

Review



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Bioarchitecture: bioinspired art and architecture—a perspective

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Art and architecture can be an obvious choice to pair with science though historically this has not always been the case. This paper is an attempt to interact across disciplines, define a new genre, bioarchitecture, and present opportunities for further research, collaboration and professional cooperation. Biomimetics, or the copying of living nature, is a field that is highly interdisciplinary, involving the understanding of biological functions, structures and principles of various objects found in nature by scientists. Biomimetics can lead to biologically inspired design, adaptation or derivation from living nature. As applied to engineering, bioinspiration is a more appropriate term, involving interpretation, rather than direct copying. Art involves the creation of discrete visual objects intended by their creators to be appreciated by others. Architecture is a design practice that makes a theoretical argument and contributes to the discourse of the discipline. Bioarchitecture is a blending of art/architecture and biomimetics/bioinspiration, and incorporates a bioinspired design from the outset in all parts of the work at all scales. Herein, we examine various attempts to date of art and architecture to incorporate bioinspired design into their practice, and provide an outlook and provocation to encourage collaboration among scientists and designers, with the aim of achieving bioarchitecture.

This article is part of the themed issue 'Bioinspired hierarchically structured surfaces for green science'.

1. Introduction

Art and architecture are a natural left hand to hold the right hand of science though their practitioners

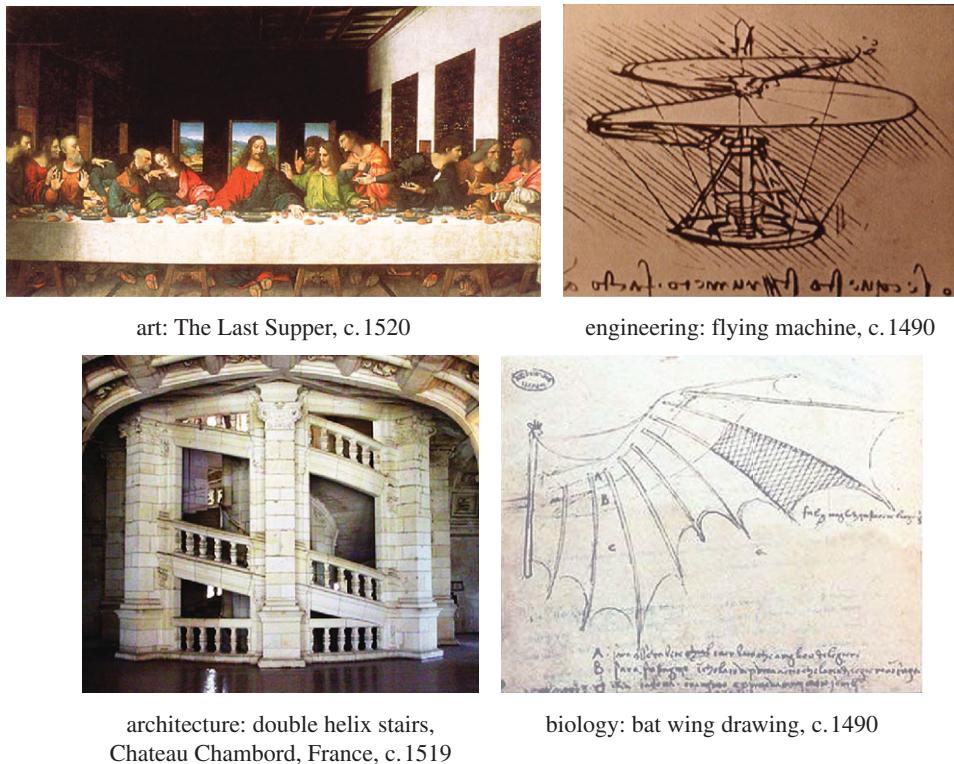


Figure 1. Examples of the artistic, engineering and biological investigation works of Leonardo da Vinci: *The Last Supper*, c. 1520 (artistic); flying machine drawing, c. 1490 (engineering); double helix stairs at Chateau Chambord, c. 1519 (architecture); and bat wing drawing, c. 1490 (biological investigation).

are often siloed, tentative to extend a hand to the other, tentative to accept the hand that is proffered. However, architecture, in particular, has a long history of a relationship at a distance to science and scientific ideals. Take for example the work of Leonardo da Vinci, figure 1. Many are familiar with his famous works of art; fewer are familiar with his fascination with engineering and architecture (evidenced by his drawings and schematics for flying machines and the intricate double helix stairs of the Chateau Chambord); fewer still are familiar with his interest in relating the biological world to engineering, architecture and art. To date, architecture has not taken full advantage of the opportunities that science has presented, particularly in the field of biomimetics, because of the self-imposed separation from scientific practitioners (and their self-imposed separation from artists and architects). There are examples of exceptions to this standard; however, they operate on the fringe of the field. Thus, there is an instinctive progression to be made from the current state of the scientific and architectural fields to full incorporation of bioinspired design to result in bioarchitecture.

To begin, we define our subjects: biomimetics and bioinspiration followed by art and architecture. Then, we proceed to offer a definition of a new field that combines these subjects: bioarchitecture. We then examine historical relationships and examples where our subjects have not quite risen to our new field. Finally, we offer an outlook and provocation to inspire collaboration among scientists and designers, with the aim of achieving bioarchitecture.

2. Defining the fields

This paper is an attempt to cross disciplines, define a new genre, and present opportunities for further research, collaboration, and professional cooperation. Because this paper is aimed at two relatively opposite fields—science and the arts—broad definitions of the specific fields

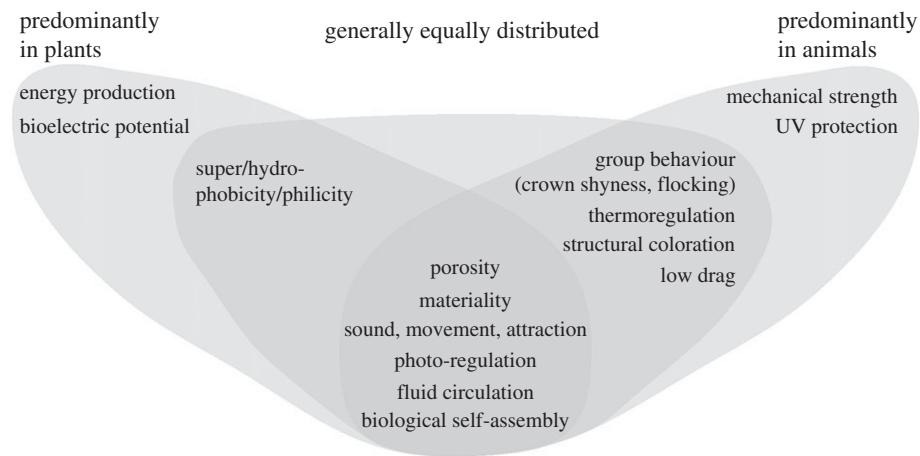


Figure 2. Overview of various properties of interest to biomimetics researchers. Properties to the far left side of the figure are found most predominantly in plants; those to the far right are found most predominantly in animals; properties to the left of centre are found in both plants and animals, but more in plants; those to the right of centre are found in both plants and animals but more in animals; those properties in the centre of the figure are found generally equally in plants and animals.

we are discussing are necessary to bring both sides together. What follows are brief overviews or definitions of biomimetics and bioinspiration, art, architecture, and our new field, bioarchitecture.

(a) What is biomimetics/bioinspiration?

Biomimetics is derived from the Greek prefix 'bio', meaning life, and root word 'mimesis', meaning imitation. Together, it means mimicking living nature. The field of biomimetics is highly interdisciplinary. It involves the understanding of biological functions, structures and principles of various objects found in nature by biologists, physicists, chemists and material scientists, and it can lead to the biologically inspired design, adaptation or derivation from living nature [1,2]. As it applies to engineering, bioinspiration or biodesign would be a more appropriate term for the field.

Nature has gone through evolution over the 3.8 billion years since life is estimated to have appeared on the Earth [3]. It has evolved species that use commonly found materials at a minimum to create high-performance features. Biological materials are highly organized from the molecular to the nano-, micro- and macroscales, often in a hierarchical manner with intricate nanoarchitecture that ultimately makes up a myriad of different functional elements [1,4,5]. Properties of materials and surfaces result from a complex interplay between surface structure, morphology, and physical and chemical properties, and how these interact with the environment. Many materials, surfaces and objects in general provide multifunctionality. Various materials, structures and devices inspired by nature and/or natural materials have been fabricated for commercial interest by engineers, material scientists, chemists and biologists, and for beauty, structure and design by artists and architects [1], though, of course, there are still areas of opportunity for research.

Figure 2 provides an overview of various properties of interest to biomimetics researchers (adapted from [2]). These include properties derived from both plants [6–10] and animals [11–32].

Figure 3 shows some examples from living nature [1] that exhibit properties desired for scientific and engineering research. While some of these examples have commercial materials that have resulted from research into their properties, as noted below, others have yet to be fully exploited.

Seashells (such as the abalone shell), bones and teeth are biomaterials that are nanocomposites with a laminated, hierarchical structure that exhibit superior mechanical properties to their

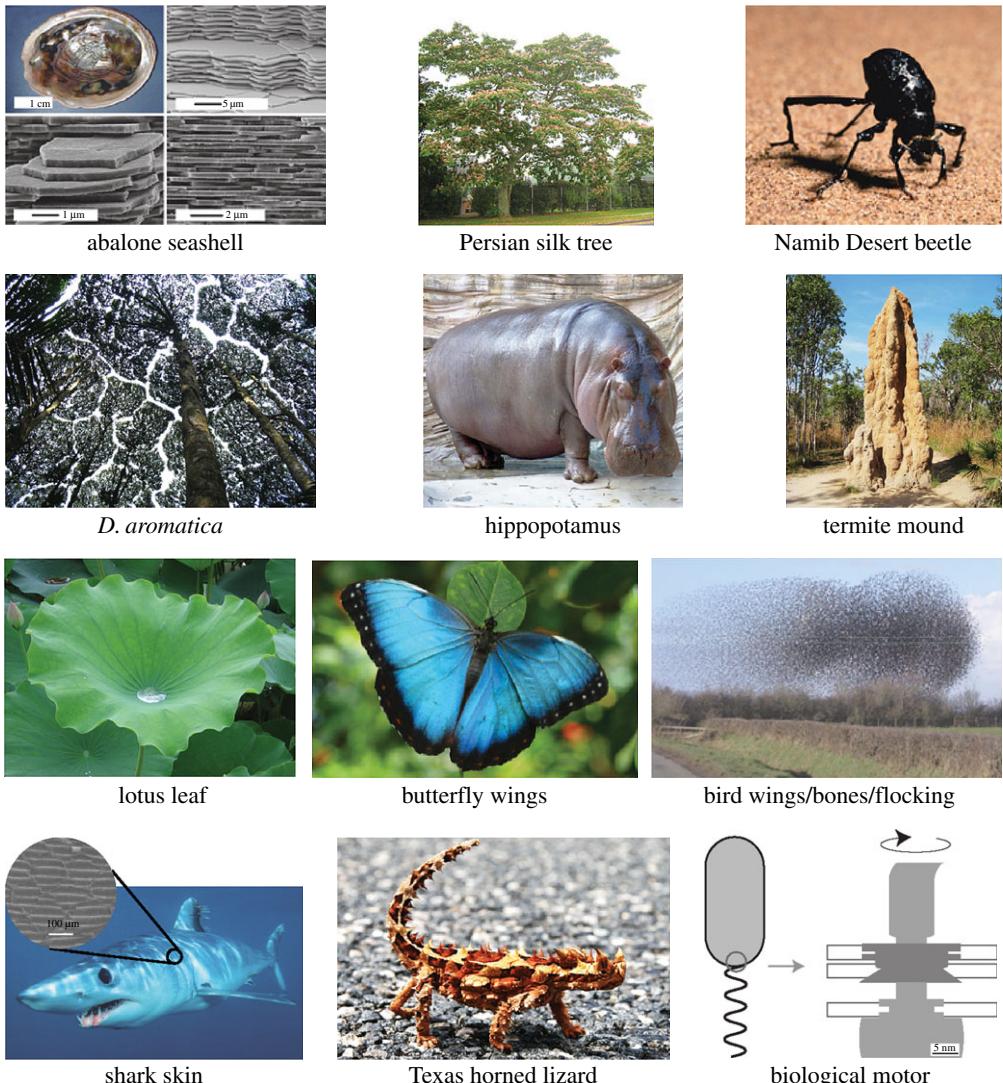


Figure 3. Montage of examples from living nature (adapted from [1]) that exhibit properties desired for scientific and engineering research.

constituents [11,24–27,30,32]. This is because biological organisms produce composites in complex, layered structures. The nacre of the inner abalone shell (*Haliotis*) derives high hardness and high toughness from a hierarchically organized, self-assembled structure. It has a mixture of brittle platelets and thin layers of elastic biomaterials, which inhibit transverse crack propagation and make the material strong and resilient.

