough to deal with the natural elements. Man seeking protection from the harsh outdoor elements motivated the need for buildings in the first place. Without protection, human skin will get burns from prolonged exposure to the sun or freezing temperatures.

Snakes, frogs, birds, and bears simply do not have enough protection in their skin alone to survive constant exposure to the elements. They seek additional protection by hiding in structures or moving into a shady or sunny spot. Our buildings are the protection and do not have the option of moving away from the elements. A building skin must be able to withstand extreme temperature and moisture conditions while remaining in the same location every day, all year around.

Therefore, I developed the research around a natural organism's skin that was able to protect its interior from the elements while remaining in place: a tree.

5.3 Purpose of tree bark

With the tree as an organism selected to model, it is important to better understand its skin, bark. Since the problems outlined in this thesis paper dealt with building skins, I limited the scope to the tree's skin, its bark. I understand that tree bark growth relies on the root and leaf system of the tree, but to better explain a thorough analysis of the biomimicry methodology, I focused the work here to one specific system of a tree. In looking at tree bark for inspiration, architects need to examine strategies for our building skins.

Seeking to understand the purpose of tree bark, the question arises: Why do trees have bark? 'Bark serves as a waterproof overcoat for the tree, helps prevent loss of water from the tree by evaporation... insulates the tree from drastic temperature changes, and in some instances, protects the tree from fire damage' (Hiller, 1983, pp. 82-85).

In his book on tree bark, Vaucher (2003) also explained the significance of bark to the tree in that, '...it protects it from external threats... Because of the protection that bark affords, rain, snow, and hail (not to mention heat, frost and ultraviolet rays) cannot reach and damage the soft and vulnerable vascular cambium' (p.24). As well as protection, Vaucher (2003) outlined that,

...bark has at least two supplementary functions. It serves as a dumping ground in which the tree can rid itself of waste products... by depositing them in zones that are about to die. On the other hand, large quantities of nutritious substances are transported with the living tissues (phloem) of the bark. (p.24).

Protection from elements, insulation, fire protection, water protection with permeability, plus ability to store waste and transport nutrients seems like a description of a successful building façade. The drawings in Figure 34 even look like bricks on a building façade. Yet typical building façades are comprised of multiple elements that are harmful to the environment to manufacture, install and maintain.

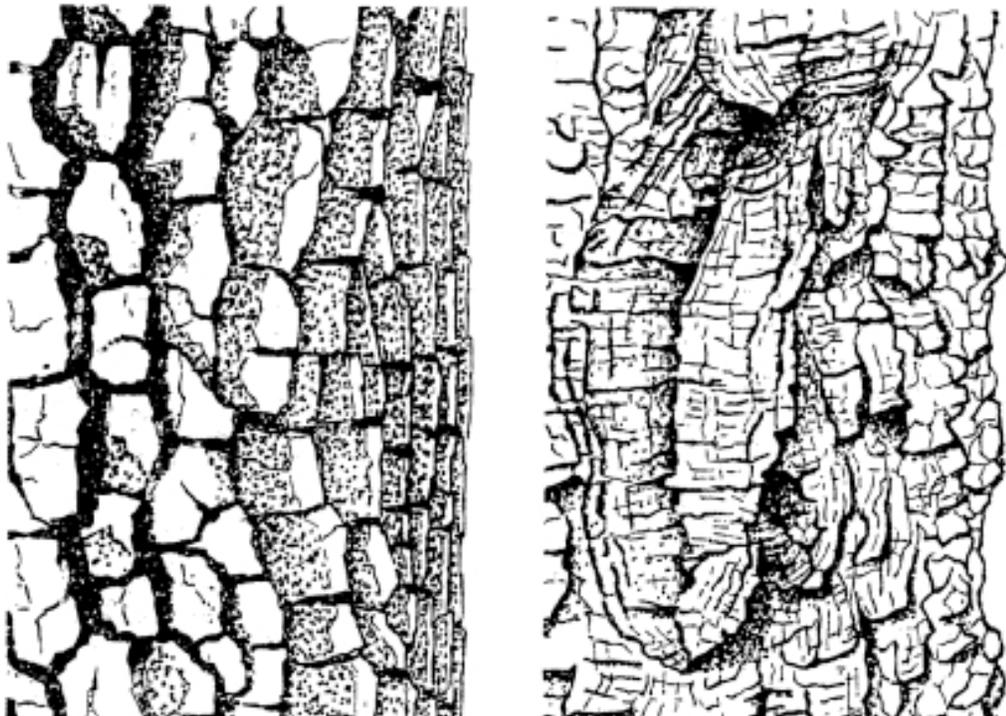


Figure 34. Images of fissure and corky bark

5.4 Bark's Appearance, Anatomy and Physiology

To better understand how building facades can operate more like these functions of tree bark, it was necessary to learn from those outside the construction industry. Therefore, I studied the appearance, structure (anatomy) and function (physiology) of tree bark with the assistance of scientists. I created drawings like the one shown in Figure 35 to bring to these interviews.

