

Nocturnal Light: Exploring the Perceptual Experience of Bioluminescence

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Submitted toward the fulfillment of the requirements for the Doctor of Architecture degree

School of Architecture

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We certify that we have read this Doctorate Project and that, in our opinion, it is satisfactory in scope and quality in fulfillment as a Doctorate Project for the degree of Doctor of Architecture in the School of Architecture, University of Hawai'i at Mānoa.

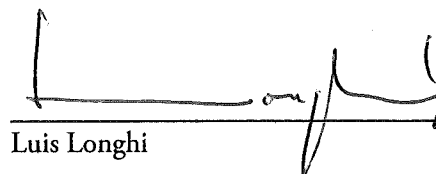
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Inspiration

It was winter of 2005. My friend Kevin and I went night fishing at a beach on O‘ahu’s south shore that would later become my most frequented fishing spot. As we set up our poles in the dark, I noticed an unusual flicker in the sand. My first reaction was that it was a reflection of the moon on a particle of sand. As my eyes adjusted to the darkness, more glowing specks were perceived along the shore, revealing themselves slowly. Kevin noticed my eyes wandering along the shore. “It’s bioluminescence,” he said.

That night was only one week into my very first semester in architecture school. I never would have expected that the phenomenon I became curious about nearly seven years ago would become the research subject to conclude my lifelong educational journey.

Abstract

At night, light has a remarkable impact on our visual perception. While modern lighting applications have fascinating effects in environments at night, the living light of bioluminescence has abilities that produce unique effects in these environments. By designing with bioluminescent light, we take advantage of a natural and regenerative light source to support new perceptions of nocturnal environments.

In determining the design capacity of bioluminescence, experimentation confirms three unique abilities of luminous algae that contrast the abilities of artificial lighting: (1) Reactive; blue light emitted as a response to physical movement (2) Nocturnal; light produced at night due to natural circadian rhythm (3) Organic; living and self-contained light with a prospect for future prominence. Image renderings visualize these abilities by introducing bioluminescence in existing nocturnal environments; as a result, bioluminescent light evokes curiosity and engagement, building an interactive experience between man, nature and light.

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Research Methods

<i>Quantitative</i>	The biology of bioluminescence and the properties of artificial lighting were topics utilizing a quantitative approach. These themes had ample and accurate data that were confirmed and validated by various sources where specific quantifiable information involving factual or scientific properties could easily be verified.
<i>Qualitative</i>	The visual quality and perceived characteristics of bioluminescence as well as the case studies required a qualitative approach. These areas of inquiry did not possess specific quantifiable data and therefore were confirmed through consistency of descriptive characteristics from various sources and personal experiences.
<i>Descriptive</i>	Analysis of the rendering exercises and the design models used a descriptive methodology where observations were initially acknowledged and subsequently analyzed in relation to the overall topic.
<i>Correlational</i>	Several relationships were compared including light and perception, artificial and natural light, light and design, and light and experience. Some of these comparisons involved a predictive approach whereas others used a relational approach to evaluate associations of existing relationships.
<i>Experimental</i>	Design experiments tested the performance of bioluminescent algae in varied conditions to answer questions related to its design abilities. The image renderings were also experiments of bioluminescent light because its abilities were tested through visual representation.

Literature Review

This dissertation encompasses a diverse range of topics beginning with the night time.

The history of the night in Western civilization is summarized in *At Day's Close: Night in Time's Past* by A. Roger Ekirch. Ekirch stresses that people were very productive at night until artificial lighting extinguished the nocturnal facets of night. He also explains a revolutionary rediscovery of man's historical sleep cycle, where dual, four-hour periods of rest are separated by a few hours of complete wakefulness. This rediscovery challenges the generally prescribed eight-hour recommendation of sleep each night.

Contrasting an historical perspective, *Nightshift NYC* continues the sociological investigation of the night in modern times. This resource provides documentation of the biological and psychological experiences of shift workers in New York City through personal interviews. Those studied include hospital workers, janitors, servers, telephone operators, police officers¹ and others. *Nightshift NYC* reflects the experiences of New York City residents but does not necessarily reflect an overall attitude toward shiftwork. *The Night Shift* provides a more comprehensive view of the issues that shift workers face, such as sleeplessness, relationships, inebriation, and early morning wakefulness². Although the main focus of these two sociological sources are labor and productivity, these books aid in understanding the usefulness of architecture at night to society.

Spiritual and experiential testimonials in defense of a dark night sky are documented in *Let There Be Night*, with the basis of each stemming from reasons such as energy conservation, spirituality, imagination, and the historical nature of mankind. Although a qualitative collection of strong opinions for preserving a dark night sky, there are credible perspectives worth considering. For example, Christian Luginbuhl explains that light pollution causes spiritual and financial losses through wasted artificial light.³ Jennifer Westerman, a former park ranger, speaks out about her experiences safely guiding sea turtles to water that are disoriented by artificial light.⁴ Therefore

¹ Sharman, Sharman, Hayes, *Nightshift NYC*, 15.

² Sharman, Sharman, Hayes, *Nightshift NYC*, 17.

³ Bogard, *Let There be Night*, 199

⁴ Bogard, *Let There be Night*, 197

insight was gained into real individual experiences and emotions regarding a dark night sky through *Let There Be Night*.