Albizia julibrissin, also known as the Persian silk tree or mimosa, has been researched for its ability to use bioelectric potential to signal impending earthquakes [9]. The mechanisms of detection are not well researched though the obvious potential for such ability is clear. In addition, it has been reported that the phytochrome cytoplasmic signalling of this plant is responsible for observed plant motion [33]. While this research has yet to translate specifically to biomimetic materials, the opportunity for such is present.

The Namib Desert beetle has adapted to its extremely arid environment to provide water collection and consumption from fog [34]. The back of the beetle is organized with macroscopic bumps that alternate between hydrophobic, waxy regions and hydrophilic, non-waxy regions.

This bumpy surface with alternating coatings, combined with hydrodynamic forces, allows the beetle to aim its back into fog, and collect the microscopic droplets for drinking and other uses [34].

Crown shyness is a phenomenon seen in many tree canopies. While the mechanisms are not well understood or definitive, several observations of causes have been reported, including sunlight blocking and mechanical abrasion [35,36]. The behaviour of trees in this manner is an area of biomimetic research that is not well explored. However, the behaviour presents opportunities for research in solar energy, durability and others.

It has been found that the hippopotamus secretes red and orange pigments in its sweat [28]. These pigments are found to provide antiseptic properties and UV protection. Although the mechanisms of these properties are not well understood [37], there is the potential for biomimetic materials to take advantage of these properties in a variety of fields, including biomedical, consumer hygiene products, and art and architecture.

Termite mounds are known to regulate heat and ventilation for their inhabitants [38]. This is achieved through a complex relationship among various mechanisms: obligate symbiosis with a heat-producing fungi, mound architecture and termite behaviour. Mound architecture has influenced human architectural design, as in the Eastgate Centre in Harare, Zimbabwe by Mick Pearce (1996) [39], as well as influencing engineering design, in the case of ecosystem regeneration [40].

The diversity of the structure and morphology of plant leaf surfaces provides multifunctional properties [7,8]. Plants use photosynthesis to harness solar energy to support plant life. Plants have also been found to be able to generate heat [10]. Plant leaves can exhibit superhydrophobicity, self-cleaning, antifouling, drag reduction, superhydrophilicity, adhesion and plant motion. Leaves of water-repellent plants, such as *Nelumbo nucifera* (lotus), are known to be superhydrophobic, self-cleaning and antifouling, due to hierarchical roughness (microbumps superimposed with a nanostructure) and the presence of a hydrophobic wax coating [41–43]. Superhydrophobicity allows water to bead strongly on the surface and to run off quickly, taking dirt and other small organisms with it, resulting in self-cleaning and antifouling.

Wings of butterflies, a family of insects, exhibit superhydrophobicity, self-cleaning, antifouling and low drag [19,44]. The wings have a hierarchical structure consisting of shingle-like scales covered by microgrooves oriented radially outward from the main body of the butterfly. The hierarchical scales create a superhydrophobic and self-cleaning surface, with low drag. Brilliant iridescent colours of the wings are created by coherent scattering across the wings' nanostructures, known as structural coloration, rather than the use of colour pigments [45].

Birds' wings consist of several consecutive rows of covering feathers that are flexible. These movable flaps develop the aerodynamic lift necessary for flight. The beautiful colours in birds' feathers are created by structural coloration [45]. Bird flocking is an area of intense interest [46]. The collective behaviour of birds can tell us much about the mechanisms of group organization and behaviour, as well as hierarchy definition. Finally, bird bones provide a wealth of biomimetic opportunity for understanding weight versus strength, morphology for stress reduction, and overall size and weight as compared to support required to carry load [47].

Shark skin, which is a model from nature for a low drag surface, is covered by very small individual tooth-like scales called dermal denticles (little skin teeth), ribbed with longitudinal grooves (aligned parallel to the local flow direction of the water). These grooved scales lift vortices to the tips of the scales, resulting in water moving efficiently over their surface [14,15,18,20,48]. The spacing between these dermal denticles is such that microscopic aquatic organisms have difficulty adhering to the surface, making the skin surface antifouling [18,49,50].

It has been found that several lizard species are able to harvest and transport water from various atmospheric sources, including fog, dew and rain [51,52]. These lizards provide a mechanism for this harvest and transport using capillary action, specialized transport channels in the skin and body posture to direct water to the mouth. The combination of these features can be useful in developing water harvesting materials for use in water-stressed regions, though no materials have yet been developed [51].

pop art painting



Campbell's Soup I, Warhol, 1968

Figure 4. The work of Andy Warhol comes as close to mimesis as any artists', and is praised not for its ability to accurately copy other work, but for the groundbreaking commentary engendered by his incorporation of the popular into the fine arts and his recognition that art is everywhere, resulting in a new movement: pop art.

Many bacteria propel themselves by a type of extremely miniature motor called a flagellum motor. These motors rotate up to 100 000 r.p.m. [53]. These are similar to an electrical motor and have a starter, rotor and drive shaft with a bushing. The flagellum motor is driven by the proton flow caused by the electrochemical potential difference across the cell membrane.

The major benefit of biomimetics research is that it allows derivation of optimal designs benefitting from improvements made during evolution of living nature and efficient use of natural resources in a more sustainable and environmentally friendly (green) manner. Biologically inspired materials and surfaces have generated significant interest and are helping to shape green science and technology.

(b) What is art and architecture?

Defining art and architecture, as disciplines, is more complicated than it may seem. Whereas science lends itself well to relatively compartmentalized definitions: this is physics; that is biology, etc., defining artistic disciplines is somewhat more difficult, given the encompassing ambitions of the fields. This is, of course, reductive, but informative when it comes to attempting to define more artistic fields where boundaries may be less circumscribed. For art and architecture, there are many definitions that can be applied.

It is important to note that for both art and architecture, there is a resistance to mimesis. Though wholly original works are preferred and prioritized in the arts, very often, homage, inspiration, interpretation, response or other ways of incorporating another artist's work occur. Even the work of someone like Andy Warhol, whose work comes as close to mimesis as any artists', is praised not for its ability to accurately copy other work, but for the groundbreaking commentary engendered by his incorporation of the popular into the fine arts and his recognition that art is everywhere, resulting in a new movement: pop art (figure 4). However, in contrast to this interpretation and

incorporation, direct copying is universally abhorred. Copying ‘steals’; it speaks to a lack of creativity, a lack of integrity and an intent to defraud. Perhaps the worst criticism that an artist or architect can receive is to be called derivative. Some of the world’s greatest cons were had at the hands of art counterfeiters; as in the case of Han van Meegeren, whose greatest forgery was a pastiche of Johannes Vermeer. Though his work has become famous in its own right, it is somewhat at the expense of artistic pride: it highlights the shame of being fooled by someone who has not employed creativity in the content of the work, but in the attempt to pass the work off as someone else’s.

Here again, science differs from art. For a scientist, there is no need to reinvent the wheel, as it were, when it comes to, for example, using formulae, processes, or other established concepts. In fact, this is the foundation of science. Scientists cite the work of other scientists with no emotion attached. Even when we look to the field of biomimetics, direct copying of nature is seen as a high ideal—creating nature’s work in a laboratory is not only a worthy pursuit, it is one that is highly coveted. This is a concept that might be foreign, if not distasteful, to contemporary artists.

What follows are proffered definitions of art, architecture and bioarchitecture. Though the fields are not easy to contain in simple definitions, it is important to provide a framework for the commentary that follows.

(i) Defining art

Typically, a lay person might define art as a visual object (usually painting, drawing or sculpture) appreciated for its beauty or the emotion that it conveys. Of course, we know that art is often expanded to the ephemeral performing arts (dance, theatre) and literary arts (literature, music), and can be broken down into creative, commercial, fine and other types of arts. Arguing for a scientific approach to design, which he considered the highest form of painting, explicitly, Ross [54] explained art as ‘the expression of Life, or, more specifically, as excellence in the matter of expression’. From there, Ross defines excellence as consistency—another matter of debate—and goes on to take up the mantle of classical (i.e. from ancient times) beauty, calling for consistency in balance (antitheses), rhythm (movement) and harmony (likeness). It is worth noting that the definition of art is a topic debated by philosophers as far back as Plato and Aristotle, who argued both the merit and form of art. Further still in philosophy comes the discussions of how we determine what art is, whether it is ‘good’, and what is its value [55]. All of this is to say that the definition of art can be as ephemeral as the work itself. For our purposes, we will focus on discrete visual objects intended by their creators to be appreciated (whether ‘liked’ or ‘disliked’) by others. This definition, for example, leaves out uniform painting of walls as a wall covering (though this is undeniably ‘painting’), but includes wall murals that might cover an entire wall, or even an entire room. Herein, typically and for ease of representation, we have confined our artistic examples to paintings, though some fashion and industrial design works are also included.

(ii) Defining architecture

With respect to architecture, while there is the lay definition as the art or practice of designing and constructing buildings, ask an architect or architectural critic, and there are much more nuanced, appropriate definitions, about none of which there is consensus. For example, one of the greatest modernist architects, Le Corbusier, famously stated that architecture is the masterly, correct and magnificent play of masses brought together in light [56]. This definition is quite vague and ambiguous (what is correct; magnificent?) and can be interpreted so broadly as to have almost no meaning. However, it can be said that ‘architecture’, for our purposes, is a design practice that makes a theoretical argument and contributes to the discourse of the discipline. This definition, while somewhat recursive, makes a distinction between what the Germans call ‘bau’, or construction, and ‘architektur’. For example, a generic tract home or office tower is not ‘architecture’ for our purposes, but Frank Lloyd Wright’s Fallingwater or Norman Foster’s 30 St Mary Axe (the ‘Gherkin’ building) certainly are, figure 5.

mundane made fantastic



Fallingwater, Wright, 1939



30 St Mary Axe (the Gherkin), Foster Partners, 2004

Figure 5. In defining architecture, a generic tract home or office tower is not ‘architecture’ for our purposes, but Frank Lloyd Wright’s Fallingwater (home) or Norman Foster’s 30 St Mary Axe (the ‘Gherkin’ office building) are.

Notably, architecture incorporates more than just buildings. For important buildings, there often is a competition held to determine who ultimately will be chosen as the architect. There are, obviously, many entries that do not get chosen to be built, and these can be more interesting and make a better architectural contribution than the chosen design that is built. Thus, it can be said that, sometimes, it is the unbuilt works that advance the discipline of architecture more than the built works do. Furthermore, architecture very often leans more heavily on art or engineering in its practice. Many structures that tend towards the purely aesthetic (such as sculpture) and purely functional (such as bridges) blur the lines between engineering, art and architecture, not to mention architects’ forays into industrial, fashion and graphic design. Typically, architecture attempts to transform something that is purely functional, or pure engineering, into something that is a blend of functions and aesthetics; though architecture occasionally takes something that is purely aesthetic and provides functionality to it.

The balance of form (aesthetics) and function is a quandary with a long history in architecture. It was Louis Sullivan who in 1896 put into words a sentiment that ran deep in architecture: form ever follows function. Though the veracity of this sentiment has flip-flopped throughout time, it can be traced back to the work of Vitruvius, and his ideas that architecture should always have firmness, commodity and delight (that is, be solid, convenient and beautiful) [57]. What this means is that, throughout architectural history, architects have wrestled with which of these declarations takes precedence. While no architect would doubt that firmness—a solid foundation—should be of paramount importance, it is the relationship of the other two that is less clear. Should architecture have more commodity—that is, be more convenient—or should it delight—that is, be more beautiful? At times, one or the other has become more important. In the case of commodity, we can see the utilitarian and Spartan architecture of the Chicago



Figure 6. Examples of the range of functional to aesthetic design using bridges as an example of a whole structure, and columns and roofs as systems within structure. More functional examples are found at the top of the figure; blended examples are found in the centre of the figure; and more aesthetic examples are found at the bottom of the figure. For bridges on the left, pictured are a concrete bridge in Big Sur, California, USA (engineer and year of construction unknown); the Erasmus Bridge in Rotterdam, Netherlands, by Ben van Berkel (1996); and the Margaret Hunt Hill Bridge in Dallas, Texas, by Santiago Calatrava (2012). For columns and roof structures on the right, pictured are a precast concrete column supporting the upper deck of a parking garage (location and engineer unknown); the Chhatrapati Shivaji Airport in Mumbai, India, by SOM (2014); and the Johnson Wax Headquarters in Racine, Wisconsin, USA, by Frank Lloyd Wright (1936).

school, which prioritized the usefulness of tall buildings with a maximized footprint on a site for commercial purposes. In the case of delight, we need to look only to follies (small-scale architecture) of eighteenth century English and French gardens, which employed intentionally created ruins, scaled replicas of temples and other small enclosures to ornament the gardens without regard to the actual usefulness of the building. While history allowed reliance on one or the other, that reliance is shunned in contemporary practice, though the balance of the two is yet difficult to achieve.