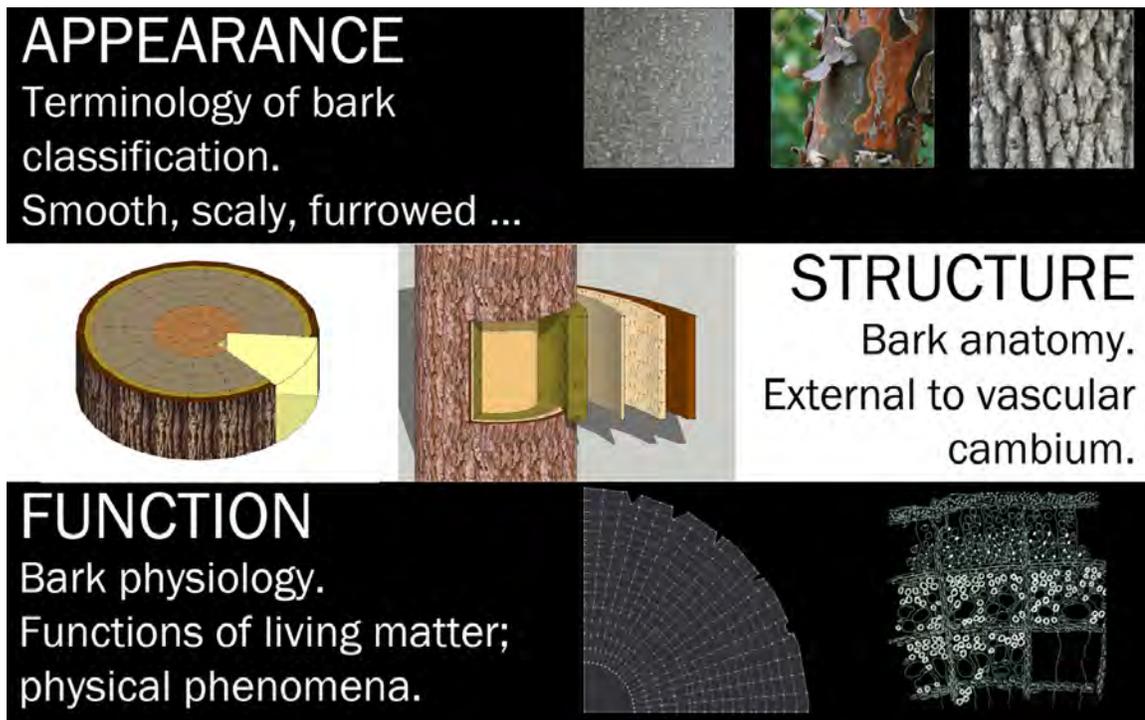


Figure 35. Summary sheet of bark's appearance, structure and function.

appearance. Trees are often identified by the distinguishing characteristics of their bark, especially in wintertime for deciduous species. However, just thinking this bark serves only an aesthetic purpose is incorrect. Like building skins, they serve multiple tasks and their bark comes in a wide array of beautiful patterns. The five basic textures of bark: smooth, peeling, flaky, furrowed and rough could be applied to building skin descriptions.