As a form of light, bioluminescence was initially examined through two books by E. Newton Harvey; Harvey thoroughly studied bioluminescence starting in the early 20th century. *Bioluminescence* and *Living Light* by Harvey both introduced the topic in layman's terms to cover basic and advanced principles governing bioluminescent light. For example, Harvey reviewed the recent history of bioluminescence starting in the 1800's and referenced a dead "glowing" chicken, in which bioluminescent bacteria developed on it once rotten. He also identified hundreds of bioluminescent organisms, giving rise to a comprehensive list of species still in circulation today. While complex, the chemical process of bioluminescence was explained and characterized for each luminous species, providing two of most complete resources devoted to the study of bioluminescence.

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Glossary of Terms

<i>Apparent luminance</i>	Perceived luminance based on amount of visible light
<i>Absolute luminosity</i>	A definite level of luminosity measured in foot candles or lux
<i>Bioluminescence</i>	The emission of light by living organisms
<i>Bioluminescent algae</i>	A general descriptor for any luminous algae, phytoplankton or dinoflagellate
<i>Brightness</i>	Perceived luminosity of light relative to surroundings
<i>Circadian Rhythm</i>	A natural cycle in humans and organisms necessary to facilitate bodily functions throughout a 24-hour period
<i>Dinoflagellate</i>	A single-celled organism, usually marine and sometimes photosynthetic
<i>Diurnal</i>	Of or relating to the day
<i>Growth medium</i>	Liquid solution used to culture and sustain bioluminescent algae, usually in the form of purified seawater
<i>Illuminance</i>	Amount or density of light directed at surfaces or objects
<i>Luminance</i>	Measurable quantity of light reflected from surfaces or objects
<i>Luminescence</i>	Light emission that radiates no heat; chemiluminescence, fluorescence, phosphorescence and bioluminescence are forms of luminescence
<i>Luminesce</i>	The act of luminescence
<i>Luminous</i>	Possessing the ability to emit light
<i>Nocturnal</i>	Of or relating to the night
<i>Pyrocystis spp.</i>	A genus of bioluminescent algae; typical species include <i>fusiformis</i> , <i>lunula</i> and <i>noctiluca</i>

<i>P. fusiformis</i>	Abbreviated term for <i>Pyrocystis fusiformis</i> , a species of bioluminescent algae
<i>P. lunula</i>	Abbreviate term for <i>Pyrocystis lunula</i> , a species of bioluminescent algae
<i>Phytoplankton</i>	Marine algae or bacteria that have photosynthetic properties; synonymous with algae in this study

Introduction

PROJECT GOALS

The goals of this project are (1) to bring awareness to a unique form of light, (2) to introduce potential design applications of bioluminescent algae and (3) compose new perceptions of nocturnal environments through bioluminescence.

The outcome of this research provides a foundation for understanding the characteristics and design potential of bioluminescence while foreshadowing its future applicability and abundance.

INITIAL HYPOTHESES

The initial question of inquiry was: “As cities continue to grow through space, is it possible to disperse people through time as well?” This question draws from the rise of globalization and 24-hour accessibility to predict the need for a 24-hour type of architecture. However, this architectural type was difficult to justify after research on human biological processes as well as the privatization of accessible space at all hours.

The focus of this dissertation shifted towards bioluminescence as a design material. Due to its perceived abilities, bioluminescence appeared to have potential architectural applicability. This formed the basis for the design exploration of bioluminescence.

SUMMARY OF RESEARCH

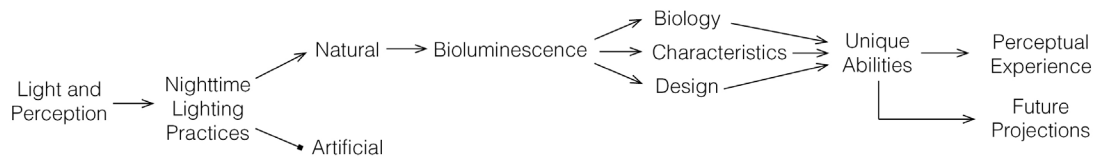


Figure 1 The research path explored in this document, source: author

Visual perception involves a process of gathering visual information, analyzing the information to expect an experiential effect based on our interpretation of the initial visual information. Case studies present various lighting practices at night ranging from practical to impractical and bright to dim. These design models use light to increase interpretations of nocturnal settings through challenging expectations of the existing setting. In addition, they demonstrate that the introduction of constructed light builds an alternate perception of the space without requiring significant architectural constructs or modifications of physical context.

Lighting sources are compared with bioluminescence, a natural form of light. The comparison indicates strong design potential in bioluminescent light, justifying why the light should be further examined in this dissertation.

Bioluminescence is natural light produced by living organisms. Background research of bioluminescence confirms its first unique ability as a divergence from artificial lighting practices:

Organic and regenerative-Living and self-contained light with reproductive and photosynthetic capabilities

Scientific utilizations of bioluminescence establishes its conventional role as a biosensor but modern design models utilizing bioluminescent organisms have only taken place as recently as 2008. Thus this dissertation capitalizes on the opportunity to explore bioluminescence as an experimental design material.

The existing design capacity of the material is introduced through precedents involving the deliberate design of bioluminescent organisms. Algal forms of bioluminescence demonstrate greater capabilities than bacterial organisms due to distinct abilities unlike other luminous organisms.