Figure 6 highlights the balance of function (engineering) and form (aesthetics) that architecture addresses in the form of bridges, as a whole structure, and columns and roofs, as systems within a structure. In bridges, we see a purely functional, concrete bridge spanning a roadway below (Big Sur, California, USA, engineer unknown). While functional, as is necessary, there is nothing to suggest anything aesthetic about the construction—there is nothing unnecessary, nothing decorative, nothing but pure engineering. The Erasmus Bridge in Rotterdam, Netherlands, by Ben

van Berkel (1996), marries the functional and aesthetic in its design. The entire bridge is designed primarily as a monument; the architectural statement and theory come first, with the structurally important cable stays and the size and weight of the upright calculated to fit within the designed ideal. Although quite far into the aesthetic realm, the bridge still has function firmly in place. The elements are sized appropriately for the span, and there is no waste or excess in the bridge. As an example, the blend of aesthetics and functions perhaps reaches its zenith here. Finally, in the Margaret Hunt Hill Bridge in Dallas, Texas, by Santiago Calatrava (2012) we see that aesthetics have overtaken the functional aspects of the bridge. While it still functions as a span and serves to safely carry from point A to B, the bridge's aesthetics overpower the functions. The size and weight of the structural components are oversized for the span—an upright of that size is not necessary for the length of the bridge, and the configuration of the cables serves no structural purpose. Indeed, the excesses here serve to increase cost and use of materials and complicate the construction.

In looking at interior spaces, we can see first a typical, precast concrete column supporting the upper deck of a parking garage (location and engineer unknown). As in the bridge example, there is nothing unnecessary, decorative or additional in the creation of the column. It is pure function. In the Chhatrapati Shivaji Airport in Mumbai, India, by SOM (2014), function and form come together as a parametric design is used to create columns that are both visually interesting and structurally important. Indeed, the use of the parametric design increases the function of the columns by reducing the quantity of material required for their construction, and concomitantly creates the aesthetic statement. In this way, we see a modern blend of form and function in a way that both advances the architectural discourse and ensures appropriate functionality. Finally, in the Johnson Wax Headquarters in Racine, Wisconsin, USA, by Frank Lloyd Wright (1936), we again see how aesthetics can overtake function. Here, the columns support nothing but their own weight; they do not function to support roof load or building structure. While they create a soft, diffuse light in the interior space, they serve only to add decorative elements to the building. Though one could argue that light is necessary in an office space, here they are oversized and overpowered for the space and the excesses increased costs and time for construction.

Most importantly, architecture is a *practice*; not necessarily the *thing* that results from the practice. In looking at the practice of architecture, it becomes important to understand on what architecture draws for that practice. There are many subjects that come together to forge new, blended areas for study, figure 7. For example, the marriage of science and mathematics gives us engineering; the marriage of art and mathematics gives us a design. The culmination of these marriages, some more strongly than others, can be thought of as architecture, since architecture incorporates all of these subjects. The strong, dashed line indicates the potential relationships for bioarchitecture. Furthermore, we can see in figure 8 how architecture can be related back to these various complex subjects; for example, when we look at art and architecture over history that has emphasized a connection to biomimetics or bioinspired design, we get the various styles of Renaissance, Rococo, Neoclassicism, Art Nouveau, Beaux Arts, Modernism and Post-Modernism.

Art and architecture throughout history have looked to nature for inspiration, as we will see in examples later. However, what is important to note is that these forays into a bioinspired design do not yet go far enough. Even these examples fail to take full advantage of what science offers.

(c) What is bioarchitecture?

As we have identified that art and architecture do not go far enough, we must offer an idea of what would suffice. We define a new discipline, calling it bioarchitecture. We attempt to draw into the practice of art and architecture not merely biomimetic, but instead, a bioinspired design. Bioarchitecture incorporates the bioinspired design from the outset in all parts of the work at all scales. This is not simply copying natural shapes or forms in plan, section, elevation or in ornamentation (on the structure, components or in discrete art objects). This is not simply incorporating bioinspired materials in the construction of a structure or the making of art. It is also not simply scaling up natural principles. Instead, bioarchitecture is a multiscale approach

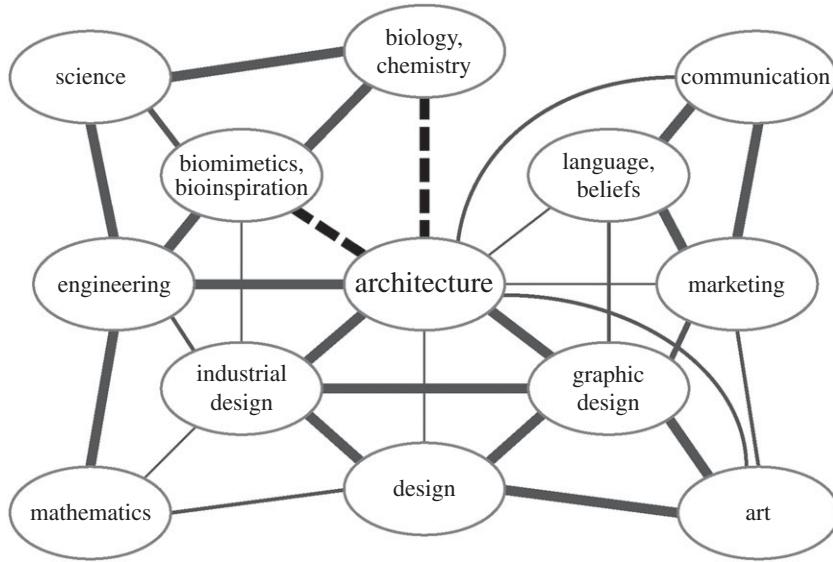


Figure 7. Schematic of the relationship of subjects to each other and to architecture. The line weight indicates the strength of the relationships among subject matters in forming a new, blended area of study. The dashed lines indicate a potential, strong relationship in forming bioarchitecture. All of the subject matters and blended areas of study can be thought of to culminate in architecture.

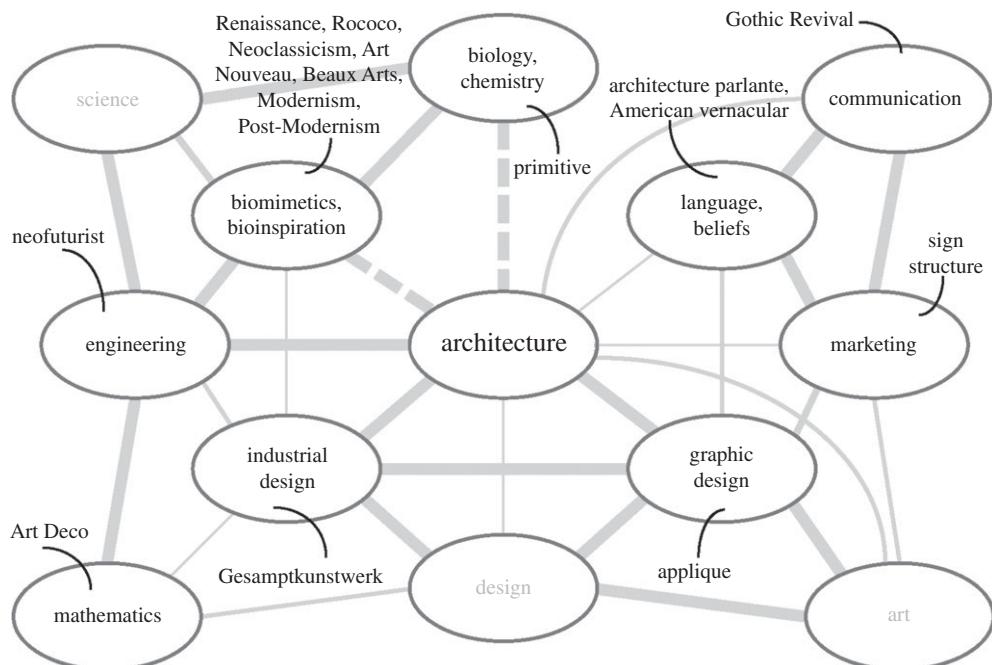


Figure 8. Schematic of the way architecture relates back to subject matters and blended areas of study. Styles of art and architecture can be situated in these areas of study.

to the incorporation into the work of solutions and opportunities that nature presents in solving universal human problems. It is an approach that is evident in the theory behind the overall design, the careful choice of materials for construction or creation, the extraction and adaptation of principles, and the cohesion of the parts in the whole.

Table 1. Artistic and architectural features and objects for direct or derived bioinspiration.

art/architecture	direct use	derived use
	biology	biomimetics/bioinspiration
<i>basics of art and architecture</i>		
structure	bones, shell curvature	molecular self-assembly, silk tree/mimosa (bioelectric potential)
skin	Namib Desert beetle, human/animal skin, straw, leaves, nests	selective porosity, water collection, oil/water separation
group behaviour (massing)	bird flocking, crown shyness	[opportunity]
fluid circulation	xylem, phloem, branching, migration	liquiphobicity/philocity, fouling, adhesion
<i>mechanicals in art and architecture</i>		
thermoregulation	hippopotamus sweat, termite mounds, panting, breathing	[opportunity]
photoregulation	eyes, plant movement (phototropism)	tracking solar
energy	photosynthesis	[opportunity]
hydrophobicity/philocity	lotus leaf, rice leaf, butterfly wing, capillary action	derived surfaces for super/hydrophobicity/philocity
<i>aesthetics in art and architecture</i>		
colour	butterfly wing, bird feathers, plant pigments	structural coloration, tuning carbon nanotubes
attraction (form)	mating dances/displays, flowers, scent	[opportunity]
materiality	shark skin riblet differentiation, lizard skin water channels, lotus leaf top/bottom differentiation	surface chemistry, interfacial properties
sound/movement	reeds, birdsong, migration, biological motor, adaptation to changing conditions	micro air vehicles, aviation, reversible adhesion

Bioarchitecture must be distinguished from organic architecture, a movement popularized by Frank Lloyd Wright throughout his long career. In organic architecture, the natural world and the architecture created within it exist in a balanced harmony. Indeed, the architecture becomes a part of the site—ideally, indistinguishable from it. The interior, exterior, contents and surroundings become of a piece. In contrast, bioarchitecture uses inspiration from living nature to drive the design, the function and materiality of the architecture. Organic architecture prioritizes the site-specific nature of the architecture—no architecture could be ‘organic’ without considering how it is the missing piece of the site puzzle. Contrary to this definition, bioarchitecture prioritizes the whole concept of the architecture, creating something that may use the natural surroundings of the site, but only insofar as they work at the scale of the whole. The idea of organic architecture seeks to incorporate architecture into nature; bioarchitecture seeks to incorporate nature into architecture.

Bioarchitecture encompasses both direct bioinspiration and derived bioinspiration. Direct bioinspiration does not require intervention by engineering. Artists and architects look directly to nature for inspiration. On the other hand, derived bioinspiration has already received the intervention of scientists and other engineers, as a layer of extrapolation and interpretation prior to that of artists and architects. As an example, artists and architects may look to the butterfly directly for inspiration for colour composition, pattern, form and delicacy. However, artists and architects may also look to the inspiration scientists and engineers have taken from the butterfly

for structural coloration, self-cleaning and hydrophobicity. Table 1 provides a list of artistic and architectural features and the objects from which they may take either direct or derived bioinspiration. Opportunities for further research to provide solutions for artists and architects are noted.

There are opportunities for architects to adapt and take advantage of the work that biomimeticists have accomplished and are pursuing. This work can be incorporated to provide not just superior materials and functions in the building of their design, but within the design itself. However, to date, the field of architecture has confined itself mainly to direct mimicry of natural shapes and ornamentation or inspired designs that incorporate one or another biological aspect. There is certainly room for architecture to expand its scope and to incorporate bioinspired aspects into the design at all scales. Intrinsic partnerships waiting for exploitation.

(d) Purpose of the paper

This paper will explain the choice of art and architecture as obvious implementers of bioinspired design, outline problems and opportunities addressed by biomimetics and architecture, and note areas of intersection that could be exploited for bioarchitecture. Furthermore, the paper will identify architecture's fundamental relationship to nature and to natural principles, especially as it relates to the golden ratio and the Fibonacci numbers. Next, the paper will review examples to date of biomimicry and bioinspiration in architecture, as well as examples that do not fit within our prescribed definitions of bioinspiration and biomimetics. Finally, the paper will present a summary of the review and an outlook for the realization of the discipline of true bioarchitecture.

3. Historicity of bioarchitecture

As stated previously, art and architecture have a long relationship to science and scientific ideals. Art has always been a faster medium, quicker to take up a topic or to express new ideas than architecture. Some of this is due, of course, to the literal speed at which art can be made, as compared to architecture. Indeed, many great architectural works of old, including almost all cathedrals, took several generations to create. Advances in technology have only sped up this process so much. However, it is still clear that there is a relationship among the three (art, architecture and science) when told through the lens of example and history, as well as some general examples of incorporation of science into art and architecture.

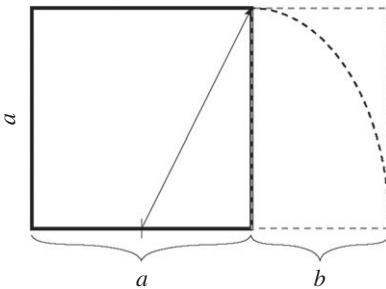
(a) Historical relationship between art/architecture and science—the golden ratio and Fibonacci numbers

Science has long acknowledged that nature imposes a certain order on itself. One way in which nature creates order is through the golden ratio. The golden ratio describes patterns found throughout not only our terrestrial environment, but the universe as well [58,59]. Scientists and mathematicians began to study in earnest the golden ratio around 450 BC though it was used prior to study for some time before by the Greeks, and Egyptians even before them, in art and architecture [60].