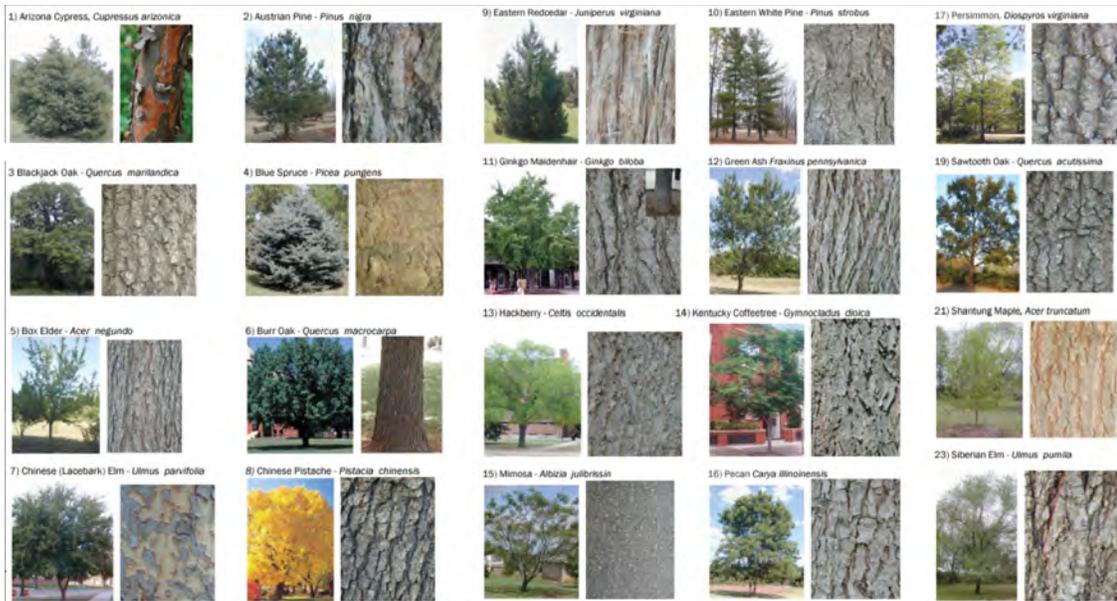


Figure 36. Study of variety of trees in central Oklahoma

Obviously not all tree bark is the same as shown in even the small sampling of trees I studied in central Oklahoma (Figure 36). Their texture, pattern, and color are widely varied, as building skins try to be. Yet these distinguishing characteristics don't just have an aesthetic purpose, they are a result of the unique conditions of site. The growth of the trunk transforms bark, and, 'This alteration is conditioned by the internal state and age of the tree itself, the composition and quality of the soil, the moisture regime, the climate, the amount of sunshine, the geographical site and elevation, the local environment...' Additional insight: 'Furthermore, bark is exposed to external factors from the onset of its formation... such that its appearance changes constantly as a result of wear and tear' (Vaucher, 2003, pp. 13, 23). Imagine a building skin's appearance being dependent upon its site and the constant changes of its exposure to the elements in a positive rather than destructive manner.

structure. In seeking to understand how tree bark's appearance is influenced by its surroundings, the next step is to analyze its structure, also known as anatomy. Raven, Evert & Curtis (1981) explained that 'bark refers to all the tissue outside of the vascular cambium and is a nontechnical term' (p. 587). Ghosh (2006) gave an additional description, "Bark refers to the dead tissues wrapping the stem. From the botanical point of view, bark demarcates all tissues external to vascular cambium..." (p.41). In Figure 37 I compared this demarcation of bark's structure to a building skin's structure for analysis purposes.

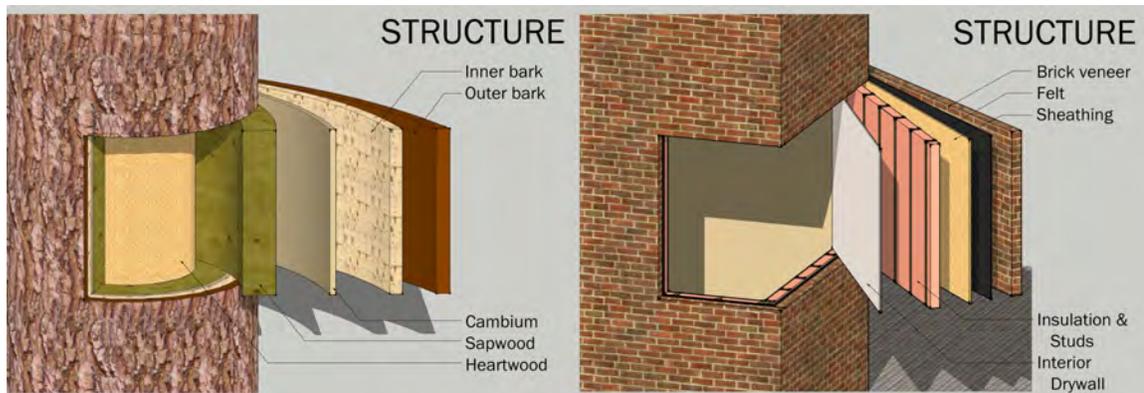


Figure 37. Comparison of natural system (left) and technological system (right).

Bark is further broken down into inner and outer bark. Without going into all of the descriptions of the layers that actually comprise a tree's skin, it is helpful to clarify some technical terms. According to botany professor Dipanjan Ghosh (2006), 'Rhytidome or outer bark is the dead part of the bark comprising the periderm and tissues external to it. The living part of the bark inside the rhytidome is often referred as the inner bark' (p.41). To visually understand the various layers of bark, I drew a series of images shown in Figure 38. As shown, the outer bark is comprised of (from outside to inside) periderm, which contains

phellem, phellogen and phelloderm, just outside the phloem. Inside the cambium layer is the xylem. For the purpose of this study and architectural application, only the phloem and xylem will be described and focused on.