A series of experiments confirm the algae's perceived abilities and guide the material towards design comprehension. Real bioluminescent algae samples (*Pyrocystis lunula* and *Pyrocystis fusiformis*) are obtained and kept under constant 12-hour light and dark cycles to sustain their natural circadian rhythm.

The algae exhibited luminesce exclusively during the “dark” cycle due to circadian rhythm and mechanical stimulation. The simulated cycles of light and dark also highlight that someone without specific training can easily manipulate the circadian rhythm of the luminous algae. Two distinct displays of luminescence of *Pyrocystis spp.* are classified through observation (1) Active bioluminescence - a bright flash directly proportional to the force of applied stimulation and (2) Passive bioluminescence - a sustained, faint twinkling in highly concentrated amounts of algae when lightly agitated.

Two more unique abilities are confirmed:

Response to stimuli -Physical stimulation required to catalyze luminescence.

Expression of a natural circadian rhythm -The ability to sense night and day, where blue light is emitted at night during the dark cycle.

Further experimentation demonstrates that (1) luminous algae are resilient organisms, (2) increased darkness strengthens visual perceptions of the algae, and (3) active flow of liquid is the main stimulus responsible for triggering the chemical reaction in bioluminescence.

Two sheets of acrylic build the basis for understanding bioluminescence's architectural applicability. A droplet of algal substance is spread thinly between the two sheets. Surprisingly in darkness, luminescence is observed only in areas touched. This test demonstrates that: (1) luminescence requires little liquid, (2) a touch-responsive surface is practical with this material and (3) the responsive surface has unrestrained geographic applicability due to its organic nature. This demonstration is consequently referred to as the *sheet method*.

Far from perfect, the experimentation helps to identify several technical challenges of bioluminescent algae: (1) the necessity of a containing device, (2) maintenance of the living organisms and (3) adequate visual contrast in darkness.

Bioluminescent light becomes visualized through rendered simulations of selected nocturnal scenarios. The scenarios are: (1) urban environments, (2) future urban environments and (3) natural environments. These simulations diversify existing perceptions of each setting through the distinguished abilities of bioluminescence. The results of the rendering simulations are:

- (1) Urban environments: Bioluminescent light twinkling over an alleyway to build curiosity toward a negatively attributed space.
- (2) Future urban environments: Bioluminescent walkways animated by the movement of pedestrians in a darker city context.
- (3) Natural environments: 1st scenario-Bioluminescent vials floating offshore to provoke an altered engagement of the shoreline; they emit light as a response to wave and tide movement.

2nd scenario-Translucent bioluminescent sheets were interlaced between tree canopies in a forest setting to expand our interpretation of a forest trail at night; luminescence is activated by tree movement, wind movement and falling leaves.

By representing the abilities of bioluminescent light in these settings, the experience of the light is depicted more accurately. Natural and human interactions activate a subtlety and curiosity of the light that couldn't have been predicted without the use of graphic visualization. Furthermore, the overlay of bioluminescence onto existing environments is accomplished through minimal material constructs and no electrical infrastructure. Thus, the experience communicated by bioluminescent light supports an increased perception of nocturnal environments through an entirely unique lighting practice.

Bioluminescent algae have strong potential as a considerable resource of the future. Prospective conditions such as climate change and a resource shift toward algae are foreshadowed as an

opportunistic context for bioluminescence. Rising atmospheric temperatures are continuing to generate natural growth of bioluminescent algae in open oceans while algal farms across the world are cultivating algae to be used food and fuel alternatives. If additional research is carried out, it's plausible that bioluminescent algae will be repurposed for fuel or food after its lifespan as a lighting element.

There are tremendous design opportunities for further investigation of bioluminescent organisms beyond algae. By examining these organisms and their abilities, we will be able to fully understand and harness the entire design potential of bioluminescence.

1

Light and Perception

1.1 Light and Perception

1.2 Design Models

1.3 Light in Perspective

1.4 Chapter One Conclusion

Chapter One explains how light contributes to the visual perception of our world by introducing design models that use light to mold our perceptions and through the comparison of various light sources.

1.1 Light And Perception

“The eye adapts to light levels automatically; the mind responds to information.”⁵

William M.C. Lam, 1977

Our environments change constantly. These changes occur physically and/or perceptually,⁶ where we expect, recognize, and interpret information in order to perceive.⁷ If perception shapes our experience of a space, then light significantly contributes to shaping this perception.

Visual perception occurs externally, where our eyes pick up reflections from surfaces and transmit the information from receptor cells in the retina⁸ to the brain. This process is coupled by the phase of expectation, where past experiences from our memory contribute to this perception. As humans, we prescribe to this automatic process every day.

According to author William Lam, perception involves a three-step process.⁹

1. The *attributive* stage of perception makes what we see meaningful and occurs directly after the brain receives visual information. Here, we understand and interpret objects and environments to validate what we see.
2. The next stage called *expectation* processes the interpreted visual information to rationalize or recognize patterns or previous associations. For example if the organizational layout of a city is recognized, we can predict the layout of areas that haven't been explored.
3. The final *affective* stage ultimately predicts the outcome and behavior of the perceived visual information, referring to past encounters to judge how the recognized information will affect us emotionally and experientially.¹⁰ Therefore sight and perception are dissimilar since perceiving requires further steps to evaluate what's visualized to predict an experiential effect.