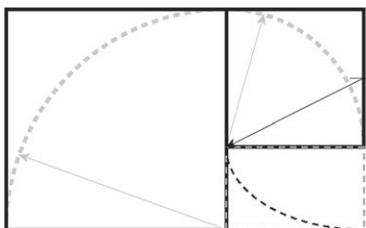
The golden ratio is a unique ratio whose proportions are considered to represent a functional and aesthetic ideal. It is defined as $(a + b)/a = a/b \approx 1.618$, where $a > b > 0$. A rectangle produced using the golden ratio is called a golden rectangle, consisting of a square combined with another golden rectangle, as shown in figure 9. A golden rectangle is produced by drawing a line from the midpoint of one side of the square to an opposite corner, then using that line as the radius to draw an arc that defines the height of the rectangle. Each golden rectangle contains an infinite sequence of squares and adjacent golden rectangles. The figure also shows how the golden spiral can be produced from the golden rectangle by drawing an arc tangent to the square, from the bottom corner of the square to the opposite corner, where it meets the square encompassed in the adjacent encompassed golden rectangle [60].

the golden ratio is given by: $\frac{a+b}{a} = \frac{a}{b} = 1.618$

where a is the side of the square and b is the short side of an adjacent golden rectangle, then $a+b$ gives the long side of the encompassing rectangle



by drawing a line from the midpoint of a side of a square, a , to an opposite corner, and using the line as the radius of an arc that determines the endpoint of b , a golden rectangle is constructed with a golden ratio



each golden rectangle encompasses an infinite number of squares with adjacent golden rectangles by drawing an arc tangent to the square, from one corner to the opposite corner and connecting these together, a golden spiral is created

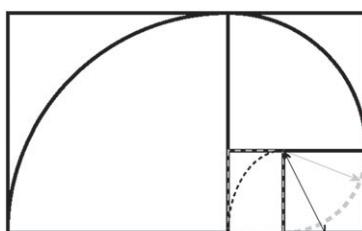


Figure 9. The golden ratio and the construction of the golden rectangle and the golden spiral, as derivations of the golden ratio (adapted from [2], Copyright © Springer, Berlin).

Leonardo da Pisa, nicknamed Fibonacci (1175–1230), discovered that a certain sequence of whole numbers, the Fibonacci numbers, approached the golden ratio, and he began studying the preponderance of examples of those numbers in nature around 1200 AD [19,60,61]. While these whole numbers do not produce the golden ratio precisely, the ratios of the numbers quickly approach the golden ratio, as the sequence continues into infinity [60]. The Fibonacci numbers are described by the mathematical expression $F_n = F_{n-1} + F_{n-2}$. The sequence begins with the seed values of $F_0 = 0$ and $F_1 = 1$. Then, the recursive expression provides the values following,

the Fibonacci sequence is defined by:

$$F_n = F_{n-1} + F_{n-2}$$

seed values	F_0	0	0	0
recursive values	F_1	1	0	0
	F_2	1	1	0
	F_3	2	1	1
	F_4	3	2	1
	F_5	5	3	2
	F_6	8	5	3
	F_7	13	8	5
	F_8	21	13	8

the ratio of each number in the sequence to its preceding number rapidly approaches the golden ratio:

$$\frac{1}{1}, \frac{2}{1}, \frac{3}{2}, \frac{5}{3}, \frac{8}{5}, \frac{13}{8}, \frac{21}{13} \text{ gives:}$$

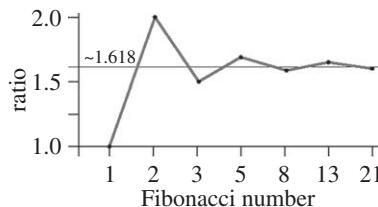


Figure 10. Fibonacci sequence shows how the sequence is calculated from whole numbers, and how the ratios of these numbers in sequence approach the golden ratio (adapted from [60]).

resulting in 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, ... and so on [58–60]. Figure 10 shows how the sequence is created out of these whole numbers and how their ratios approach the golden ratio. In the figure, the Fibonacci sequence, F_n , is placed to the left; in the centre, the sequence is displaced by one number, F_{n-1} , and to the right, displaced by two numbers, F_{n-2} . This shows how the sequence is calculated. Examples of the Fibonacci numbers in nature include the number and sequence of patterns on pineapples and sunflower heads, as well as the number of petals on flowers.

Figure 11 shows examples from nature that demonstrate the prevalence of the golden ratio and the Fibonacci numbers [19,61]. Shown are the Milky Way galaxy, a sunflower head, dahlia petals and a nautilus seashell. The golden spiral is demonstrated in the images of the Milky Way galaxy, the seed growth in the sunflower head and a nautilus seashell. When the golden rectangle height is divided by its width, the golden ratio of 1.618 is calculated, as demonstrated with the Milky Way galaxy. Furthermore, Fibonacci numbers are also present in the arrangement of petals in a dahlia flower [58,59].

The proportions of the golden ratio are not only in living nature, but also in the organization of our entire universe from the smallest to largest scale. Because of this, ancient thinkers considered these proportions divine and beautiful [57]. Inspired by the beauty of these proportions, artists have exploited the golden ratio in their works. Figure 12 provides examples of the golden ratio in various works of art. Leonardo da Vinci's work *A Head of an Old Man* employs the golden spiral to organize the proportions of the lower face to the upper, as well as the location of the ear, nose

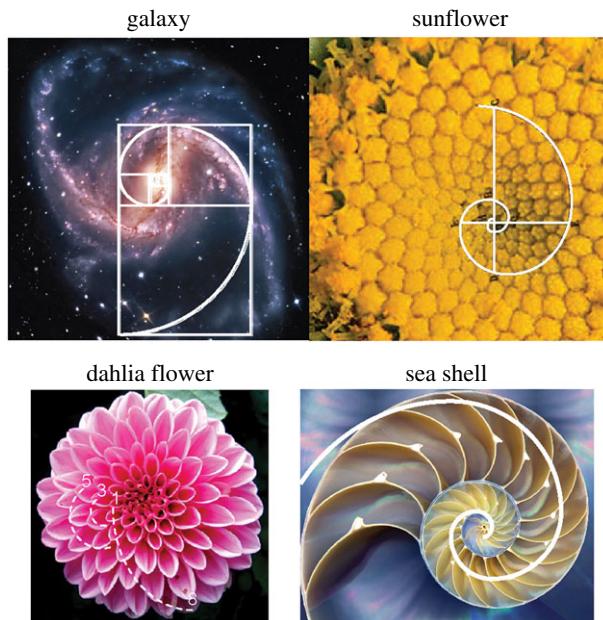


Figure 11. Montage of images showing examples of the golden ratio, golden rectangle, and Fibonacci numbers found in nature. Examples include the galaxy, sunflower head, flower petals, and sea shell. The golden rectangle and Fibonacci or golden spiral are superimposed on select images. Such proportions and patterns are considered beautiful and are believed to enhance performance of systems found throughout nature (adapted from [61]).

and hairline. Da Vinci's second pictured work is the Mona Lisa, where the golden spiral draws the viewer's gaze from the eye line, around the shoulders, and ending on her hands. Finally, Michelangelo's David uses the golden proportion in a way that is akin to classical architecture, discussed below, with the head consisting of ' b' , the torso ' a ' and the lower body is ' $a + b$ '.

Architects, too, have relied on the golden ratio for functional aesthetics even prior to its discovery [60]. The 'mystical' beauty found using the golden section is exemplified in architecture from ancient temples [62], to medieval churches [60,62] and, more recently in the mid-twentieth century, in the work of Le Corbusier [60], who used the golden ratio to define his oeuvre. Figure 13 shows two examples of ancient architecture that incorporate the golden ratio at various scales and in various attributes. The first, the Parthenon, finished approximately 432 BCE, is among the most well-known ancient architectures. The west façade, as built, was perfectly circumscribed within a golden rectangle. Furthermore, the plan shows a proliferation of golden rectangles in the inner chamber of the temple, called the cella (the entire plan, including the cella and the surrounding covered walkway called a stoa, constitutes a 'two-square' rectangle, which is part of another, related proportion system sometimes used). Adjacent to the Parthenon on the Acropolis is the Erechtheion, finished approximately 406 BCE. Leaving aside the fairly odd (for the time), site-driven construction of the Erechtheion, it too was built using various iterations of the golden ratio in its attributes. The west façade includes two variations on the golden rectangle—one vertically and another horizontally arranged. Additionally, when looking at the Caryatid Porch to the south, we see that the roof structure is supported by six caryatids, columns in the shape of women. The proportions of the women conform to the golden ratio perfectly.

As stated previously, the golden ratio can be found throughout the known world and is mathematically applied to worlds we are only just discovering. As a starting point, these proportions are excellent bioinspiration. However, this is merely the starting point for what nature has offered scientists and now artists and architects as building blocks. As science has

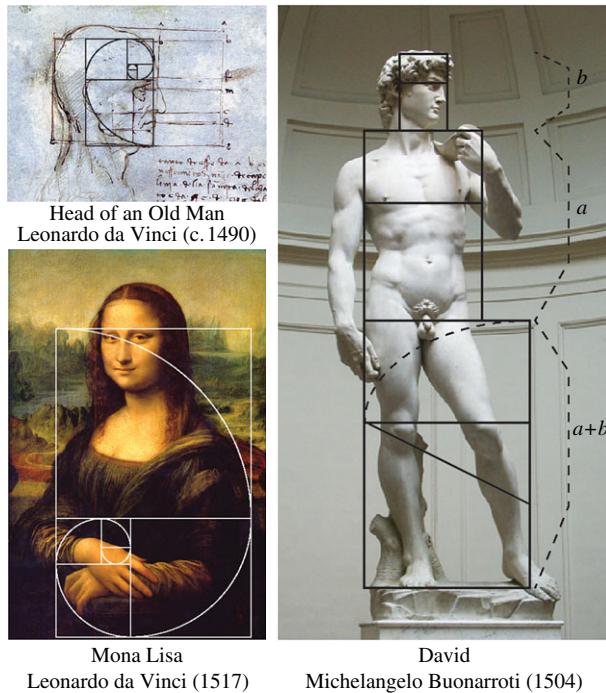


Figure 12. Examples of the golden ratio in various works of art, such as *A Head of an Old Man*, Leonardo da Vinci, c. 1490; *Mona Lisa*, Leonardo da Vinci, c. 1517; *David*, Michelangelo, c. 1504. Golden rectangle, spiral, and proportions are overlaid to show the relationship.

progressed, especially the rapid, scalar discoveries of the twentieth and twenty-first centuries, there are concurrently more opportunities for art and architecture to expand their practice.

(b) Inspiration from non-living nature

Art and architecture's relationship to science is not limited to the living biological realm, as we would limit bioarchitecture. However, these examples show the range of influence the natural world has had on the world of art and architecture, and leave room for more clear examples from *living* nature. What follows here are examples of inspiration from non-living nature in art and architecture.

Figure 14 provides examples of inspiration from non-living nature in art. Pictured are *Resonance* by Kendall Buster (2010), *The Event of a Thread* by Ann Hamilton (2013) and *Nimbus Cukurcuma Hamam* and *Nimbus LOT* by Berndnaut Smilde (2012, 2013).

Resonance was inspired by the location of the installation—a Princeton University chemistry laboratory building—and for the form, used references to the ball model of molecules. This sculpture is to be applauded for bringing art and science together in a clever and useful way. However, as the inspiration is not derived from living nature, nor is there a way to say rightly that the sculpture incorporates principles from living nature, we cannot say that it is bioinspired. Instead, it incorporates principles from the physical world; transcending mode of production, the model is an appropriate artistic response to chemical bonds and chemical formulations.

The Event of a Thread uses the power of collective movement and changes to air current made thereby to shape an experience of space [63]. Although using human power, the art cannot be said to be inspired by principles extracted from the human body and transformed in the art itself. Instead, we see that the wind and manipulation of air current are the inspiration for this experience, and that the agency of humans over that manipulation transforms the action of wind on the environment.