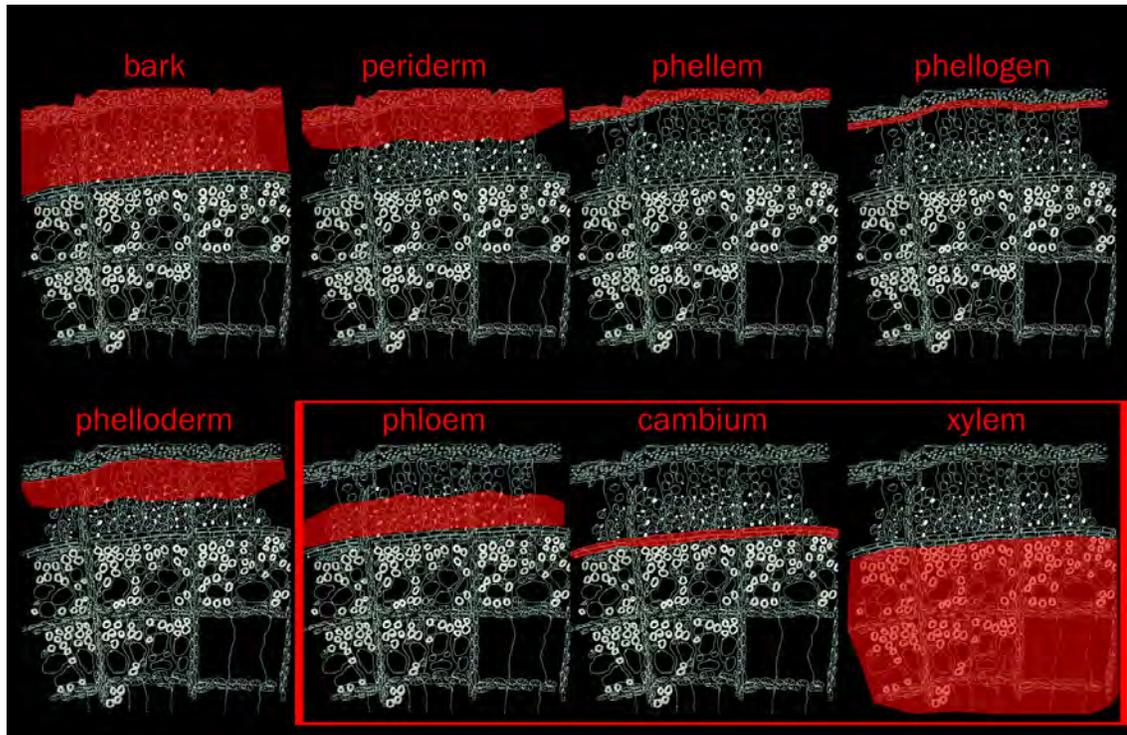


Figure 38. Cross section showing layers within bark.

Raven et al. (1981) gave details: 'The vascular tissue system consists of the two conducting tissues, xylem and phloem. The dermal tissue system is represented by the epidermis, the outer protective covering of the primary plant body, and the later by the periderm, in the secondary plant body' (p.403).

function. A more detailed description of phloem and xylem led to research into its function, or physiology. 'The part of the inner phloem actively engaged in the transport of food substances is called functional phloem.' And that 'Xylem is the principal water-conducting tissue of vascular plants. It is also involved in the conduction of minerals, in food storage, and in support' (Raven et

al., 1981, pp. 472, 406). Phloem and xylem work in concert to move water and nutrients up and down the tree and their relationship to each other is shown in a drawing I created in Figure 39.

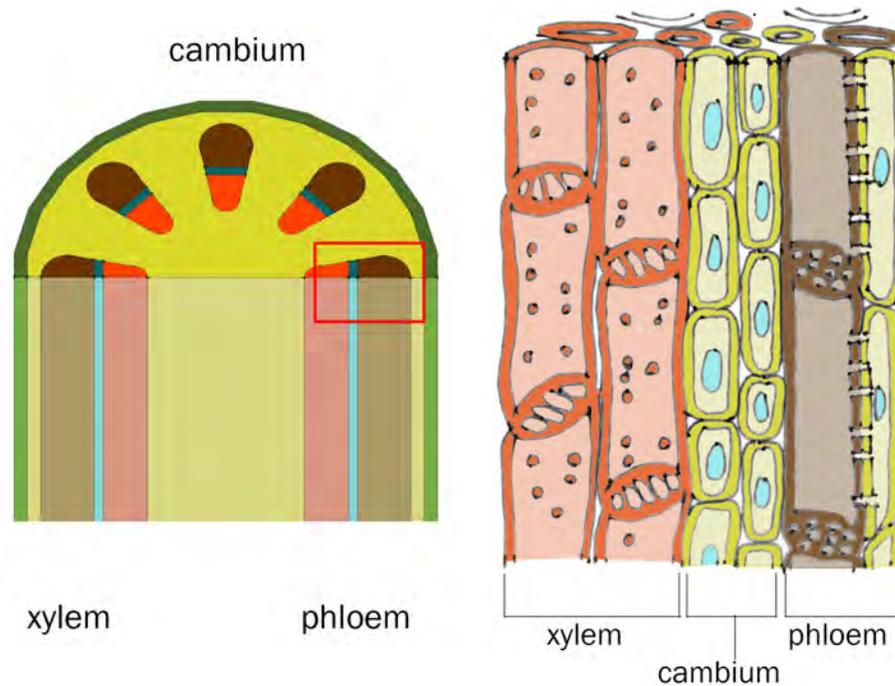


Figure 39. Overall (left) and detail (right) of phloem and xylem relationship

While they work in conjunction with each other, they also serve different purposes. Represented in the drawing I generated (Figure 40), phloem carries manufactured food from the leaves to the roots and xylem carries water and minerals from the roots to the leaves.