⁵ Lam, *Perception and Lighting*, 70

⁶ Lam, *Perception and Lighting*, 31

⁷ Lam, *Perception and Lighting*, 35

⁸ Michel, *The Shape of Light*, 8

⁹ Lam, *Perception and Lighting*, 33

¹⁰ Lam, *Perception and Lighting*, 34

Designers such as Dan Flavin (1933-1996) have established that lighting molds our perception of space. Flavin, known to “combine traditions of painting and sculpture in architecture with acts of electric light defining space,”¹¹ is recognized for his use of fluorescent luminescence as a design medium in the creation of site-specific installations that interact with constructed environments. These interactions suggest that altered perceptions of space are subject to viewer interpretations.

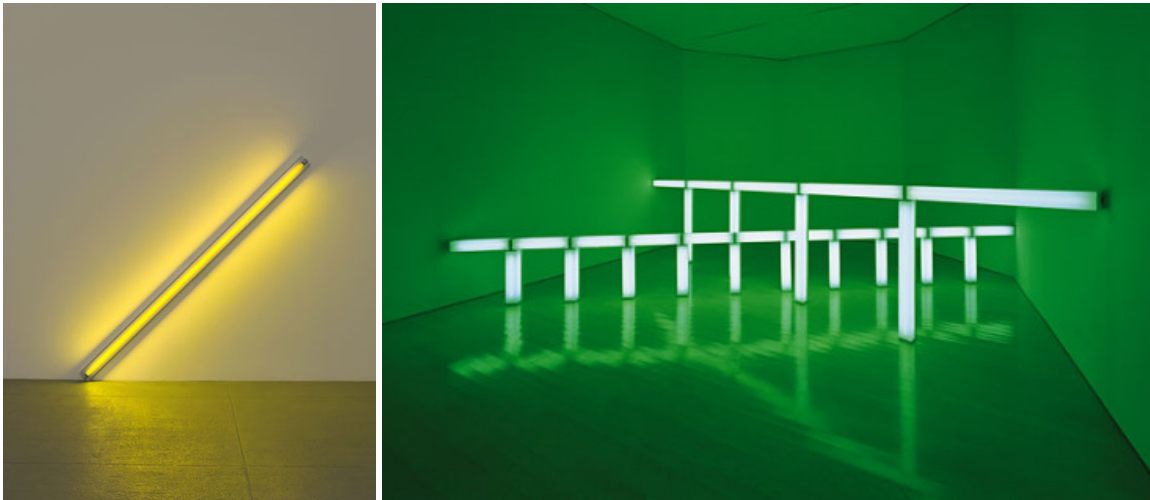


Figure 2 “the diagonal of personal ecstasy”¹²

Figure 3 “greens crossing greens”¹³

Flavin’s early work, although nearly half a century ago, questions what’s expected of an industrial light source. His unconventional way of utilizing light provokes reconsideration of the spatial dynamics of a room and his work has gone onto become more complex and colorful over the years, furthering light as an exploratory spatial element.

Another artist, Olafur Eliasson, has demonstrated how nature can artificially infuse itself into built environments, bridging the gap between architecture and art through three-dimensional installations. Like Flavin, Eliasson employs light as a constant medium throughout his projects, highlighting that light has a consistent impact on human visual perception.

¹¹ Raghen, *The Architecture of Light*, 11

¹² Dan Flavin, *the diagonal of May 25, 1963 (to Constantin Brancusi)*, 1963, Yellow fluorescent light, 8 ft. (244 cm) long on the diagonal, Dia Art Foundation, Beacon.

¹³ Dan Flavin, *greens crossing greens (to Piet Mondrian who lacked green)*, 1966. Green fluorescent light, first section: 4 ft. (122 cm) high, 20 ft. (610 cm) wide; second section: 2 ft. (61 cm) high, 22 ft. (670 cm) wide. Solomon R. Guggenheim Museum, New York, Panza Collection.

The Weather Project, staged in London's Tate Modern, is one of Eliasson's most recognized works. A large, artificial light simulates the sun within an indoor space to fuel the desire for natural light and artificially mimic the weather around us. This model is dynamic, using fog and changes in illumination to reevaluate our perception of an indoor space. The desired effect is accomplished through the yellow, subdued quality of the light which alters not only our expectation of indoor artificial light but the traditional interpretation of an interior space. Through this work Eliasson highlights the often unnoticed disparity between sight and visual perception.



Figure 4 Eliasson's Weather Project replicates the sun through artificial light¹⁴

In these examples, light and darkness are easily controlled and manipulated due to an enclosed, interior setting. Today, current lighting practices employ light in existing nocturnal environments to alter visual perceptions without completely altering the physicality of the context.

¹⁴ Olafur Eliasson, the Weather Project, 2003. (Turbine Hall, London, UK)
http://www.olafureliasson.net/works/the_weather_project.html.

1.2 Case Studies

At night, natural and sociological environments are constantly changing (*see Appendix to learn more about shiftwork*). The dark night sky is an ideal background for constructed light due to increased visual perceptibility. The following models showcase fabricated light through various practices and environments at night without substantial physical constructs to support entirely new visual and architectural perceptions of each setting.