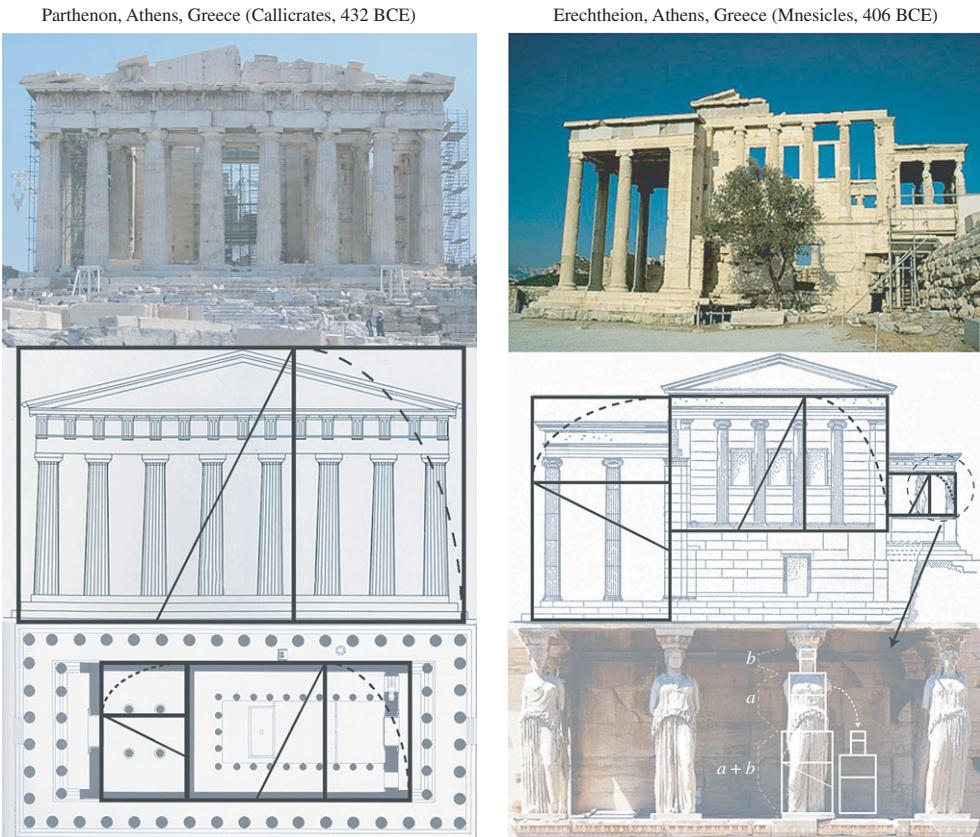


Figure 13. Examples of ancient architecture that incorporate the golden ratio and golden rectangle at various scales and in various attributes. The Parthenon (Callicrates, 432 BCE) is on the left, the Erechtheion (Mnesicles, 406 BCE) is on the right.

Quite obviously, Nimbus Cukurcuma Hamam and Nimbus LOT are inspired by clouds, which, while a part of the natural world, are not a part of living nature. However, the artist here manipulates the formation of clouds and transforms their purpose and ephemeral nature to create a momentary, transient experience made permanent through photography [64].

Figure 15 provides examples of inspiration from non-living nature in architecture. Pictured are the Royal Salt Works in Arc-et-Senans, France, by Claude-Nicholas Ledoux (1775); the Atomium in Brussels, Belgium, by André Waterkeyn (1958); Blur in Yverdon-les-Bains, Switzerland, by Diller + Scofidio + Renfro [65]; and the London Aquatic Centre, UK, by Zaha Hadid (2011).

The Royal Salt Works were commissioned by Louis XVI, and were constructed, radically, not near the extraction point of the salt, but instead at the source of the fuel to distil it: a large forest. The Royal Salt Works were constructed in a period where there was nostalgia and sentiment that favoured a return to the rustic and a rejection of the slick, smooth classical styles, as well as ornate baroque. Taking as inspiration the product of the works, Ledoux created rusticated columns that reflect the form of rock salt (halite). However, though the inspiration is drawn from nature, again, the inspiration is not from *living* nature. Therefore, this cannot properly be called bioinspired. Instead, it is inspired from non-living nature, and derives not only form, but meaning, site significance and functionality from the halite. This is not mere copying of form; the inclusion of the salt crystals into the columns is a testament to their cultural and economic significance, as well as their literal strength.

The Atomium was constructed for the 1958 World's Fair in Brussels, Belgium, and follows the grand tradition of fantastical buildings for such events. The Atomium is constructed in the form



Figure 14. Examples of inspiration from non-living nature in art: Resonance by Kendall Buster (2010), inspired by molecular structure (left); The Event of a Thread by Ann Hamilton (2013), inspired by wind (left); and Nimbus Cukurcuma Hamam and Nimbus LOT by Berndnaut Smilde (2012, 2013), inspired by clouds (left).

of an inhabitable body-centred cubic iron crystal. However, though iron may be an element that is found in things in living nature, it is not living nature itself. Thus, once again, the architecture falls outside of bioinspiration. Here, the use of the crystal makes for a striking and memorable iconic structure, and contributes to the larger commentary on the place of world's fairs in cultural history.

Perhaps the most interesting building inspired by non-living nature in this list, Blur uses technological advancements and an exploration of what exactly makes something a building to create an architectural experience that is unlikely to be repeated. Another world's fair pavilion (Swiss Expo 2002), Blur funnelled visitors into a fog that blotted out everything from the person standing adjacent to the visual and auditory noise that surrounds us daily. Much like the work of Smilde above, Diller + Scofidio + Renfro manipulate cloud formation to force that experience in an isolated locale. Unlike Smilde, Diller + Scofidio + Renfro were able to create a more extended, immersive experience. This allowed for the cloud to become inhabited by visitors to the building and repurposed the cloud for things both literal (video screen at night) and figurative (low-definition removal from high-definition life) [65].

Knowing that the natural world inspires even in the simple appreciation of the aesthetics of shape, we can easily see how the rolling waves of the ocean inform the free-form shape of the London Aquatic Centre. Here, Hadid uses the power of a crashing wave to translate into the anticipated power of Olympic athletes in competition in the Centre. The volume of the wave was

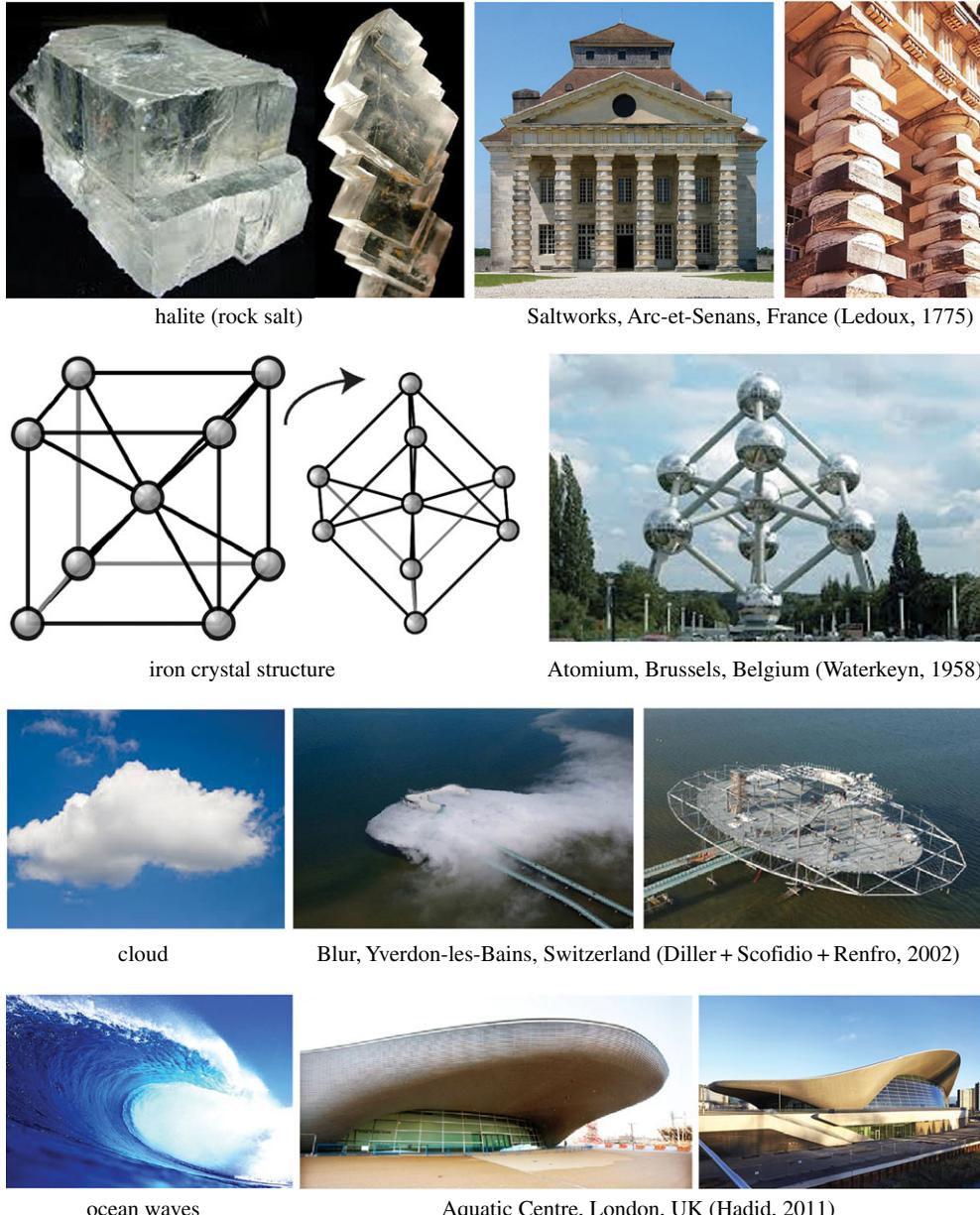


Figure 15. Examples of non-living nature in architecture: Royal Salt Works in Arc-et-Senans, France, by Claude-Nicholas Ledoux (1775), inspired by salt (halite) crystals (left); the Atomium in Brussels, Belgium, by André Waterkeyn (1958), inspired by the model of body-centred cubic iron (left); Blur in Yverdon-les-Bains, Switzerland, by Diller + Scofidio + Renfro [65], inspired by clouds (left); and the London Aquatic Centre, by Zaha Hadid (2011), inspired by ocean waves (left).

capable of encompassing the expected attendance, and provided a connection between nature's water and the artifice of competition swimming.

4. Biomimetics and bioinspiration in art and architecture

Scientists and engineers take inspiration from living nature for the purpose of functionality and commercial applications. Artists and architects take inspiration from nature for similar purposes, but with the added dimension of aesthetics. They incorporate many bioinspired ideas in both

ornamental and functional ways. Various patterns found in nature are used by artists for beauty and design. Furthermore, structural coloration from nanostructured surfaces is being developed for possible use by artists to produce vivid, durable colours that may not be possible by colour pigments. And one could imagine the revolution in art if, instead of being cordoned off in a museum, objects of fine art were self-cleaning, antifouling, UV protected, hydrophobic and oleophobic, allowing for a fundamental change in the way we experience art, and permitting intimate contact with the works.

Artists and architects often develop design strategies by incorporating patterns and organization found in natural forms [66,67]. Moreover, as nanostructured surfaces or materials with functional hierarchy are developed, these, too, are being incorporated into design practice ranging from the nanoscale to the macroscale. Another term, 'biornametics', has also been used to describe this emerging practice of bioinspired design [67]. However, this term may be more limiting in its connotation, since we specifically eschew the idea of 'ornamentation', that is, applied excess decoration, in our definitions.

What follows are examples of biomimetics in art and architecture, where mimesis is fundamental to the objects created. For reasons discussed above regarding direct copying, biomimetics is not the ideal approach for art and architecture, though there is no denying that it happens. The reason that we believe that mimesis is an inadequate approach is that copying in the realm of art and architecture, as discussed above, fails to bring appropriate creativity and authorship to the project. Further, copying disregards translation and extraction of principles from nature. Then, we examine more closely examples of bioinspired design in art and architecture. While these examples travel further down the road towards bioarchitecture, they do not quite rise to the level we have defined. Bioinspired art and architecture move away from direct copying, but fail to integrate principles extrapolated from nature at all levels of the project. The projects lack a cohesiveness or holistic approach.

(a) Biomimetics in art and architecture

At its most basic, biomimetics is the mimicking of living nature. At a macroscale, art accomplishes this through direct copying of natural figures. Figure 16 shows four examples of bioinspired antique jewellery pieces, crafted by Van Cleef and Arpels in the early 1900s, and three paintings: Mount Corcoran by Bierstadt (1877), Water Lilies by Monet (1906), and The Afternoon Meal by Melendez (1771). The brooches are inspired by a snowflake, butterfly, orchid and sycamore leaf. The forms are copied exactly—or as exactly as the medium allows—and do not extract or adapt any function or forms. Similarly, the paintings demonstrate a fascination with representing landscape and living nature, but without adaptation or use of functions derived from the natural world. However, the works of Bierstadt and Melendez fall into an artistic style called 'sublime', which can be said to flow from the power and scale of natural elements, and using high contrasts of light and dark to convey a sense of restlessness in nature.

Architects, too, accomplish direct representation in various ornamental motifs. Figure 17 shows examples inspiration from living nature and architecture resulting from direct representation. First, we see morning glory vines compared to the enclosure panels of the art nouveau Porte Dauphine for the Paris Metro by Hector Guimard (1899). Art nouveau aspired to incorporate nature into architecture using new material discoveries (cast iron) and decorative motifs. Next, we see an acanthus leaf incorporated into the capitals of the columns adorning the neoclassical US Capitol building by William Thornton (1800). Neoclassical architecture discarded the divine proportions of the golden ratio used so prominently in Greek architecture as too limiting, instead relying solely on the material (marble) and the shapes to reference classical architecture. Finally, we see a dahlia head compared to the rose window of the gothic Sainte Chapelle Cathedral in Paris, France, designed for King Louis IX in 1248 [68]. Gothic architecture drew inspiration from the divine: light, space and, as here, nature.