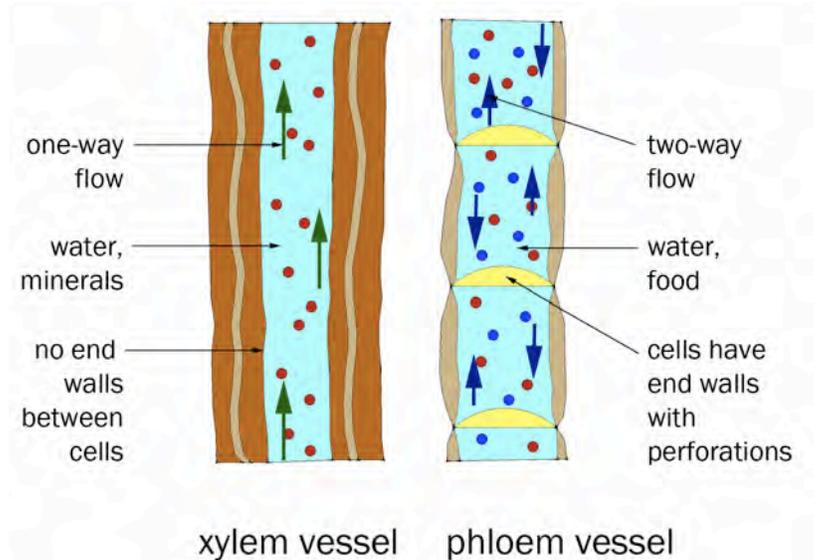


Figure 40. Movement of water and nutrients in xylem and phloem.

For the tree to stay alive and grow the movement through the phloem and xylem is critical. How do these elements move up and down the tree? Multiple theories were discovered in my research, but Raven et al. (1981) provided the most succinct explanation.

The xylem is the main conducting mechanism and there have been three main possibilities explored over the years. It can be pushed up, pulled from the top or pumped up. The pushing and the pumping possibilities have been ruled out. So we are left with the hypothesis that water is pulled up through the plant body (p. 527).

The movement of water and minerals is pulled up by tension and hydrostatic pressure due to evapotranspiration, which is the sum of evaporation and transpiration through the leaves. Raven et al. (1981) explained how the action occurs and the role xylem plays in fluid movement.

Because of the extraordinary cohesiveness of water, this tension is transmitted all the way down the stem to the roots, so that water is

withdrawn from the roots, pulled up the xylem, and distributed to the cells, which are losing water to the atmosphere. However, this loss makes the water potential of the roots more negative, thus increasing their ability to extract water from the soil... (p.527).

The movement of fluids as shown in Figure 40 assumes that the xylem and phloem act as a plumbing system for the tree which can give inspiration to designers for building plumbing within a building skin. Therefore it is not surprising that their form is similar to pipes as observed in Figure 41.

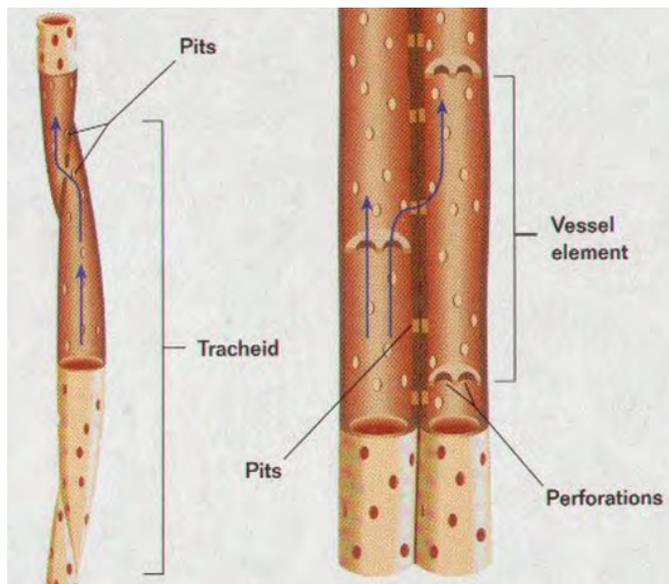


Figure 41. Xylem 'piping'

Scientists Dawson & Lucas (2005) even described these cells as piping. 'Some xylem cells, the vessel elements, are joined end to end and have connecting walls with one or more holes in them, so each series of cells functions as a single pipe known as a vessel' (p.14).

architectural materials. A description of piping in tree bark gives a direct application to buildings. Plumbing in buildings already uses piping, but it

and manufacturing building skin materials will require a new set of lenses. Analyzing exterior building skins shows that architects already use natural materials for many of them. For building skins the construction industry currently extracts from the earth when using wood siding, brick or stone. It also manufactures tile, concrete, glass, and metal using elements from the earth. Materials like plastic and EIFS are largely chemically constructed, but even they use fossil fuels extracted from the earth. Rather than continue to take from the earth, then heating, beating and treating it for use on a building, why not use our ingenuity to construct materials that behave like these natural elements do?

