

Bio-Inspired Daylighting: Relationships Between Six Biological Informed Design Frameworks

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ABSTRACT

This paper explores daylighting relationships between six bio-inspired design frameworks for nature-based strategies in architecture, including: biophilic, bioregional, bioclimatic, biomimetic, biomorphic, and biomaterial perspectives. How are these frameworks related, distinct, and/or integrated? The six bio-inspired frameworks discussed in this paper provide related but varied perspectives on nature and biology-inspired daylighting design. Integrating daylighting with one or more of these bio-inspired approaches is a strategic method to promote passive and low-energy strategies toward net-positive energy and sustainable design goals while simultaneously leveraging health benefits for humans, other species, and the planet. While designs inspired by nature and biology are found throughout architectural history, during the past decade - and particularly the past several years of the global pandemic - the relationship between nature, health, and light have gained increased attention in the design disciplines. This paper explores: 1) why a bio-inspired design perspective for daylighting is important, 2) how the six frameworks mentioned above might translate into daylighting design, 3) case studies of biophilic daylighting design at 10 Maggie's Centers (cancer care centers), 4) daylighting relationships between the six frameworks, and 5) lessons to expand contemporary daylighting design theory and practice.

Keywords: Daylighting Design, Bio-inspired Design, Biophilic Design

INTRODUCTION:

This paper explores the relationships between six different bio-inspired design frameworks for daylighting-focused, nature-based strategies in architecture. The frameworks include biophilic, bioregional, bioclimatic, biomimetic, biomorphic, and biomaterial perspectives. Each of the six bio-inspired frameworks provides a different perspective on nature and biology-inspired daylighting design. Integrating daylighting with one or more of these bio-inspired approaches is a strategic method to promote passive and low-energy strategies toward net-positive energy and sustainable design goals while simultaneously leveraging health benefits for humans, other species, and the planet.

A growing body of scientific research has developed supporting the positive impacts of human contact with nature through strategies such as gardens, views, daylight, natural materials, and nature symbolism and imagery.^{1 2 3} While nature and biology inspired designs are found throughout architectural history, during the past decade - and particularly the past several years of the global pandemic - the relationship between nature, health, and light have gained increased attention in the design disciplines.⁴ Architects Pamela Mang and Bill Reed, of the *Regenesis Group*, illustrate the important relationship between access to nature and sustainability: "...it is only in relationship to place that humans experience the intimacy and responsibility to the living world and find a meaningful identity and role for themselves... The caring about a mutuality of relationship that comes from deepening connection with a living place is essential to launching and sustaining a regenerative process."⁵ Towards this end, the paper explores: 1) why a bio-inspired design perspective for daylighting is important, 2) how the six frameworks mentioned above might translate into daylighting design, 3) case studies of biophilic daylighting design at 10 Maggie's Centers (cancer care

centers), 4) daylighting relationships between the six frameworks, and 5) lessons to expand contemporary daylighting design theory and practice.

WHY A BIO-INSPIRED DAYLIGHTING PERSPECTIVE?

Daylighting has long been revered by designers - and building occupants - for its aesthetic, atmospheric, and experiential benefits, which can be readily coupled with sustainable design performance goals and metrics. The importance of daylighting and electric lighting for health and sustainability benefits is reflected in the ever-growing number of related performance metrics, such as the Living Building Challenge, LEED, Fitwel, and the WELL Building Standards.⁶ The evolution of solid-state lighting, controls, and other more efficient and versatile electric lighting technologies has led to an evolution in the role of architectural daylighting. While daylighting still plays a key role in energy and greenhouse gas reductions, electric lighting efficiency improvements have reduced the impact of daylighting to offset lighting loads.⁷ With this shift, the focus of daylighting has begun to expand to include its potential to improve occupant health and wellbeing. Daylighting is a primary means for designers to provide occupants with views of nature; awareness of changing patterns of sun, wind, weather, time, and seasons; and enriched sensory experiences of nature's sounds, smells, and visual and nonvisual phenomena. Documented physiological benefits of daylighting include improved visual comfort, reduced fatigue, and the significant impact on circadian rhythms to improve sleep, mood, cognitive abilities, and decrease stress hormones.^{8 9 10} Architectural daylighting is inherently bio-inspired and responsive to nature; however, strategies must be approached intentionally to achieve health and sustainability goals. The following discussion explores the intersections between daylighting design and six bio-inspired design frameworks.

What is Bio-Inspired Design?