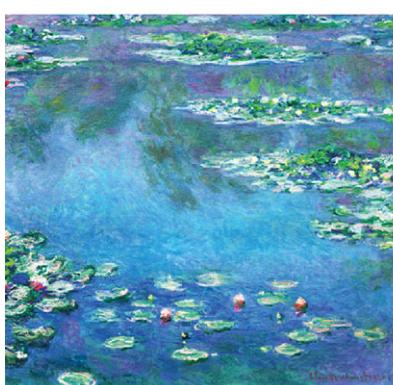
However, again, direct representation is generally eschewed in the arts for a more inspired interpretation; mimesis is a fairly facile way to incorporate nature into design without actually



brooches (Van Cleef and Arpels, early 1900s)



Mount Corcoran (Bierstadt, 1877)



Water Lilies (Monet, 1906)



The Afternoon Meal (Melendez, 1771)

Figure 16. Examples of biomimetics in art: antique jewellery pieces, crafted by Van Cleef and Arpels in the early 1900s; Mount Corcoran by Bierstadt (1877); Water Lilies by Monet (1906); and The Afternoon Meal by Melendez (1771).

delving into the organization or properties nature provides at various scales. Biomimetics in art and architecture is a limiting process, halting exploration at predictable achievements and with only superficial study; more can be demanded of the disciplines.

(b) Bioinspiration in art and architecture

Artists and architects alike strive to move beyond direct representation into an inspired practice. This can take many forms, but particularly when working from nature, they derive properties and principles from nature's objects and incorporate this organization into their work. This is done not as merely direct representation or ornament to the design, but as an integral part of the making of the work.

(i) Art

Artists especially have struggled to find a way to incorporate nature's possibility in their work without mere direct representation. Figure 18 shows the work of four artists that have made strides in this regard: Composition in Gray and Light Brown by Piet Mondrian (1918), Bone Chair and Bone Armchair by Joris Laarman (2006, 2008), Quadversal (fashion collection) by Iris van Herpen with Warren Du Preez and Nick Thornton Jones (Spring/Summer, 2016) and Biocouture Skirt by Suzanne Lee (c. 2013).

Composition in Gray and Light Brown incorporates the golden spiral into the arrangement of the various rectangles in the composition. This spiral, while not obvious without overlay, serves



Figure 17. Examples of biomimetics in architecture: enclosure panels at Porte Dauphine by Hector Guimard (1899), inspired by vine plants (left); columns on the US Capitol building by William Thornton (1800), inspired by the acanthus leaf (left); rose window of Sainte Chapelle Cathedral [68] for Louis IX by an unknown architect (1248), inspired by flower petals (left).

to draw the viewer's eye around the painting to a focus, much the same way that the golden spiral does for the *Mona Lisa*. However, unlike the *Mona Lisa*, the rigidity of the golden ratio is not followed; while there is use of its proportion in the overall composition, the proportion is not used exclusively. Without a direct representation of the spiral, the composition still incorporates it as an integral part of the organization and derives from the ratio the beauty and utility of mathematics and simple geometric shapes.

For the Bone Chair and Bone Armchair, Joris Laarman studied the way that the interior structure of bones grow and, using sophisticated software, created the structure for his chair in much the same way. The process involved reducing material where the structure could be light and increasing it where the structure needed to be strong [69]. This created a chair that is structurally very strong and sturdy, yet light, both in actual weight and in appearance. Moreover, since the chairs were 3D printed, they were 'grown' in the studio, deriving not only composition and structure but construction from nature's processes.

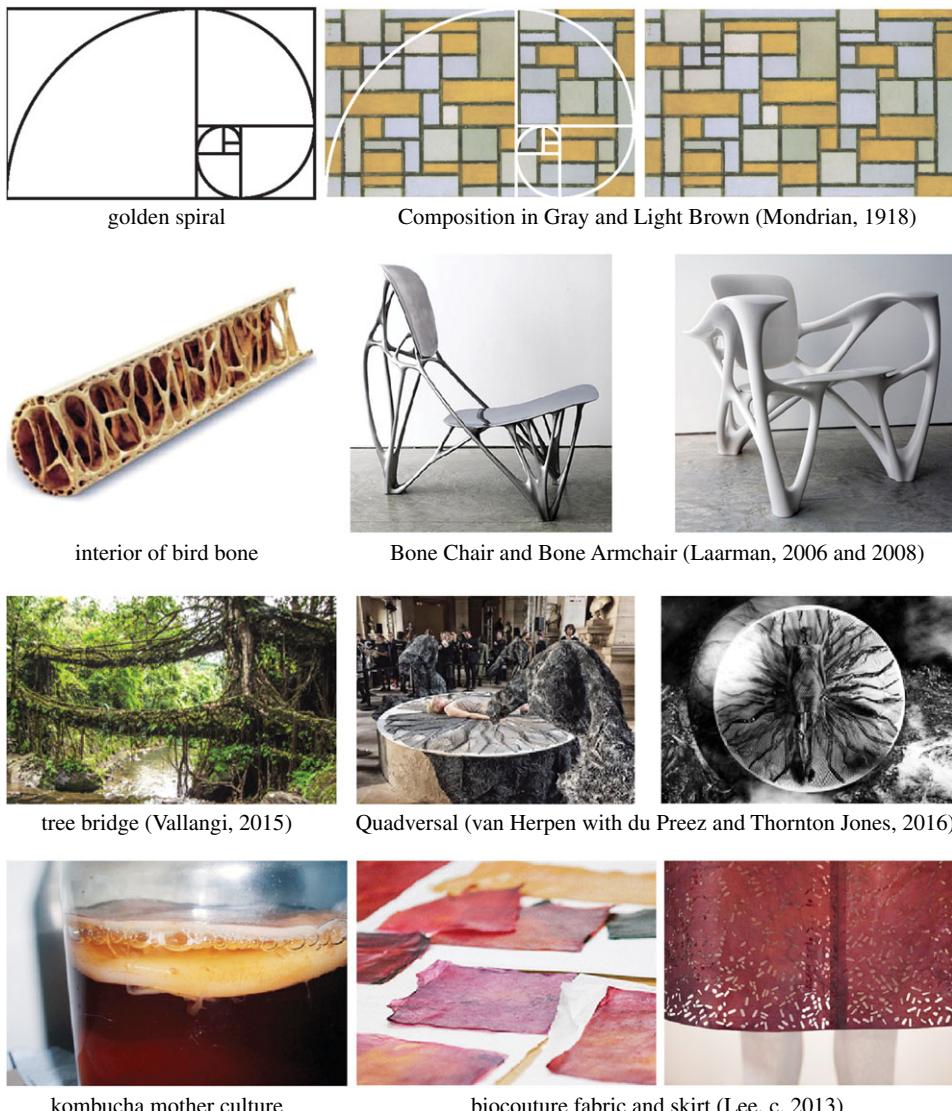


Figure 18. Examples of bioinspiration in art: *Composition in Gray and Light Brown* by Piet Mondrian (1918), organized by the golden ratio; *Bone Chair* and *Bone Armchair* by Joris Laarman (2006, 2008), inspired by bone structure (left); *Quadversal* (fashion collection) by Iris van Herpen with Warren Du Preez and Nick Thornton Jones (Spring/Summer, 2016), inspired by a tree bridge in India (left); and *Biocouture Skirt* by Suzanne Lee (c. 2013), inspired by the growth of bacteria in a kombucha mother culture.

Quadversal by Iris van Herpen with Warren Du Preez and Nick Thornton Jones (Spring/Summer, 2016) capitalizes on the idea of growth and intermixing inherent in living nature, particularly with trees. Central to the *Quadversal* collection is a dress that interprets growth, subverting the ‘premade’ notion of fashion, and creating a dress in real time to the particular setting and model on which it is made. Fashion construction techniques such as weaving, cutting, and folding are translated into a means of growth. Further, the form taken by the dress suggests the manner in which tree canopies interact—branches weaving above—and the manner in which the eye travels through a densely wooded area.

Inspired by the way that nature grows and creates, Suzanne Lee began to explore how microbes, bacteria, fungi, and yeast all create a fabric of themselves as their means of survival [70]. In harnessing that growth potential, Lee has created fabric and garments from that fabric

that are environmentally friendly in their creation, result in zero waste and are compostable at the end of their life cycle, allowing for a feedback loop in an industry increasingly noted for its environmental impact in the growth of fibres (plant, animal and chemical) and its waste. Indeed, in her exploratory practice, Lee has inspired others to incorporate nature's processes, resulting in some prototypes of future products, such as self-healing concrete [70].

These artists have demonstrated a progression of possibility when it comes to incorporation of bioinspiration into artwork. Laarman and Lee, especially, have certainly capitalized on technological advancements and have welcomed science into their work. Van Herpen, on the other hand, has capitalized on the translation of biological concepts into her work. While these may not quite go far enough, it is clear that the path to bioarchitecture, as applied to art, is laid through these examples.

(ii) Architecture

While architects have not struggled quite like artists have to incorporate bioinspiration into their practice, it is still not typical to find bioinspired architectural practice, let alone bioarchitecture. However, there are several practices that have demonstrated an incorporation of nature into the design. While these do not quite go far enough to be called bioarchitecture, they do incorporate nature not merely in form or decoration, but as integral to the design. In this section, we explore bioinspiration from three living sources (macro-/microscale plant, macroscale animal, and molecular-scale life in general). Finally, we highlight some art and architectural projects that, while using natural inspiration, do not derive their properties from *living* nature, and several projects and attributes that are identified *ex post facto* as having similarities to some object of living nature.

Bioinspiration in architecture: plants

Figure 19 shows architecture drawing its inspiration from plants in nature. Pictured are Durham Cathedral in Durham, England, built under the direction of William of St Carilef (completed c. 1100) [68]; La Sagrada Familia in Barcelona, Spain, by Antoni Gaudí (1882); the Nakagin Capsule Tower in Tokyo, Japan, by Kisho Kurokawa (1972); and Lilypad project by Callebaut [71].

Durham Cathedral is a Romanesque cathedral built in northeastern England. The Romanesque style originated in Normandy, and from there, spread to other parts of Europe, including England. Prior to this style of architecture, cathedrals and churches were built with quite thick exterior load-bearing walls, relatively low ceiling height, and very small windows piercing the walls. To reduce wall thickness and still increase wall height, methods of dematerialization and interior load-bearing support in construction were explored. The construction of Durham Cathedral relied on an understanding of the relationship between the top of a tree (branches, leaves, and the impact of external forces such as wind thereon) and the support provided by the trunk of a tree. Trees that are too top heavy (or, in other words, have insufficient trunk support for the load of the top) fall over either on their own, or in a strong wind. Thus, the interior support columns for Durham are sized to accommodate the weight of the ceiling above and the increased forces that act on a higher roof line. This redistributed the load and allowed the exterior walls to become thinner, as well as taller. This exploratory practice created an avenue for the rise of Gothic architecture, where wall thickness was reduced further still, wall height continued to increase, and, because of the dematerialization of the walls, the inclusion of stained glass windows proliferated [68].

Inspired by much in the natural world, Antoni Gaudí began construction on the cathedral of La Sagrada Familia (The Holy Family) in 1882. It is wrought in a southern-style of art nouveau influenced by the political discord in Spain of the Catalan people, subjugated by the Castilians several centuries prior [68]. Gaudí eschewed the rigidity of style dictated by writers of northern architectural and artistic theory. Instead, Gaudí solved the classical problems of height and weight in his cathedral in novel ways using nature's solutions. He noted that very tall, thin trees support the load of their tops and of external forces by tilting, rather than remaining rigidly upright.