555 KUBIK, Hamburg, Germany 2009

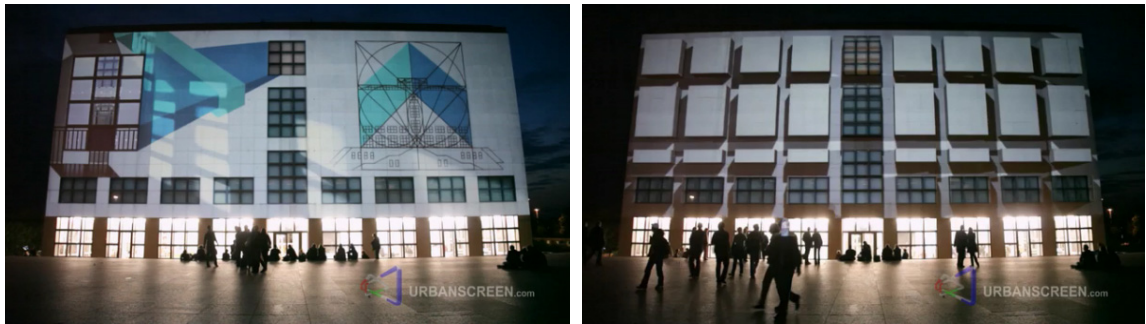


Figure 5 Video projection technology allows for a dynamic façade¹⁵

Video projection onto building façades are now a commonplace nighttime practice as a creative and artistic expression. Pictured above is URBANSCREEN's project titled "555 Kubik," which engulfs the façade of a Hamburg art museum. This example represents dynamic illumination as a means of reinterpreting the Hamburg building itself.

As a result, the information we absorb is visualized as luminance on the façade. This causes us to process the information absorbed and perceive it relative to our understanding of past experiences with the same façade in order to analyze and judge how the new information will consequently affect us. Therefore the effect varies individually depending on past encounters with the environment and technology, as well as past encounters with the perceived video information.

Most importantly, through this technology, we perceive an alternate nocturnal environment in addition to the existing setting; thus, the weightless addition of projected light composes a new architectural understanding of the setting.

¹⁵ "555 Kubik," URBANSCREEN, accessed April 4, 2012, <http://www.urbanscreen.com/usc/41>.

VECTORIAL ELEVATION, Vancouver, B.C. 2010



Figure 6 Searchlights act as spatial markers¹⁶

Another example of the use of illumination to reconstruct how nocturnal environments are perceived is Vectorial Elevation by Rafael Lozano-Hemmer. As a synthesis of architecture, light and global communication, eighteen searchlights organize into positions that are programmed through a public website.¹⁷ Visibility of the light stretches fifteen kilometers and attracts the attention of hundreds of thousands of viewers worldwide.

Again, this design model utilizes a high concentration of light as a form-giver to a visible and perceivable structure while being both weightless and temporal. The light source used was xenon, which contains a wire filament within a gas container to stabilize the temperature of the light to allow for greater lumens-per-watt efficiency than traditional incandescence.¹⁸

As a catalyst for the altered understanding of this specific setting, the light itself strongly imposes an ethereal architectural form onto the existing architectural context, suggesting that an alternate spatial experience is fabricated purely through light.

¹⁶ Douglas Farmer, "False Creek Spot Light Test," photograph, 2010, *Douglas Farmer Photography*, http://www.douglasfarmerphotography.com/2010_01_01_archive.html.

¹⁷ Lozano-Hemmer, *Algunas Cosas Pasan Mas Veces Que Todo El Tiempo / Some Things Happen More Often Than All of the Time*, 69

¹⁸ Xenon vs LED Flashlight Bulbs, Fenix Flashlight, last modified September 4, 2011, <http://www.fenixlight.com/blog/post/2011/09/04/Xenon-Versus-LED-Flashlight-Bulbs-What-is-the-Difference.aspx>

LUMINARIE DE CAGNA CATHEDRAL, Light Festival Ghent, Belgium 2012

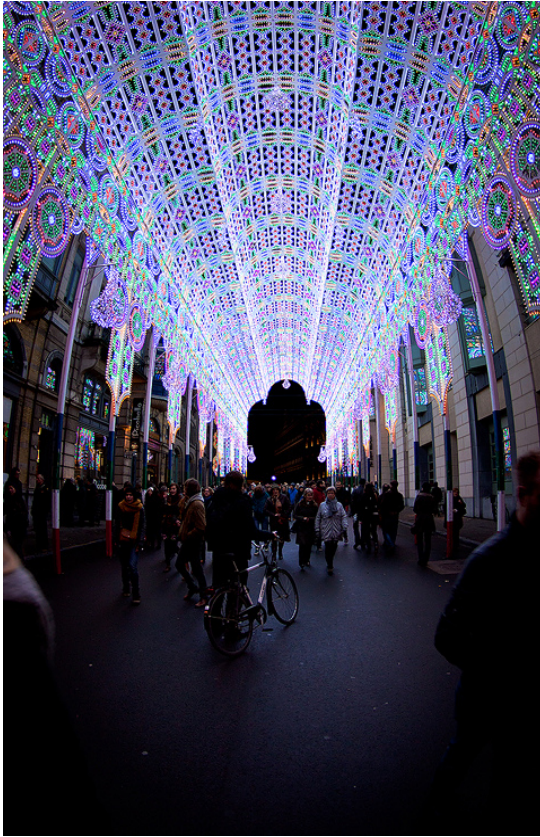


Figure 7 A “cathedral” constructed of LED lights shapes our perception of this space at night¹⁹

Another environment at night is shaped through low luminosity LED lighting. At a light festival in Belgium, a full-sized “cathedral” is constructed completely out of LEDs. The project is designed by Luminarie De Cagna, a company that has specialized in artistic light installations since the 1930s.²⁰ The design utilizes existing buildings as a supporting structure where the 55,000 LEDs span over an existing street to enclose public liminal space.