The terms "nature" and "biology" are not easily defined, as these concepts have evolved over time, and they vary based on discipline. For the purpose of this paper, "biology" is defined as: *"The plant and animal life of a region or environment, and the life processes especially of an organism or group."*¹¹ The concept of "nature" is broadly defined to include all life forms, including human and other species: *"Nature" refers to the phenomena of the physical world, and to life in general... The term "nature" may refer to living plants and animals, geological processes, weather, and physics, such as matter and energy. The term often refers to the "natural environment"... and in general areas that have not been substantially altered by humans, or which persist despite human intervention.*¹²

The concept of "biophilia" (from *bio*: life + *philia*: love of) was introduced by psychologist Eric Fromm in his 1973 book *The Anatomy of Human Destructiveness*: *"Biophilia is the passionate love of life and of all that is alive; it is the wish to further growth, whether in a person, a plant, an idea, or a social group."*¹³ Biologist and naturalist E.O. Wilson popularized the term in his seminal 1984 text *Biophilia: The Human Bond with Other Species*.¹⁴ Wilson's "Biophilia Hypothesis" suggests that there is an innate need for human connection with nature.¹⁵ Yet biophilic design is just one of a number of bio-inspired design strategies. Others include design perspectives that are also informed by biology, nature, and environmental forces, including bioregional, bioclimatic, biomimetic, biomorphic, and biomaterial frameworks (Figure 1).

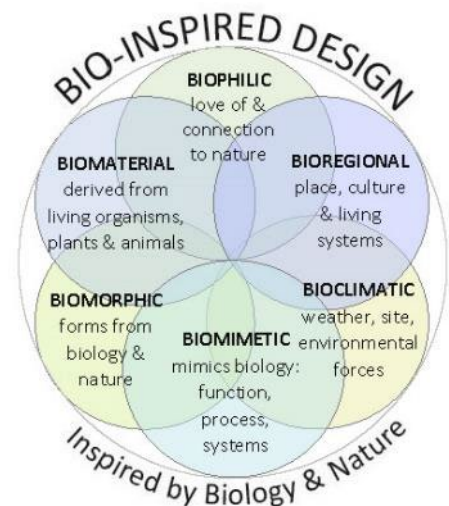


Figure 1: Six Bio-Inspired Design Frameworks: Biophilic, Bioregional, Bioclimatic, Biomimetic, Biomorphic, and Biomaterial.

Bio-inspired daylighting design can include any combination of these six frameworks. The definitions and design focus of each bio-inspired framework and how each might inform daylighting design are compared in Table 1, below. While each framework has specific daylighting design goals and strategies, all are concerned with enriching the dynamic and living relationships between the occupants, design, and local contexts, such as the unique conditions of place, site, culture, environmental forces, local flora and fauna, materials, form, processes, and/or ecological systems.

HOW THE BIO-INSPIRED FRAMEWORKS TRANSLATE INTO DAYLIGHTING DESIGN


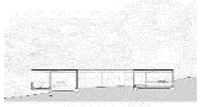
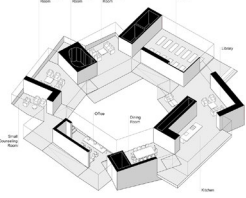





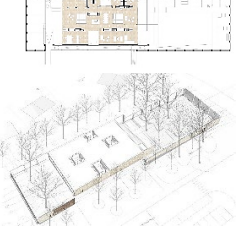

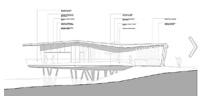

The integration of daylighting with the six frameworks reveals distinctions as well as similarities and overlaps. Biophilic daylighting design strategies to foster experiences of nature and environmental forces are most easily integrated with all frameworks and across daylight consideration of site, building, room, and details. Bioregional and bioclimatic daylighting design respond to the specific luminous conditions of the region, site, and micro-climatic forces of place and nature. Biomimetic and biomorphic approaches to daylighting draw inspiration from the forms, processes, systems, or materials of nature (biomorphic is a subcategory of biomimetic that focuses on form). Biomaterials - broadly defined here as materials that are derived from living organisms such as plants and animals; minimally processed and/or retain attributes of nature - can be integrated with other frameworks to consider luminous opportunities of structure, finishes, and detailing (Table 1).