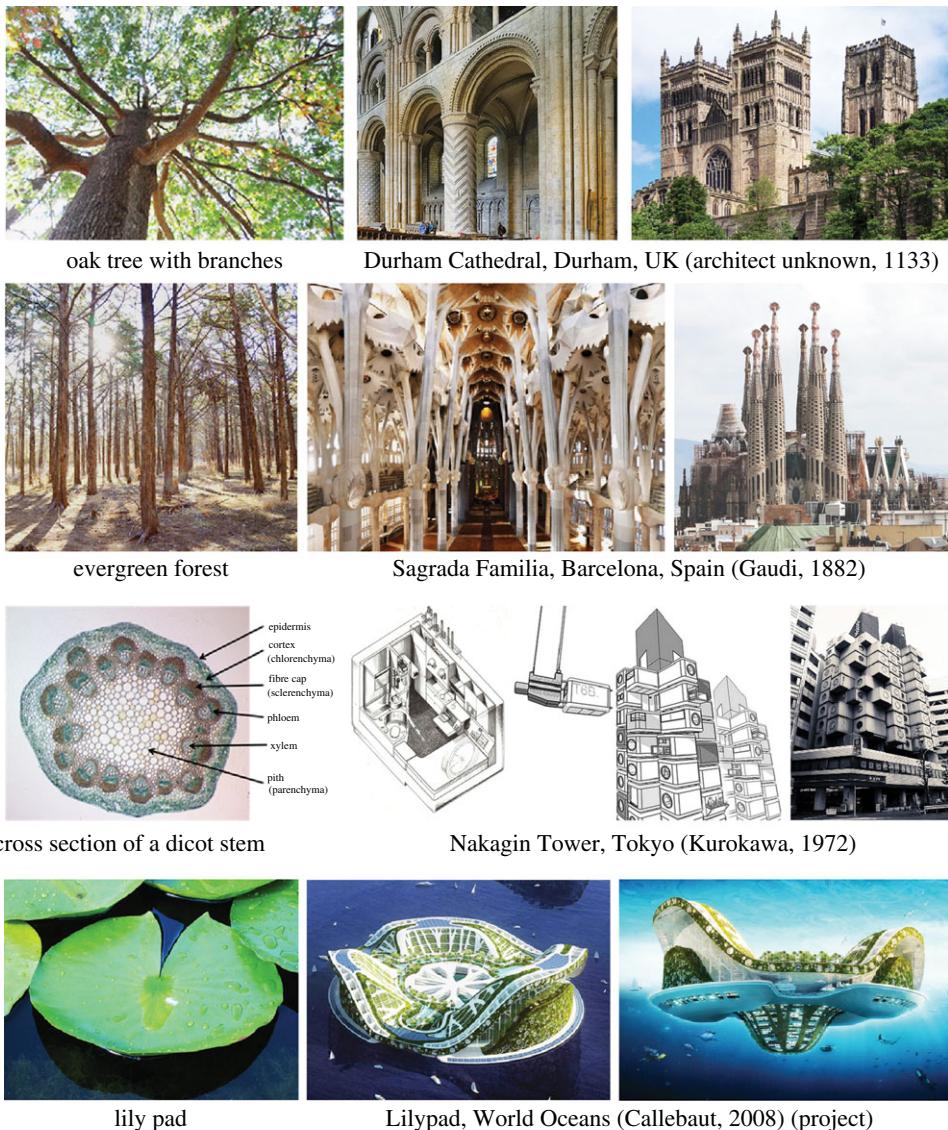


Figure 19. Examples of bioinspiration in architecture derived from plants: support columns in Durham Cathedral in Durham, UK, under the direction of William of St Carilef (completed c. 1100) [68], inspired by individual trees (left); support columns in La Sagrada Familia in Barcelona, Spain, by Antoni Gaudí (1882), inspired by groups of trees (left); Nakagin Capsule Tower in Tokyo, Japan, by Kisho Kurokawa (1972), inspired by dicot structure (left); and Lilypad project by Callebaut [71], inspired by a lily pad (left).

Thus, for the load-bearing columns of the interior of his cathedral, Gaudí chose tall, thin columns that branched to draw load from various points, distributing the weight over a greater area, yet drawing it down one, thin column. This allowed Gaudí to build a tall nave with more dematerialized external walls.

Nakagin Capsule Tower, produced out of the Metabolist movement in post-war Japan, used cellular discoveries of the time to reduce the essential living requirements to discrete, interconnected blocks suitable for rapid growth and expansion [72,73]. The Metabolists were fascinated by the new scanning electron microscope images of metabolic and cellular organizations. They extracted out of these images ideas of cellular replication, organization and

efficiency of function. From these ideas, they scaled up and created projects that addressed rapid, post-war urban growth [73]. Thus, Nakagin Capsule Tower was constructed of nearly identical individual pods, or cells. These cells would cycle with the building framework: growth of the framework, growth (addition) of the cells, use during a cellular lifecycle, removal of cells that had reached the end of their useful life and replacement with new cells. The idea of this building was to allow the framework to remain whole, but allow a life cycle for the individual cells.

The Lilypad project by Callebaut [71] sought to address an imagined, but not unrealistic, future world where millions of people become displaced by rising ocean levels due to climate change. Each Lilypad could house 50 000 inhabitants and would be entirely self-sufficient. While literally in the shape of a lily pad, the project draws inspiration from ecosystems at large. The floating system is inspired by the broad, flat leaf of the Nymphaeaceae family of plants (not to be confused with the lotus, which is of an entirely different order), specifically, the Victoria Regia [71]. Callebaut extracted the principle of floating, and added thickness to the project, creating space for inhabitants and incorporating other natural processes. He envisioned a 'breathing' skin of polyester fibres covered with a layer of titanium dioxide to process atmospheric pollution using ultraviolet rays in a manner similar to plant (specifically, tree) respiration. By floating, Lilypad takes advantage of hydrothermal action in the ocean, tidal flows, gyre action, as well as various forms of inexhaustible energy (solar, wind, biomass etc.). Lilypad draws out various principles from a multiplicity of natural and living systems to create a refuge for future climate escapees. This is perhaps the closest example to bioarchitecture.

Bioinspiration in architecture: animals

Figure 20 shows architecture drawing its inspiration from animals in nature. Pictured are Exeter Cathedral in Exeter, England, by an unknown architect (completed c. 1400); Institut du Monde Arabe in Paris, France, by Jean Nouvel (1987); La Tour Eiffel, in Paris, France, by Gustave Eiffel (1889); and the Milwaukee Art Museum in Milwaukee, Wisconsin, USA, by Santiago Calatrava (2001).

Exeter Cathedral approached the issue of the weight of the ceiling and roof structure not from the position of support for increasingly high loads, but from the idea of reducing the actual load of that roof structure. To accomplish this, the designers turned to the structure of the human body, specifically the ribs and intercostal spaces. Architects found that by replacing the ceiling with vaults of strong ribs, and filling the spaces between these ribs with much thinner, lighter materials, the weight of the ceiling was reduced. This allowed for taller ceilings without concomitant significant increases in the load.

More modern bioinspired structures often take a more technical approach to incorporation. Nouvel's Institut du Monde Arabe looked at the various benefits of the iris of the eye. The artificial irises incorporated into the skin of the building open and close automatically using sensors to detect sunlight. In addition to regulating light entry to the building, they are also used to automatically regulate heat, closing the apertures when the temperature sensors reach a designated level. Simultaneously, these irises provide a cultural reference with their shape. Indeed, they recall the motifs of Arabian art and architecture with its geometric form and scalar replication.

For the 1889 World's Fair, engineer Gustave Eiffel's firm created the Eiffel Tower to serve as the entrance to the fair. While it may be trite to say, the Eiffel Tower is truly a marvel of engineering. Eiffel used a truss network based on force diagrams derived from those of the long bones of the human body, in particular, the femur. These force diagrams allowed Eiffel to determine where the structure needed strength and support, and where it could be cut away. The results of this work are seen in the delicate, lace-like nature of the Eiffel Tower. Minimal materials were used to create it, saving time, money, and resources.

The Milwaukee Art Museum by Santiago Calatrava (2001) is the final example of bioinspiration derived from animals. Here, Calatrava designed a solar-sensitive wing that, like a bird, can open and close. While taking the principle of the mechanical operation of the bird

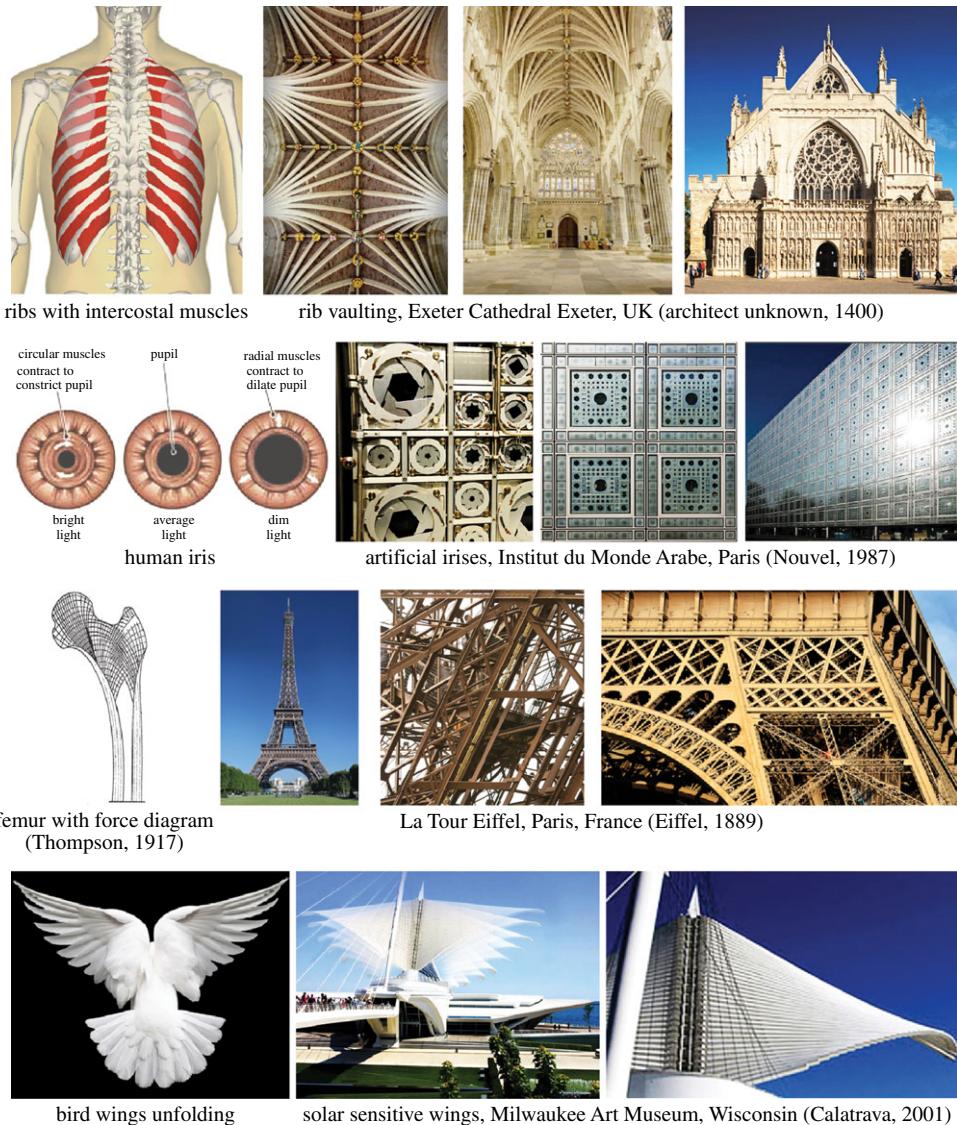
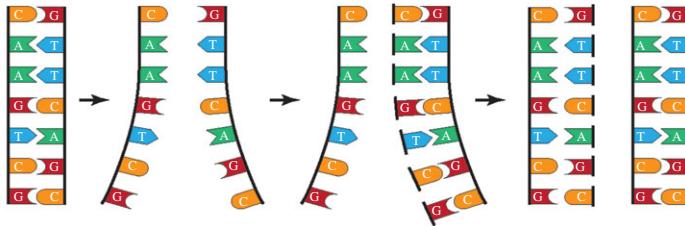


Figure 20. Examples of bioinspiration in architecture derived from animals: rib vaulting in Exeter Cathedral in Exeter, UK, by an unknown architect (completed c. 1400), inspired by ribs with intercostal muscles; the skin (enclosure) of the Institut du Monde Arabe in Paris, France, by Jean Nouvel (1987), inspired by the human iris (left); La Tour Eiffel, in Paris, France, by Gustave Eiffel (1889), inspired by force diagrams of bones (left); and the Milwaukee Art Museum in Milwaukee, Wisconsin, USA, by Santiago Calatrava (2001), inspired by bird wings (left).

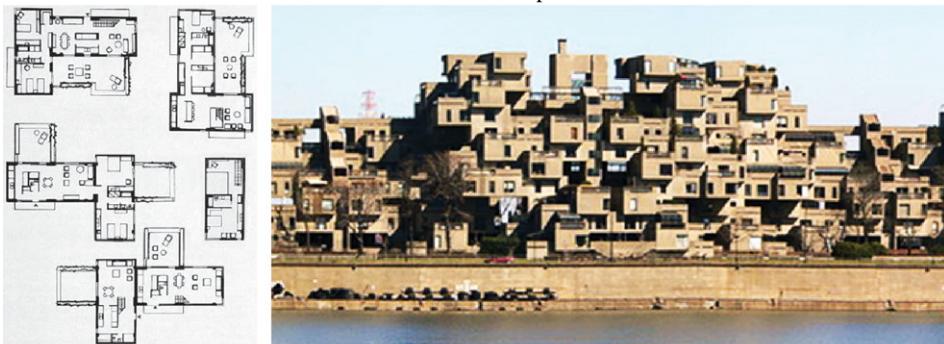
wing, it does not attempt to make the building fly, of course. Instead, the wings open and close to provide solar protection for the museum and for attendees, allowing shade to take over the roof structure of the museum building.