5.5 Collaborations

A new approach of looking to nature for inspiration will require collaborating with biologist, botanists, zoologists and other scientists. To make this possible will require more knowledge about nature and utilize the expertise of scientists as team members. Adding a biologist along with structural, electrical and mechanical engineers will create a unique collaboration that is critical to making buildings biomimetic. Their knowledge of the natural world and applicable technology will continue to advance and bring about the possibilities of new materials.

In order to better communicate with scientists about how building skins function I produced a series of diagrams illustrated in Figure 42.

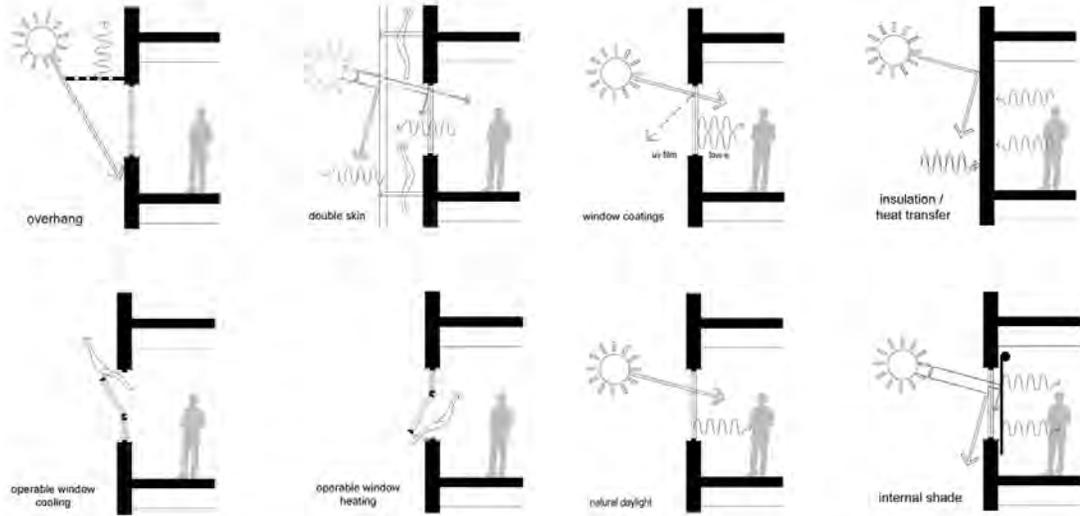


Figure 42. Building skin diagrams

During the interviews, it was interesting to see how quickly scientists picked up on the concepts and that they also use diagrams to communicate with, as demonstrated in Figure 43 by University of Oklahoma zoology professor Penny Hopkins.

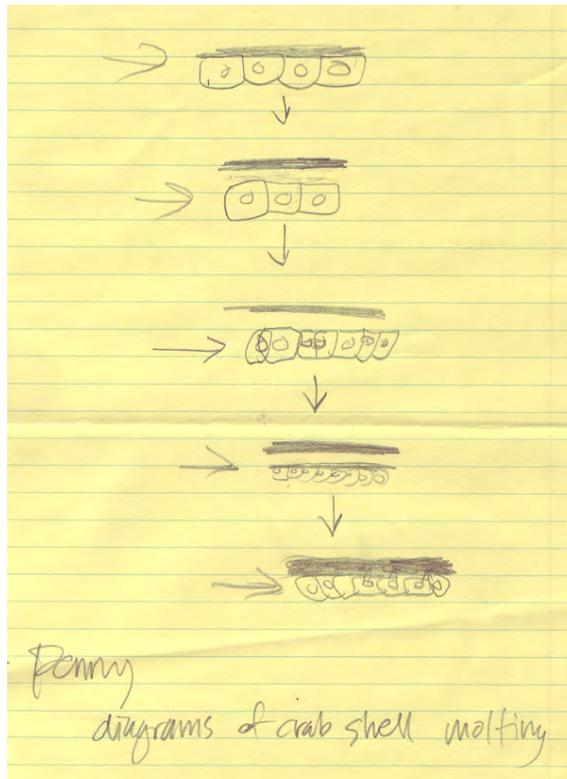


Figure 43. Sketch of crab molting process

It was also a beneficial exercise to utilize proper terms for bark and natural systems. For example in architects use the term 'regionalism', while scientists use the term 'speciation' is used. Which means the development of species.

Another advancement in science that this study can make use of is the growing of skin in the medical field. To behave like tree bark, a building skin will need to grow, so studying how others manufacture growth is beneficial. They are showing that the future is being designed. For instance, scientists at the University of Sheffield have created a biodegradable bandage seen in Figure 44.