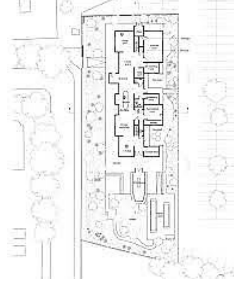




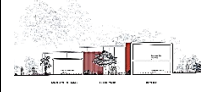







BIOPHILIC Connections to nature for health & well-being	BIOREGIONAL Respond to regional forces, nature, and systems	BIOCLIMATIC Respond to site & climatic forces	BIOMIMETIC Mimic nature's form, process, systems, materials	BIOMORPHIC Mimic nature's forms (subcategory of biomimetic)	BIOMATERIAL Utilize materials derived from living organisms (plants & animals)
Daylight Goals Daylighting to provide connections to nature for health, experiential, and ecological benefits. ¹⁶	Daylight Goals Daylighting to celebrate the unique qualities of region and place, including climate, culture, flora, fauna, landscape, topography, water, ecological systems, etc. ¹⁷	Daylight Goals Daylighting response to site and bioclimatic forces: Sun, wind, daylight, humidity, solar radiation, precipitation, etc. ¹⁸ Daylight integration with passive solar & natural ventilation.	Daylight Goals Daylighting strategies inspired by biology and nature's biomimetic form, process, systems, and materials. ¹⁹	Daylight Goals Daylighting forms inspired by nature. 1) Anatomical Biomorphism: inspired by human anatomy, 2) Vegetal Biomorphism: inspired by plants, 3) Zoomorphic Biomorphism: inspired by animals. ²⁰	Daylight Goals Daylighting relationship to "natural" material selections, particularly those derived from living organisms such as plants and animals. ²¹ Emphasis on minimally processed, non-toxic, cruelty-free, biodegradable, materials, etc.. ^{22 23}
Strategies - Daylight emphasis on health and wellbeing. - Siting, form, and envelope for views & connection. - Envelope and sensory experiences. - Luminous properties of materials, forms, details. - Atmosphere appropriate to program - place.	Strategies - Daylight emphasis on regional conditions for siting building form, and envelope. - Optimize the specific qualities and connections to the region, site, landscape, flora, fauna, and ecological and natural systems.	Strategies - Daylight response to specific site and micro-climate forces and conditions. - Integration of passive strategies for light, heat, air. - Diurnal and seasonal conditions. - High-performance and renewable systems.	Strategies - Daylight emphasis on lessons from biological forms, processes, systems, and/or materials to inform design across scales. - See also Biomorphic.	Strategies - Daylight emphasis on biological form to inspire massing, section, and details. - Subcategory of Biomimetic.	Strategies - Daylight emphasis on luminous properties of structure, materials, and details. - Minimally processed, healthy materials. - Consider luminous qualities of reflectivity, absorption, transparency, translucency, etc.

Table 1: Comparative summary of daylighting goals and strategies for six bio-inspired frameworks.

EXAMPLE ILLUSTRATION OF BIO-INSPIRED DAYLIGHTING IN SELECT MAGGIE'S CENTERS

To explore the six bio-inspired daylighting frameworks, ten Maggie's Centers were compared to consider how daylighting strategies were employed in projects with design concepts explicitly related to nature to foster health and well-being. Over the past three decades, leading architects from around the world have designed, or are planning, thirty-four Maggie's Centers at National Health Service (NHS) hospital sites in the United Kingdom and abroad. These facilities provide non-medical care for people with cancer along with their families, friends, and caregivers. Whether explicit or implicit, each of these ten projects illustrates a combination of bio-inspired daylighting concepts. A comparative summary of bio-inspired and daylighting concepts and strategies at the select Maggie's Centers is provided in Table 2.

TEN BIO-INSPIRED MAGGIE'S CENTERS	PROJECT	SPATIAL ORGANIZATION	Biophilic	Bioregional	Bioclimatic	Biomimetic	Biomorphic	Biomaterial	KEY: BIO-INSPIRED FRAMEWORKS X _ Emphasis X _ Secondary X _ Tertiary
	1. Maggie's Glasgow: 2011 Architect: OMA Landscape: Lily Jencks 		X	X	X			X	Emphasis: Biophilic
			Concept: "... a ring shape around a landscaped internal courtyard ... nestled among the woodland." ²⁴ Strategies: Interlocking spaces around internal garden. • Sidelighting: Views in and out to garden, woodland, and prairie. Borrowed light and views between spaces. • Skylight: wood clad meditation space with views to sky. • Floor to ceiling glazing; transparent & translucent glazing. • Wood, glass, concrete; domestically scaled furnishings. ²⁵						
	2. Maggie's Aberdeen: 2013 Architect: Snøhetta with Halliday Fraser Munro 		X			X	X	X	Emphasis: Biomorphic
			Concept: Pavilion in a parklike setting. ²⁶ "Pebble or shell on the grass; creating a feeling of safety and protection." ²⁷ Strategies: Single and two-story volumes in a shell-like form. • Sidelighting for views to the site and garden. • Exterior and second floor terrace; connect to earth and sky. • Reinforced concrete shell, timber and glass. • Warm interior finishes with protective shell. ²⁸						
	3. Maggie's Lanarkshire: 2014 Architect: Reiach-Hall Landscape: Rankinfraser 		X	X	X			X	Emphasis: Biophilic
			Concept: "...matrix of garden courtyards; porous ...extension of landscape; visibility and outlook; places of privacy & inook." ²⁹ Strategies: Sheltering linear building; exterior & interior gardens. • Perforated brick wall wraps rectilinear building (east-west). • West garden entry and private east garden; water features. • Sidelighting; views through building to rear garden. • Two courtyards; reflective lightwells capture sun and sky. • Two interior gardens with glass doors; views, light, and air. • White brick, white-washed wood, warm materials. ³⁰						
	4. Maggie's Oxford: 2014 Architect: Wilkinson Eyre, Landscape: Touchstone Collab. 		X	X	X			X	Emphasis: Bioregional
			Concept: "... a treehouse, ... maximizes the relationship between the inside spaces and its natural wildlife setting." ³¹ Strategies: Three elevated "wings"; extend into landscape. • Sidelighting connects to views, light, air, seasonal site. • Operable glazing and glass doors; sensory experiences. • Balconies: extend rooms into site. • Envelope: expanses of glazing with operable glass doors • Landscape: designed to protect adjacent land; woodland and water-edge plants; enhance wildlife and habitat. ³²						