The Luminarie De Cagna Cathedral presents visible light in a precise manner through a variety of colors and with consistent luminosity. A deeper perception of this space is born through its aesthetic intricacy that arguably cannot be conceived during the day. This project embodies a luminous aesthetic rather than an illuminated method in contrast with previous case studies. Here, the shaping of visual perception is accomplished in low luminosity, adding to the lighting methods that affect our understanding and experience of a space at night.

¹⁹ “Cagna Illuminations,” Light Festival Ghent, accessed March 3, 2012, <http://www.lichtfestivalgent.be>

²⁰ Luminarie De Cagna company website, last modified April 4, 2012, <http://www.decagna.com>.

LUCEDENTRO CERAMIC MOSAIC



Figure 8 Photoluminescent ceramic tiles in light and darkness²¹

As a non-electrical light source, photoluminescent technology by the company Lucedentro allows this bathtub to glow in the dark.²² Photoluminescence is the absorption and emission of light through the exchange of photons.²³ In this example, photoluminescent substances are infused into hundreds of ceramic tiles to produce a soft glow, changing the way we view and experience this tub. This application of photoluminescence illustrates that small amounts of luminosity can lead to significant perceptual changes of the space.

Without the use of electricity, this case study demonstrates how chemically-based light becomes integrated into an ordinary environment. A new perception of the room is born, along with a new experience of the entire washroom.

²¹ Illuminating Tile Mosaic - glowing in the dark tiles by Lucedentro, Trendir, February 10, 2010, <http://www.trendir.com>

²² Products, Lucedentro company website, accessed April 2, 2012, <http://www.lucedentro.com/eng/prodotti.aspx>

²³ Photochemical reaction, International Union of Pure and Applied Chemistry, accessed April 4, 2012, <http://goldbook.iupac.org/P04585.html>.

Review of Case Studies

These case studies represent the diversity of models which use light (and a degree of darkness) to impose or overlay of additional layer of understanding within a setting. Through the perceptual process, visible light greatly contributes to the overall experience and atmosphere.

Due to the apparent darkness of these models, it should be kept in mind that the human eye naturally adapts to surrounding lighting conditions. This phenomenon, called light adaptation,²⁴ takes 10 to 30 minutes and is crucial while observing light or luminance at night or in complete darkness. Through this process the human eye becomes 600 times more sensitive to light at night than in the day.²⁵ Therefore individual experiences of these case studies depend on both light adaptation and associative expectations of the environments and lighting practices presented.

WHAT'S WAS GATHERED?

1. Temporal or ethereal applications of light bring new dimensions of understanding to nocturnal settings without requiring considerable architectural or structural elements.
2. Visible light increases our visual perception of an environment at night by revealing information that wasn't originally perceived.
3. Light occurs in a multiple forms, environments, colors and luminosities; therefore the application of light should be appropriately suited for the proposed environment to produce the desired effect.
4. Contrast is an important compositional element towards accurately perceiving visible light.

²⁴ Michael, *The Shape of Light*, 17

²⁵ Clark, "Notes on the Resolution"

WHAT'S MISSING?

1. These models do natural variables such as wind and rain as part of the design context. Also, the diurnal character of these examples are missing.
3. Individual user interactions and emotional experiences are unknown and vary due to personal assumptions and perceptions.
4. These case studies do not encompass the myriad of light sources available today.

The following section compares various light sources to understand each selected light relative to one another. The sources chosen are not a comprehensive list of light sources but represent common or familiar types. This comparison also introduces a natural form of light called *bioluminescence*.