Doctors take a biopsy of patients' skin cells, which are attached to the scaffold before the dressing is applied over a wound. The skin cells multiply and grow over the scaffold, which eventually dissolves and leaves the patient's own cells in its stead (Anthes, 2009, para. 6).

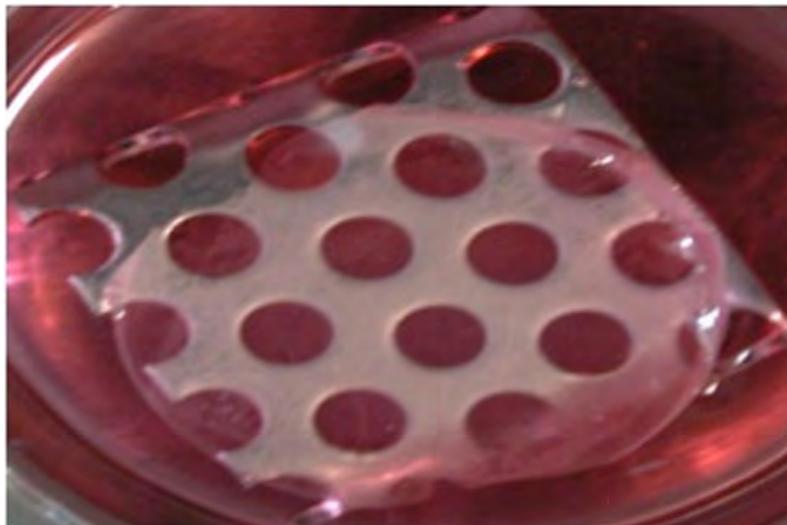


Figure 44. Scaffold Bandage

The biotechnology company Vomaris has produced an electric bandage that significantly speeds the healing of a wound.



Figure 45. Electric Bandage

This innovation, shown in Figure 45, is described here, 'The surface of the bandage... is covered in microbatteries which are inert when dry. Wetting the bandage activates the circuit, and small currents are applied over the surface of the wound' (Anthes, 2009, para. 7).

Architects already use the support of consultants who are experts in their fields because architects lack expertise in a specific area like structural and mechanical systems. So consulting with the scientific fields can benefit the construction industry in the same manner.

6.0 Discussion

6.1 Differences in this study

New discoveries like these, give architects unique opportunities to solve the energy inefficiency and loss of place problems. Five areas are highlighted here to show how this phenomenological approach, using tree bark as a model, is different than the other work outlined throughout the thesis paper.

different than past. Historically, designers drew inspiration from nature. However, nature was imitated mainly in aesthetic and structural terms. What is different today is that recent scientific discoveries of nature's design give architects a new understanding of how a natural system operates. Such a new understanding could be used to solve design problems with the study of natural principles. If DaVinci and Gaudi were working today, they would find an entirely new set of areas to study in nature at the molecular level.

different advanced material. This approach will also create building skins that are more than integrated, responsive, high tech and vegetative. While these are great advancements, a biomimetic building skin based on natural principles, will set it apart and be better for the environment. For example, The Live Within Skin Wall is a '...modular vertical garden [that] integrates living vegetation with the built environment so that the walls can be proactively used to address issues of air quality, storm-water runoff, thermal insulation, and sound attenuation' (Brownell, 2009, para. 1).



Figure 46. Live Within Skin Wall

While this skin is intriguing and utilizes biology, it is still not fully biomimetic. As shown in Figure 46, the skin is still partially standard metal that does not breathe and simply supports a biological system instead of behaving like one. Taken further, an entire wall system could grow like a plant as a substitute of using metal that supports biological growth.

different metaphor. Biomimicry provides designers a methodology to set new directions to make buildings efficient. Building skin technology is advanced, but is still based on the machine metaphor. Rather than the machine, a tree is a more appropriate metaphor as its skin solves many of the same issues that a building skin attempts to resolve. But a tree does so without harming the environment.

different consultants. To understand how nature works out these issues will require the construction industry to use a completely different set of consultants, namely scientists. Inviting these scientists to the design table gives architects a unique approach to design.

different standard. Current sustainable design is measured based on prescriptive standards like Leadership in Energy and Environmental Design (LEED). A biomimetic approach is a method that could actually be regenerative to the environment and be truly sustainable. 'According to leading biomimetic thinker Bill Reed (who co-chaired the development of LEED standards from the outset), we could "have a world full of LEED platinum buildings and still destroy the planet"' (Levitt, 2008, para. 3).

summary. The energy problem that architects are facing today is too critical to continuing solving it with the same methods. A different approach is required if regaining place and creating truly efficient buildings are to occur.