TEN BIO-INSPIRED MAGGIE'S CENTERS	PROJECT	SPATIAL ORGANIZATION							KEY: BIO-INSPIRED FRAMEWORKS
			Biophilic	Bioregional	Biodinamic	Biomimetic	Biomorphic	Biomaterial	X _ Emphasis X _ Secondary X _ Tertiary
	5. Maggie's Manchester: 2016 Foster + Partners Landscape: Dan Pearson: 		X	X	X			X	Emphasis: Bioregional
			Concept: "Set in a peaceful garden, existing green space inspired design; natural themes to engage the outdoors." ³³ Strategies: Central spine; set in a garden landscape. <ul style="list-style-type: none"> • Linear building: skylight runs the length of spine. • Sidelighting and borrowed light from skylight for views, light, air, and seasonal solar. Therapeutic gardens. • Mezzanine level for more private spaces with sky connection. • Greenhouse for connection to growth and related activities. • Sheltered exterior terraces and outside garden rooms. • Exposed timber structure; warm materials, tactile fabrics.³⁴ 						
	6. Maggie's Oldham: 2017 Architect: Alex de Rijke, dRMM Landscape: Rupert Muldoon 		X	x	X			X	Emphasis: Biophilic & Biomaterial
			Concept: "...the building floats above a garden framed by pine, birch and tulip poplar trees. From a central oasis, a tree grows up through the building bringing nature inside." ³⁵ Strategies: Sheltered rectilinear form with views on south-north. <ul style="list-style-type: none"> • Building above a garden; open plan with east private spaces. • Sidelighting: views from seating on north and kitchen to south. • Exterior terraces on south extends kitchen to garden entry. • North moveable wall to adjust size and privacy of spaces • Smaller rooms contained in a "thick wall" to east. • Cross laminated timber interior & exterior, vibrant color.³⁶ 						
	7. Maggie's Royal Marsden: 2019 Abj Rogers Design Landscape: Piet Oudolf 		X	X	x			X	Emphasis: Biophilic
			Concept: "...four volumes, clad in red glazed extruded terracotta, and set in an idyllic garden...based on a diagram from users' experiences of existing centers." ³⁷ Strategies: Sited around a courtyard and communal kitchen. <ul style="list-style-type: none"> • Four volumes with different programs and atmospheres. • Sidelighting and clerestories: connect to site & link interior views. • Visual and physical connections to garden, courtyard, and sky. • Design to have sun track through interior throughout day, changing qualities of light in time and seasons. • Red terracotta exterior relating to existing buildings; interior high chrome colors related to activities.³⁸ 						
	8. Maggie's Yorkshire: 2019 Architect: Heatherwick Studio Landscape: Heatherwick Studio 		X	x	X	x	X	X	Emphasis: Biophilic
			Concept: "...[building as] a grouping of large-scale planters of varying sizes...The rooftop garden, native English species..." ³⁹ Strategies: Four "garden planters" built into a sloping site. <ul style="list-style-type: none"> • Interlocking forms with views into adjacent gardens. • Sidelighting and clerestories connect to gardens and interlocking spaces for views, light, and air. • Exposed wood timber structure, plaster, and natural finishes. • Informal spaces; people encouraged to engage building.⁴⁰ 						
	9. Maggie's Cardiff: 2019 Architect: Dow Jones Architects Landscape: Cleve West 		X	X			X	X	Emphasis: Biomorphic and Bioregional
			Concept: "A series of pitched roofs...provide an uneven and undulating collections of pitches that look both like a bunching of houses and the local [mountain] landscape." ⁴¹ Strategies: Sheltering exterior street form and envelope. <ul style="list-style-type: none"> • Protective envelope wraps building on the east, south and west; floor-to-ceiling glazing opens to north garden. • Sidelighting to east, south, and west: small apertures in private spaces; protective atmosphere; Welsh tradition • interior, warm finishes, soft furniture.⁴² 						