1.3 Light in Perspective

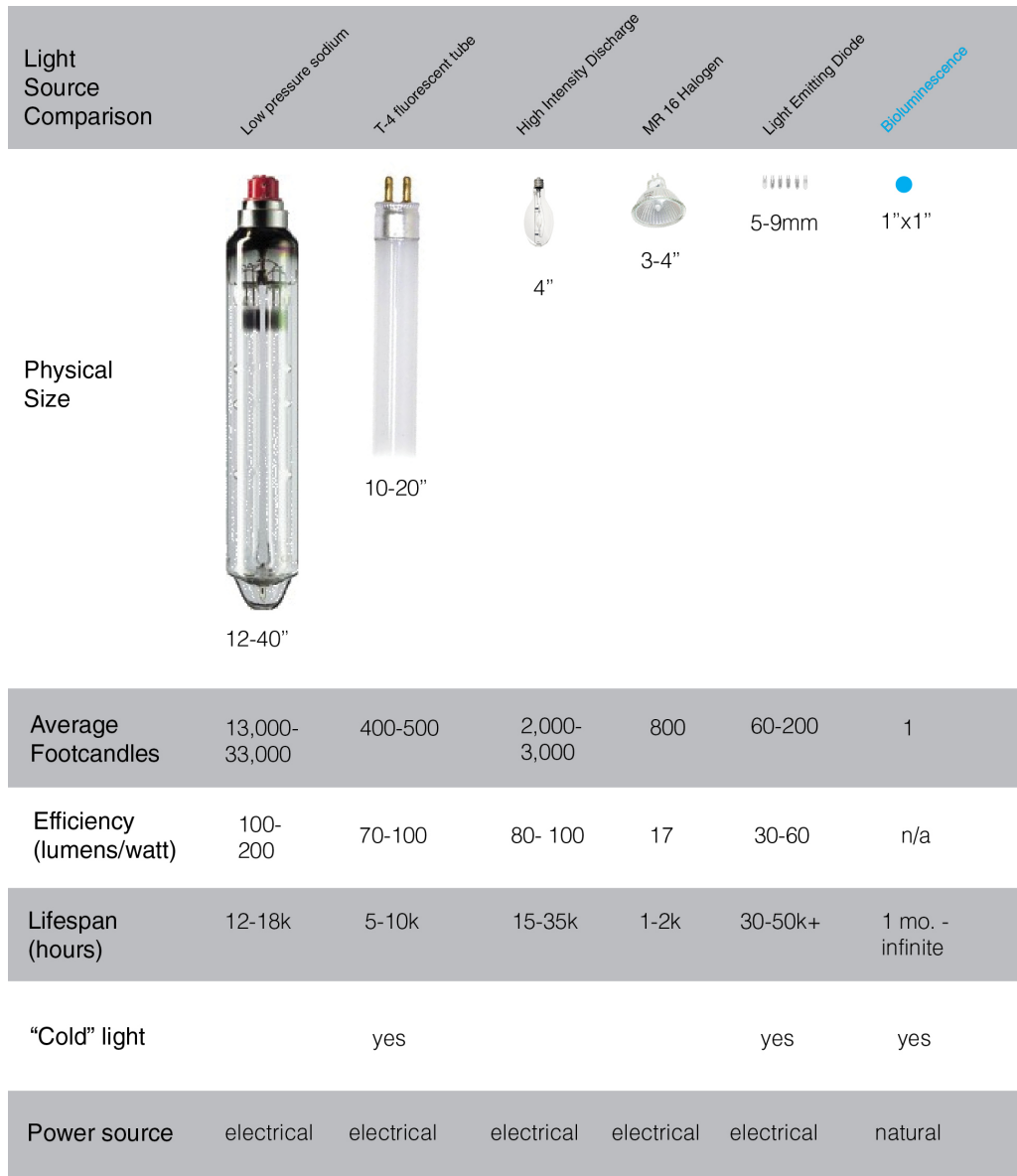


Figure 9 Comparison of various light sources, source: author

The chart above compares various lighting sources ranging from conventional incandescent bulbs to low pressure sodium streetlights. Of all the lights described, there are drastic differences in the characteristics of bioluminescent light that contrast other lighting types. The physical size of bioluminescence compared to its lumen output is relatively insignificant but its natural and "cold" properties are rare in any documented light source. "Cold" refers to minimal amount of radiant heat emission from the light.

DISTINCTION OF BIOLUMINESCENT LIGHT

As a lighting practice, bioluminescence is attractive as a unique form of light. Due to its natural origin, bioluminescence not require electrical infrastructure. Therefore its implementation works in a wide range of physical scales while dismissing the need for structural framework. Certain bioluminescent organisms are known to possess a regenerative quality, strengthening its potential for growth and cultivation. Natural forms of light, such as the moon and stars cannot be directly harnessed and manipulated by man; whereas bioluminescence is a natural light available for human manipulation. This possibility builds a strong case for bioluminescent light to be physically designed. These propositions prompt bioluminescent light to be further examined as a lighting practice in order to expand on the possibilities of artificial lighting in nocturnal environments.

LUMINESCENCE

To understand bioluminescence further as a light source, it is a type of luminescence. Luminescence characterizes the creation of light with little or no thermal heat radiation. Fluorescence, phosphorescence, photoluminescence and chemiluminescence are other forms of luminescent light sources. Chemiluminescence and bioluminescence both require a chemical reaction to produce non-electrical light.

Like bioluminescent light, chemiluminescence uses luciferin and luciferase in conjunction with ATP to produce light. For example, a glow stick uses chemiluminescent technology to combine the same chemical components of bioluminescence it is cracked and shaken. The real distinction of bioluminescent light is that it's a living form of light rather than a chemically-based light.

1.4 Chapter One Conclusion

Visual perception is an important process towards guiding our experience of spaces at night. Today, modern lighting practices transform architectural experiences of nocturnal spaces, often with minimal constructs. In addition to the various forms and intensities of lighting applied the deliberate and careful integration within the proper context is most conducive to achieving the desired experiential result.

After various forms of light are identified, the contemporary models did not utilize any natural forms of light. Due to its drastic differences in size, luminosity and origin from other artificial light sources, *bioluminescence* is a potentially unique lighting practice. The next chapter elaborates on this natural source of light.

2

A Natural, Living Light

2.1 Bioluminescence

2.2 Design Models

2.3 Chapter Two Conclusion

Chapter Two introduces bioluminescence and explains its basic characteristics. Design models utilizing constructed bioluminescent light provide an overview of existing design research related to the material.

2.1 Bioluminescence

“A world without a sun and without fire would be no means be a dark world.”

-E. Newton Harvey 1940

Bioluminescence is the visible light emitted from living organisms. Known as “living light,” bioluminescence is derived from *bio* in Latin and *luminescence* in Greek.²⁶ Perennial or nocturnal darkness has led to the biological development of this natural light. Bioluminescence is critical for organisms’ survival in underwater environments, caves, coastal areas and various other habitats.