6.2 Problems

Numerous issues must be overcome in this new method of creating building skins based on tree bark.

dead versus alive. Architecture is typically seen as dead, while natural organisms are seen as alive. So the thought is that these two are incompatible. Yet the construction industry says that a building has a lifecycle and lifecycle analysis and assessment are performed on them. While the components of a building are typically made of inert, dead, materials, the building, as a whole, functions like a living organism. Moreover, tree bark is comprised of living and dead cells. The inner bark is living tissue, growing pushing dead cells towards the outside of the tree as it ages. As the tree ages, it

forms the outer bark, also called the rhytidome. 'The outer bark is the only part of the tree comprised entirely of dead tissues' (Raven et al., 1976, p. 472).

nature too difficult. Another problem to overcome is the perception that architects will find it too difficult to understand nature's principles enough to apply them to buildings. However, Buckminster Fuller once challenged designers to 'Dare to be naïve.' Architects already utilize consultants to further understand systems they are not trained to fully comprehend. An easy solution will be to add a scientist to the list of consultants so that designers will not have to rely on their limited knowledge of natural systems. One consultant is already pushing architects out of their comfort zone: 'Balmond's strength is that he guides architects into uncertain terrain' (Glancey, 2007, para. 14).

complicated systems. Architects may also think that to produce a building skin based on tree bark will require numerous complicated elements. However, Hensel et al. revealed that: 'Biological material systems are self-assembled, using mainly quite weak materials to make strong structures... Biology uses very few materials to construct its structures...' (p. 15). The real lesson to be learned is in how natural systems organize these simple materials. Architects could use existing technology, like pipes, and assemble them differently to achieve more efficient results.

summary. These problems should not cause designers to give up and avoid designing biomimetic building skins. They should, however, cause them to look at nature and ask, "How and what in nature is a good example that more closely matches the conditions buildings deal with?"

6.3 Potential architecture?

Looking at tree bark and applying it to building skin reveals a few areas to follow. These are not meant to be a complete analysis of application, but to offer some examples building skins could utilize.

thin skin. The composition of a biomimetic building skin should be seen as a thin membrane. 'Typically the outer bark is composed largely of successive layers of dead inner bark tissue and the periderms themselves are only thin sheets making up a small fraction of the whole outer bark' (Whitmore, 1962, p.193). Contrast this composition with the thick and varied systems used in architectural skins. To change, a building skin, '...could be more responsive and instead of relying on 'mass' for protection against the elements, it would make more sense to use a series of lightweight layers which deal with thermal performance, shading, wind deflection and even power generation' (Wilkinson, n.d., p. 1).

hybrid. These new building skins could also be a hybrid of 'living' and 'dead' systems. This paper has already pointed out that tree bark is a combination of living and dead cells. So an architectural skin would not need to be built from all living or all dead materials, but like nature, use a hybrid system.

water use. The live portion of a biomimetic building skin would require a constant supply of water and nutrients like trees need. And it would have to be more than collected rainwater, which is an inconsistent source. Wastewater in buildings, however, could be used to supply the skin with a constant nutrient source. And evaporation through the skin could move the water throughout the

façade.

growth. To be truly biomimetic, a building skin would need to grow. One option is to grow a skin in a nursery per the project specifications. This may require taking air and soil samples from the site location, sending it to the nursery to begin growing the façade while the project is under construction. Once the project is ready, it is then shipped to the site for installation. Another option is to grow the skin in-situ. As the project is under construction, a 'living' medium can be applied to a framework. The skin then responds to on-site conditions to grow and continues to change throughout the life of the project.

Growing materials for man-made technology sounds like a crazy and futuristic concept. However, there is a company named Ecovative is growing mushrooms for packaging, what they call "myotecture." 'The company's first product, a green alternative to Styrofoam, is taking on the packaging industry. Called Ecocradle, it is set to be shipped around a yet-to-be-disclosed consumer this spring.' They pour a mixture containing mushroom spores into a specified form and left to grow. 'A week or two later, the finished product is popped out and the material rendered biologically inert.' Looking beyond packaging, 'Ecovative's next product, Greensulate, will begin targeting the home-insulation market sometime next year' (Fisher, 2010, p. 49).

6.4 Conclusion

These ideas are meant to inspire an approach to building skin designs that will solve the problems of inefficiency and loss of place. Architecture cannot continue to attempt to solve these problems with more of the same technology. A more efficient air-conditioner is better, but it still does not solve the true issues of efficiency and loss of place. A new shift to solve these problems is needed in order to achieve a more efficient building skin and one that is appropriate to its place. Architects should look to tree bark as a model because it is efficient with resources and is adapted to its local climate.

Below are seven aspects that can serve as a basis for a new approach toward creating a better building skin that behaves like a natural skin. They are intended to be a descriptive of a way of thinking, not prescriptions or requirements.

1. Be indigenous.
2. See the building façade as a skin, not a barrier.
3. Study nature's principles, not just its forms.
4. Build on the shoulders of giants (DaVinci, Gaudi, etc.)
5. Utilize algorithmic software.
6. Use the tree as a metaphor.
7. Collaborate with those outside the construction industry.

These should act as a set of tenets that challenge architects to make building skins that are truly beneficial to nature. This is just the beginning for architects.

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