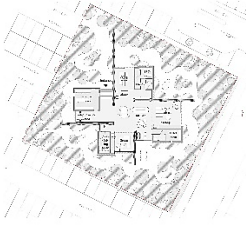
TEN BIO-INSPIRED MAGGIE'S CENTERS	PROJECT	SPATIAL ORGANIZATION	Biophilic	Bioregional	Bioclimatic	Biomimetic	Biomorphic	Biomaterial	KEY: BIO-INSPIRED FRAMEWORKS X _ Emphasis X _ Secondary X _ Tertiary	
			X	X	X			X		Emphasis: Bioregional
	10. Maggie's Southampton: 2021 Architect: AL_L Landscape: Sara Price 		Concept: "...imagine that a piece of the garden had been transported from the New Forest... had always been there." ⁴³							
			Strategies: Pinwheel plan, four "blade" walls to gardens. No distinction between inside and outside spaces.... ⁴⁴							
			<ul style="list-style-type: none"> • Form developed for views, daylight, natural ventilation. • Four ceramic stoneware block walls reach into landscape. • Sidelighting: Operable glass walls connect to seasonal gardens. • Wood, concrete, metal, warm pastel colors. • Exterior corners clad in rippled stainless steel to reflect garden. • Landscape inspired by New Forest species.⁴⁵ 							

Table 2: Comparative bio-inspired and daylighting design concepts and strategies at ten Maggie's Centers.

Maggie's Centers Bio-Inspired Design Concepts

The designs of all ten projects were based on a language of nature, gardens, and/or related metaphors, including concepts such as: a ring around a garden courtyard, a pebble in the grass, a matrix of garden courtyards, the building as extension of the landscape, a treehouse, a peaceful garden, floating above a garden, an idyllic garden, garden planters, roofs like mountain, and a forest transported (Figure 2). Fostering a relationship between visitor, nature (site, flora, and fauna), and environmental forces (changing sun, wind, lighting quality, and time) are essential elements that give shape to each project. Note the frequency of biophilic, bioregional, and bioclimatic strategies, in which the unique and specific conditions of place, environmental forces, and local flora and fauna are celebrated through visual, physical, and sensory connections, as indicated previously in Table 2.

- BUILDING AS...**
1. A ring around a garden
 2. A pebble or shell in the grass
 3. A matrix of garden courtyards
 4. A treehouse
 5. A peaceful garden
 6. A floating space above a garden
 7. An idyllic garden
 8. Three garden planters
 9. A mountain landscape
 10. A forest transported

Figure 2: Nature design concepts for ten select Maggie's Centers.

Maggie's Centers Bio-Inspired Daylight Strategies

Daylighting is central in the design of each Maggie's Center siting, building form, section, envelope, window design and detailing to foster the health and sustainability benefits of designing with nature, site, and environmental forces. Common bio-inspired daylighting strategies include the following:

1. *Site for Light, Wind, and Nature:* The projects optimize site design and orientation for diurnal and seasonal access to sunlight, reflected light, and/or indirect daylight. Site design and envelope designs engage the changing weather, sky, day to night shifts, and seasonal luminous conditions.
2. *Landscape to Celebrate the Luminous Quality of Place:* Sensory experiences are integrated with luminous and thermal qualities of different landscape spaces, elements, and materials. Luminous and thermal variety gather seasonal light and heat or provide shade and refuge. Light patterns and shadow-play interact with landscape features, materials, colors, textures, and water elements.
3. *Make Nature a Visual and Luminous Focus:* Daylighting designs of the building form, windows, and envelope capture views, changing qualities of light over time, and physical, visual, and/or sensory connections. Strategies include sidelighting, skylights, courtyards, balconies, and terraces.
4. *Keep the Building Thin & Connected to Place:* The three common building forms include linear bars, clustered pods, and outstretched wings to gather light, air, sun, view, and garden access from

multiple directions. Four projects employ linear configurations with internal courtyards or gardens, four clustered pods (with one in a shell), and two thin or radial wings that reach into the site.