Bioinspiration in architecture: replication of discrete units

Figure 21 shows architecture drawing its inspiration from replication at the molecular level in nature. Pictured are Habitat 67 in Montreal, Quebec, Canada, by Moshe Safdie (1967); the Takara Beaufillion Pavilion in Osaka, Japan, by Kisho Kurokawa (1970); and the Disney Contemporary Resort Hotel in Orlando, Florida, USA, by Welton Becket (1971). Each of these examples looks



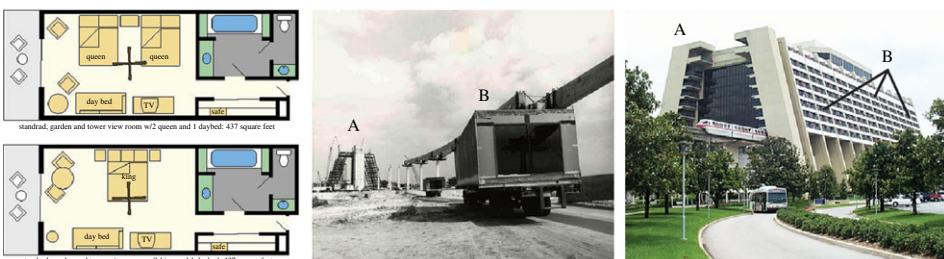
schematic of DNA replication



Habitat 67, Montreal, Canada (Safdie, 1967)



Takara Beuillion Pavilion, Osaka, Japan (Kurokawa, 1970)



Disney Contemporary Resort, Orlando, Florida, USA (Becket, 1971)

Figure 21. Examples of bioinspiration in architecture derived from replication, such as that found in DNA (top): Habitat 67 in Montreal, Quebec, Canada, by Moshe Safdie (1967); Takara Beuillion Pavilion in Osaka, Japan, by Kisho Kurokawa (1970); and Disney Contemporary Resort Hotel in Orlando, Florida, USA, by Welton Becket (1971).

at the replication provided by DNA, and the benefits that can be derived therefrom. To begin with, there is an expediency provided by having a kit of parts that can be assembled in various arrangements, yet allowing for flexibility in spaces or configurations. Further, there is an egalitarian sense in arranging the kit of parts such that no individual part is emphasized more than another or has significant benefits over another. As well, there is a desire to ensure that the whole is greater than the sum of its parts; that the parts that contribute to the whole are not the focus, but instead create the unity of the whole. Finally, the ease of repair and replacement of the parts makes the incorporation of replication principles attractive for bioinspired architecture.

Summary

Through these projects, we can see a progression from mimesis to inspiration, which approaches true bioarchitecture. In bioinspiration, no longer are the works mere copies of living nature, as in biomimetics, but instead, they extract a principle (or principles) from nature, seek to understand that principle, and then incorporate the principle into a new medium, design, or other end result. For works to rise to what we have called bioarchitecture, care must be taken to ensure these principles are incorporated from the outset of the design process and at all scales of the project. Without this holistic approach, the works fail to take full advantage of the opportunities presented by science.

5. Outlook: balance, application and provocation

Given the review of the state of both biomimetics/bioinspiration and architectural and artistic incorporation of the same, the question remains: how to strike the appropriate balance of incorporation at all scales without veering into camp or austerity (in form), or ornament or minimalism for their own sake (in materiality)? Artists and architects have addressed this problem previously. The nascent field of bioart has certainly managed to blend successfully science and art. Artistic responses to cultural constructs using what is recently possible via scientific research blend biology and art using living cells. The work of bioartists capitalizes on scientific research in bioengineering and genetic alteration. An example is the work of the studio SymbioticA, which uses advances in induced pluripotent stem cells (iPSS) to address their artistic statement. In their piece *In Potentia* (2012), shown in figure 22, they created organized iPSS into a 'brain' with a life support network. The electrical impulses from the brain were then converted to digital signals that output as musical tones, in an effort to provide commentary on the obsession with consciousness arising from contemporary Western culture.

For architecture, the balance has been achieved outside the realm of scientific blending, finding answers to the form–function quandary. An example of this is the work of De Stijl architect Gerrit Rietveld, whose Schröder House (Utrecht, Netherlands, 1924) uses a minimal footprint and moving walls to create flexible space, figure 23. The functions—the standard home spaces of living, sleeping, bathing, eating—are blended with the form, using ideas of expansion and contraction to create dynamic, changeable space. No longer were the form and function static and compartmentalized, but space took on the form that the function required at the time, yet was available for other functions at their appropriate time. This house turned 'form ever follows function' on its head, proving that neither form nor function is subservient to the other, but are interrelated and dynamic.

(a) How architects have applied balance to incorporation of living nature's principles

For bioarchitecture, the successful blending of nature's principles at all scales requires a balance similar to that seen above in art's solutions for blending science and art, and architecture's solutions for blending form and function. For the incorporation of principles from living nature, the balance of concrete representation (aesthetics) and abstraction of principles (function) is a crucial one. If the object of inspiration is used in too concrete a manner, the architecture falls into the mimicry realm. If the object of inspiration is used in too abstract a manner, the principles are drawn out so far that the connection to the object of bioinspiration is lost. Bioarchitecture strikes the appropriate balance using principles not just for one part or element of the design, but by incorporating principles at all scales.

Figure 24 highlights examples of projects that are either too formal/aesthetic (too concrete) or too functional (too abstract) in their incorporation of principles from living nature. Here we see architects' attempts to incorporate nature, and where they have failed to strike an appropriate balance to be considered bioarchitecture.

blending science and art: bioart



In Potentia (SymbioticA, 2012)

Figure 22. Bioartists capitalize on scientific research in bioengineering and genetic alteration. Pictured is In Potentia, by SymbioticA (2012).

blending form and function: De Stijl



Schröder House, Utrecht, Netherlands (Rietveld, 1924)

Figure 23. Balance achieved by architecture outside the realm of scientific blending: Schröder House in Utrecht, Netherlands by Gerrit Rietveld (1924).

On the left side of figure 24, we see examples of projects that are too concrete (overly aesthetic) specifically mimicking the form of the lotus, a plant that holds a wealth of properties for bioinspiration. Pictured are the Lotus Temple in New Delhi, India, by Fariborz Sahba (1986); the ArtScience Museum in Singapore, by Moshe Safdie (2011) and the Lotus Building in Wujin, China, by Studio 505 (2013). All three of these take only the form of the lotus into consideration, not its properties, when creating the building. This is mimicry—while interesting to look at, nothing about the principles of the lotus has been extracted for use in the buildings; they are merely direct representations of the flower. However, the incorporation of the functions of the lotus leaf into the design and materials of a building, rather than merely copying the shape for the building itself, would be inspiration. If the architects had, for example, used the principles of the shape of the lotus leaf and its nanostructure to create a self-cleaning roof that mitigated the water run-off and the adapted grey water for use in the building or grounds maintenance, this would be at least the beginnings of bioarchitecture. If the architects had gone too far, for example, by incorporating only lotus-inspired materials such as self-cleaning glass into a structure that had no connection to the principles of the lotus, the abstraction loses its bioarchitectural balance.

form: too concrete

Lotus Temple, New Delhi (Sahba, 1986)



function: too abstract

Water Cube, Beijing, China (PTW Architects & Arup, 2007)



ArtScience Museum, Singapore (Safdie, 2011)



Lotus Building, Wujin, China (Studio 505, 2013)



Audubon Society, Columbus, OH (DesignGroup, 2009)



Bullitt Foundation, Seattle, WA (Miller Hull, 2012)



Figure 24. Using bioinspiration: examples of too concrete (left) and too abstract (right) appropriations. On the left, three buildings that mimic the form of the lotus: the Lotus Temple in New Delhi, India, by Fairiborz Sahba (1986); the ArtScience Museum in Singapore, by Moshe Safdie (2011); and the Lotus Building in Wujin, China, by Studio 505 (2013). On the right, three buildings that extract only materiality from objects of inspiration: the Water Cube in Beijing, China, by PTW Architects and Arup (2007); the Grange Audubon Society in Columbus, Ohio, USA, by DesignGroup (2009); and the Bullitt Foundation Center in Seattle, Washington, USA, by Miller Hull (2012).

On the right side of figure 24, we see examples of projects that are too abstract (over-functional). Pictured are the Water Cube in Beijing, China, by PTW Architects and Arup (2007); the Grange Audubon Society in Columbus, Ohio, USA, by DesignGroup (2009); and the Bullitt Foundation Center in Seattle, Washington, USA, by Miller Hull (2012). Here, the teasing out of the principles has gone so far that we cannot say that the building itself is bioinspired. In the Water Cube, self-cleaning materials were used to cover the water bubble design. However, nothing about the objects from living nature that inspired these materials can be said to inspire anything else about the design. In fact, at best, this building could be said to fall into inspiration from non-living nature, or, more properly, mimicry of non-living nature. For the Grange Audubon Society, many wonderful environmental principles were incorporated, from materials to landscape. However, there is no biologically derived inspiration that drives the design or creates a cohesive whole out of the kit of parts. The Bullitt Foundation Center is another building that incorporates incredible advances in green technology and green practices into the design. Its solar 'hat' that extends beyond the traditional (and technical) bounds of the site provides sufficient energy to supply the entire building, despite its site in cloudy Seattle. Further, it incorporates water cisterns, passive solar lighting and heating, cooling via operable windows, and an increased emphasis on

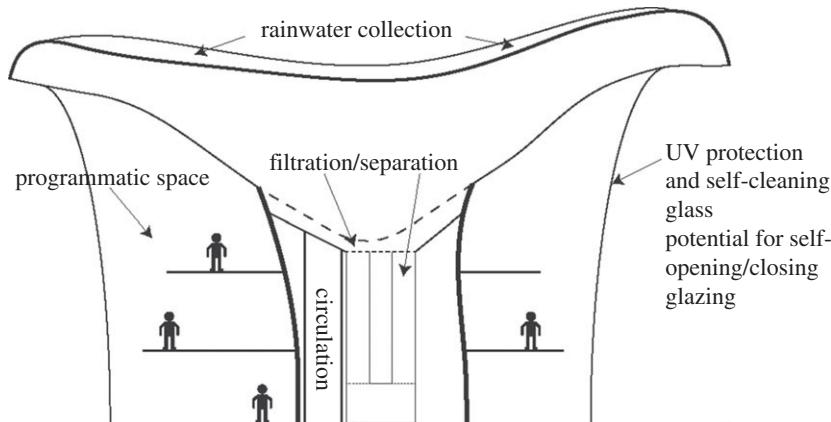


Figure 25. Schematic example of a potential bioarchitecture building by blending functionalities from various species in nature: the form of the lotus leaf can be used for both aesthetic and functional purposes to collect rainwater, as well as form the roof structure; superhydrophobic materials for surfaces can provide efficient collection of rainwater and ensure self-cleaning and antifouling surfaces; filtration provided by selective porosity can provide water for building uses; the principles of plant circulation can provide efficient transport of people through the structure; and principles from the operation of the human iris can provide self-regulation of heat and light by opening and closing the glazing (windows).

the health of the people in the building by prioritizing and encouraging use of stairs (also saving energy in decreased elevator use). However, though many of the materials and ideas may be derived from natural objects, again, there are no unifying, naturally derived principles that create the architecture.

(b) Where do we go from here?

Bioarchitecture, as we have defined it, is a practice yet to be achieved. We have seen the opportunities presented by biomimetics and bioinspired engineering discoveries, as well as areas of opportunity for further research, *table 1*. Here is a prime area for provocation: if scientists and artists/architects were to work together on future research, there is the potential for blending not only at the outset of a project, but from the inception of the research into properties and principles. We could see that scientific research could contribute not only to the advancement of its own field, but to the advancement of the discourse in art and architecture as well. A new niche and a new genre could form, though the parameters of such collaborations are left to those brave and willing enough to cross disciplines in this manner.

We have also seen the evolution of artistic and architectural practice, where incorporation of bioinspired parts advances the discipline. However, we have also witnessed the pitfalls of this burgeoning field. Too concrete or direct a use of biomimetics, and its use will overtake the architectural design, resulting most often in mimicry. Too abstract, and the architecture fails to connect to the biomimetic ideal and concomitantly fails to take advantage of the full scientific opportunity presented. What we can see from these examples is that there is a balance to achieve between form and function; between ornament/aesthetics and adaptation of principles. Architects have found a solution to this balance through previous practice; in architectural parlance, a balance is struck between 'ducks and decorated sheds' [74]. In this balance lies the opportunity for architects to integrate bioinspired design at all scales and at the root of the design process, creating bioarchitecture.

We provide in figure 25 a schematic offering of bioarchitecture, blending properties and functionalities from various species. If we look at the lotus leaf, we can engage not only its shape for aesthetic purposes, but for functional purposes, as it is ideal for rainwater collection. Using

nature-inspired superhydrophobic materials for the surfaces of the roof structure, we can provide efficient collection of that rainwater, and ensure a self-cleaning and antifouling surface as well, reducing cleaning and maintenance costs. Filtration of the collected water by selective porosity can provide potable water for building uses. By employing the principles behind plant circulation, the efficient transport of people en masse through the structure can be achieved. Finally, energy production and self-regulation of temperature and light can be achieved using principles from photosynthesis and the operation of the human iris.

Bioarchitecture, as a practice, can provide a means to cross disciplines and take advantage of scientific opportunities presented without pastiche or amalgamation, but instead through cohesive, thoughtful design practice. The impetus for future research and implementation is here.

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