5. *Create Luminous Sections:* Building sections are kept thin or carved out (to become thin) with courtyards for light, air, views, and garden connections. Four projects employ open mezzanines for more private activities, while maintaining views and access to light, sun, air, and site.
6. *Design Envelope for Activities, Time, and Seasons:* Community gathering spaces include bi-lateral or multi-lateral daylighting with expansive sidelight glazing and operable doors for overlook and access to outdoor rooms. Quieter counseling and meeting spaces generally include bilateral light from clerestory windows and/or strategically placed sidelighting for views, while providing privacy. Windows are carefully considered to create program-appropriate relationships to light, air, and solar gains depending upon the desired atmosphere, activities, privacy, and season.
7. *Use Dynamic and Responsive Envelopes:* Envelope are designed to enable visitors and staff to engage landscape spaces. Adjustable windows, shading, drapes, and window treatments provide flexibility in adjusting luminous qualities on a seasonal and diurnal basis.
8. *Consider Window Orientation:* Daylighting is provided from multiple orientations to experience the changing diurnal and seasonal colors, sun angles, illumination levels, and atmospheric qualities of direct, indirect, and reflected light throughout the day and seasons. Consider morning, mid-day, afternoon luminous qualities and movement.
9. *Consider Luminous Properties of Natural Materials:* Materials are selected to create the desired atmosphere to foster health and well-being while providing appropriate luminous comfort. Eight of the ten projects employ a quiet and calm palette of warm materials, colors, and textures from timber, wood finishes, fabrics, soft furnishings, and warm colors. Two projects celebrate high chroma colors to create a dynamic and uplifting quality with colors symbolic of natural elements (earth, water, sun, sky, and plants).

DAYLIGHTING RELATIONSHIPS BETWEEN THE SIX BIO-INSPIRED FRAMEWORKS

Discussed below are “three options” that illustrate relationships between the six bio-inspired frameworks employed by the Maggie’s Centers:

1. *Option One: Biophilic, Bioregional, Bioclimatic, and Biomaterial Emphasis:* Seven of the ten projects emphasize a regional and place-centered approach to the daylighting to provide physical, visual, and sensory connections to site and nature. The relationships between these frameworks are illustrated in Figure 3 and include Projects 1, 3-7, and 10, in Table 2). The daylighting strategies are also integrated with seasonal considerations for natural

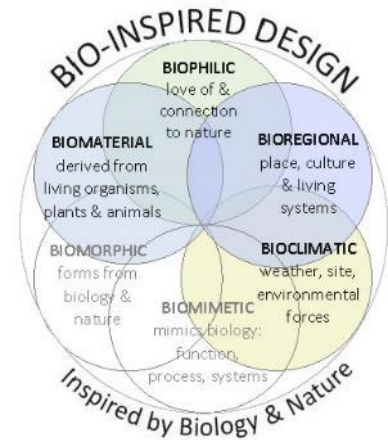


Figure 3: Option One: Biophilic, Bioregional, Bioclimatic, and Biomaterial Emphasis.

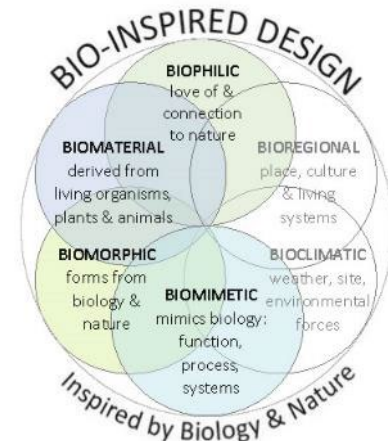


Figure 4: Option Two: Biophilic, Biomimetic, Biomorphic, and Biomaterial Emphasis.

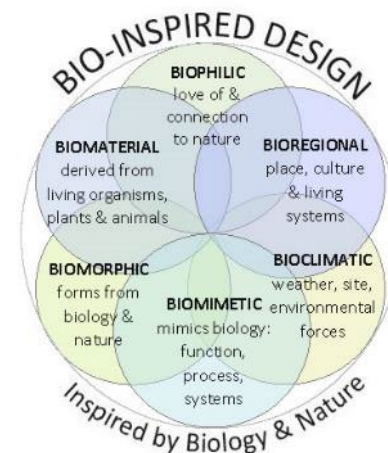


Figure 5: Option Three: Integration of six frameworks.

ventilation and passive solar. Luminous and thermal properties of materials are considered within the context of health and local and regional materials.

2. *Option Two: Biophilic, Biomimetic, Biomorphic, and Biomaterial Emphasis:* Two projects addressed biomimetic and/or biomorphic strategies to shape the building form and massing to evoke nature imagery or symbolism. The relationships between these frameworks are illustrated in Figure 4 and include Projects 2 and 9, in Table 2). The biomimetic and/or biomorphic strategies were the least common, with a focus on biomorphic form (a pebble in the grass and a mountain). The building forms, sections, and materials were also designed to respond to biophilic, atmospheric, and programmatic daylighting goals.
3. *Option Three: Integration of Six Frameworks:* Only one project includes daylighting strategies related to all six frameworks. The relationships between these frameworks are illustrated in Figure 5 and include Project 8, in Table 2). Biomimetic concepts informed the design of the overall building and site as a series of gardens (green roof and surrounding gardens replicate native English gardens), the biomorphic building massing as “three planting containers”, and the interior timber structure as a forest landscape. The sloped site and pod-like form of the building optimizes bioregional and bioclimatic strategies for daylight access between levels with visual and physical connection to the earth and sky throughout the day and seasons. Timber construction, warm finishes, and concrete floors connect to earth and forest to create a bright and welcoming luminous atmosphere.

CONCLUSIONS: LESSONS TO EXPAND DAYLIGHTING DESIGN THEORY & PRACTICE

A bio-inspired approach to daylighting design provides a powerful opportunity to integrate health and well-being with broader sustainable design goals. Several lessons to consider include:

1. *Use Regional and Place-Based Bio-Inspired Strategies:* When daylighting design strategies are coupled with bioregional and bioclimatic design strategies that harvest onsite sun and wind for passive solar integration, daylighting can foster human health connections to nature and environmental forces while reducing energy and greenhouse gas emissions.
2. *Explore Metaphoric, Symbolic, and Material Nature Strategies:* Biomimetic, biomorphic, and biomaterial strategies can celebrate nature symbolism, metaphors, and physical and sensory connections while also considering how daylight relates to form, finishes, and details to achieve health and environmental benefits.
3. *Intentionally Integrate Health and Sustainable Agendas:* Despite the complexity and challenges of integrating daylighting design strategies to foster health, while simultaneously considering energy, greenhouse gas reductions, and environmental impacts, it is only through such an integrated approach that these parallel advances and innovations in the lighting industry and allied design professions will foster ever-higher sustainable and regenerative design performance.
4. *Explore Biophilic Daylighting Design as the Overarching Framework:* Biophilic design could be considered an “overarching” bio-inspired framework that integrates the strategies and design benefits of the other five frameworks. Biophilic design guides (such as *Terrapin’s 15 Patterns of Biophilic Design* and Stephen Kellert and Elizabeth Calebrese’s *Experiences and Attributes of Biophilic Design*) can be used to explore the biophilic integration of the other frameworks.^{46 47} Biophilic daylighting strategies can intentionally integrate health and wellbeing benefits within the broader sustainability potentials of the other five frameworks.
5. *Consider Health Benefits to all Life:* Simultaneously consider how integration of bio-inspired daylighting strategies for health and sustainability can expand a human-centered approach to lighting design to also reduce impacts and benefit other species and the planet.

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ENDNOTES

- ¹ Browning, Bill and Ryan, Catie, *Nature Inside: A Biophilic Design Guide*. London: Royal Institute of British Architects, 2020, 5.
- ² Nikos A. Salingaros, "Biophilia and Healing Environments," New York: Terrapin Bright Green, 2015, <https://www.terrapinbrightgreen.com/wp-content/uploads/2015/10/Biophilia-Healing-Environments-Salingaros-p.pdf>.
- ³ William Myers, *Bio Design: Nature, Science, Creativity*, New York: Museum of Modern Art, 2019, 6-9.
- ⁴ Lee Jaewook, Mohamed Boubekri, Jiyoung Park, "Daylighting, Human Health, and Design for Sustainable Green Buildings; A Systemic Review," *Journal of Green Building* (2022) 17 (4), 151-178, <https://doi.org/10.3992/jgb.17.4.151>.
- ⁵ Pamela Mang and Bill Reed, "Designing from Place: A Regenerative Framework and Methodology", *Building Research and Information*, January 2012, 8-9.
- ⁶ International Living Future Institute, Seattle, WA: Living Building Challenge, <https://living-future.org/lbc/>; Leadership in Energy and Environmental Design (LEED), Washington D.C.: U.S. Green Building Council: <https://build.usgbc.org>; WELL Building Standard, New York: International Well Building Institute: <https://www.wellcertified.com/certification/v2/>; Fitwel, <https://www.fitwel.org/>.
- ⁷ U.S. Department of Energy, "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications, Washington D.C., 2019.
- ⁸ May Wo, Piers MacNaughton, Jaewook Lee, Brandon Tinianov, Usha Satish, and Mohamed Boubekin, "Access to Daylight and Views Improves Physical and Emotional Wellbeing of Office Workers: A Crossover Study, *Frontiers in Sustainable Cities*, Volume 3, 2021, <https://www.frontiersin.org/articles/10.3389/frsc.2021.690055/full>.
- ⁹ M. Knoop, et al. "Daylight What Makes the Difference? *Lighting Research and Technology*, 2020; 52: 423-442.
- ¹⁰ International WELL Building Institute, "Light," WELL Building Standard, version 3, <https://standard.wellcertified.com/v3/light>.
- ¹¹ Mirian Webster <https://www.merriam-webster.com/dictionary/biology> and Biology Dictionary: <https://biologydictionary.net/>.
- ¹² Ducarme, F. and Denis Couvet. (2020) "What does 'Nature' Mean? Palgrave Communications. <https://www.nature.com/articles/s41599-020-0390-y>. Environment and Ecology. "What is Nature?" <http://environment-ecology.com/what-is-nature/108-what-is-nature.html>.
- ¹³ Eric Fromm, *The Anatomy of Human Destructiveness*, New York: Holt Rinehart and Winston, 1973, 377.
- ¹⁴ Edward O. Wilson, *Biophilia: The Human Bond with Other Species*, Cambridge: Harvard University Press, 1984, 1.
- ¹⁵ Ibid.
- ¹⁶ Terrapin Bright Green, 15 Patterns of Biophilic Design: <https://www.terrapinbrightgreen.com/>.
- ¹⁷ Bioregional Congress, *Bioregions*: <http://wp.bioregionalcongress.net/>
- ¹⁸ US Green Building Council, *Bioclimatic Design*: <https://www.usgbc.org/articles/bioclimatic-design>
- ¹⁹ Biomimicry Institute, *Biomimicry*: <https://biomimicry.org/>
- ²⁰ Tanushree Saluja, "Characteristics of Biomimic Architecture," *Rethinking the Future*, <https://www.re-thinkingthefuture.com/architectural-styles/a3194-characteristics-of-biomimic-architecture/>
- ²¹ James Parkes, "The Dezeen Guide to Bio-based Materials in Architecture, Design, and Interiors," *Dezeen*, December 9, 2021, <https://www.dezeen.com/2021/12/09/dezeen-guide-biomaterials-architecture-design-interiors/>.

-
- 22 World Press, *Material Strategies: Innovative Applications in Architecture*: <https://arch5541.wordpress.com/>
- 23 Brownell, B. and M. Swackhamer, *Hypernatural: Architecture's New Relationship with Nature*. Princeton Architectural Press, 2015.
- 24 Maggie's Centres, "Architecture and Design – Glasgow", <https://www.maggies.org/our-centres/maggies-glasgow/architecture-and-design/>.
- 25 OMA, "Maggie's Gartnavel, Office Work", <https://www.oma.com/projects/maggie-s-centre-gartnavel>.
- 26 Maggie's Centres, "Architecture and Design – Aberdeen", <https://snohetta.com/projects/23-maggie39s-cancer-caring-centre>.
- 27 Snohetta, Maggie's Caner Caring Center, <https://snohetta.com/projects/23-maggie39s-cancer-caring-centre>.
- 28 Ibid.
- 29 Maggie's Centres, "Architecture and Design – Lanarkshire", <https://www.maggies.org/our-centres/maggies-lanarkshire/architecture-and-design/>.
- 30 Charles Blahut, "Maggie's Lanarkshire" *Architect*, October 15, 2015, https://www.architectmagazine.com/project-gallery/maggies-lanarkshire_o.
- 31 Maggie's Centres, "Architecture and Design – Oxford", <https://www.maggies.org/our-centres/maggies-oxford/architecture-and-design/>.
- 32 WilkinsonEyre, Maggie's Centre, Projects: <https://www.wilkinsoneyre.com/projects/maggies-centre>.
- 33 Maggie's Centres, "Architecture and Design - Manchester", <https://www.maggies.org/our-centres/maggies-manchester/architecture-and-design/>.
- 34 Foster + Partners, Maggie's Manchester, Projects, <https://www.fosterandpartners.com/projects/maggie-s-manchester/>.
- 35 DRMM Studio, "Maggies Oldham": <https://drmmstudio.com/project/maggies-oldham/>.
- 36 Maggie's Centres, "Architecture and Design - Oldham", <https://www.maggies.org/our-centres/maggies-oldham/architecture-and-design/>.
- 37 AB Rogers, "Royal Marsden": <https://www.abrogers.com/portfolio/maggies-at-the-royal-marsden/>.
- 38 Maggie's Centres, "Architecture and Design - Royal Marsden", <https://www.maggies.org/our-centres/maggies-at-the-royal-marsden/architecture-and-design/>.
- 39 Heatherwick Studio, "Maggie's Centre", <https://www.heatherwick.com/project/maggies/>.
- 40 Maggie's Centres, "Architecture and Design - Yorkshire", <https://www.maggies.org/our-centres/maggies-yorkshire/architecture-and-design/>.
- 41 Heatherwick Studio, "Maggie's Centre", <https://www.heatherwick.com/project/maggies/>.
- 42 Ibid.
- 43 AL_A, "Maggie's Southampton, UK", <https://www.ala.uk.com/selected-projects/maggies-southampton/>.
- 44 Ibid.
- 45 Maggie's Centres, "Architecture and Design - South Hampton", <https://www.maggies.org/our-centres/maggies-southampton/architecture-and-design/>.
- 46 Terrapin Bright Green, 15 Patterns of Biophilic Design: <https://www.terrapinbrightgreen.com/>.
- 47 Kellert, S. and E. Calabrese, *The Practice of Biophilic Design*, 2015, <https://www.biophilic-design.com/>.