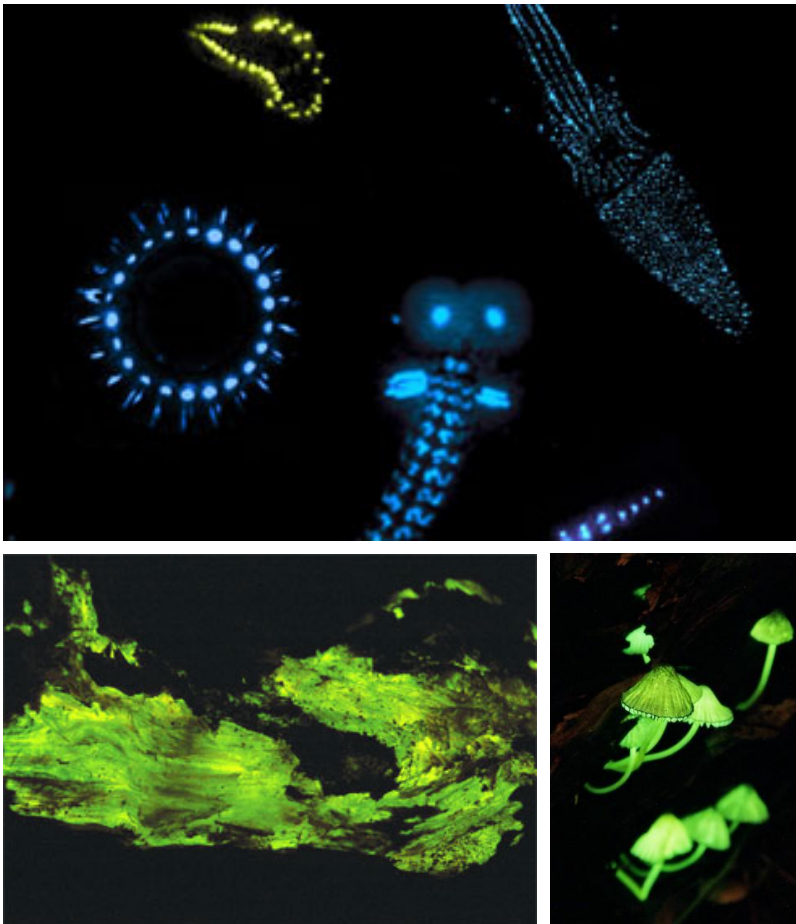


Figure 10 Various forms of bioluminescence including marine organisms, luminous wood and glowing fungi²⁷

²⁶ Horsburgh, *Living Light: Exploring Bioluminescence*, 15

²⁷ (1) Edith Widder, untitled, photograph, 2008, *NOVA scienceNOW*, <http://www.pbs.org/wgbh/nova/nature/bioluminescent.html>.

(2) John Denk, “The glow of honey mushroom hyphae.” photograph, 2008, *Chicago Wilderness Magazine*, http://chicagowildernessmag.org/issues/fall2008/myn_foxfire.html.

(3) Mainichi Shimbun, untitled, photograph, 2005, *Pink Tentacle*, <http://pinktentacle.com/2006/05/rainy-season-brings-glow-in-the-dark-mushrooms/>.

TYPES OF ORGANISMS

Bioluminescent organisms have evolved as much 50 times throughout history to represent hundreds of species.²⁸ Fireflies and anglerfish are well-known for their luminous abilities. The following list conveys the diversity of bioluminescent organisms recognized today:²⁹

- Fungi
- Algae and phytoplankton
- Bacteria
- Sharks and rays
- Squid and jellyfish
- Bathypelagic fish
- Fireflies
- Centipedes and millipedes

(See appendix for comprehensive list)

NATURE'S USE OF BIOLUMINESCENCE

Every luminous organism has evolved to bioluminesce for vital reasons. Darkness or the nighttime is crucial for the perceptibility of bioluminescence. Therefore relative darkness corresponds to the effect of the light to other organisms. The following list summarizes these organisms' biological uses described by Haddock, Moline and Case:³⁰ startle, counter-illuminate, misdirect, distract, "burglar alarm," lure prey, stun prey, illuminate prey, and attraction.

(See appendix for entire list of biological uses)

²⁸ Haddock, Steven H.D., Moline, Mark A., and Case, James F. "Bioluminescence in the Sea" (2010), *Annual Review of Marine Sciences* (2010): 10.1146/annurev-marine-120308-081028.

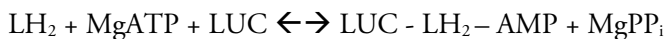
²⁹ Source: Haddock, Moline and Case, "Bioluminescence in the Sea," 445

³⁰ Source: Haddock, Moline and Case, "Bioluminescence in the Sea," 464

HOW IT WORKS

Bioluminescence is the product of a chemical reaction. In 1885, Raphael Dubois discovered the components of the chemical reaction required to produce light when experimenting with luminous clams in hot and cold water.³¹ According to Dubois, bioluminescence uses two primary chemicals: luciferase (catalytic enzyme) and luciferin (light producing pigment). Basic bioluminescent light requires these two chemicals and the addition of oxygen. Luciferase combines with oxygen and triggers luciferin to produce oxyluciferin and light. Oxyluciferin is a neutral byproduct while light is the main product of the chemical reaction.³²

Step one where a catalyzing element calls luciferase to react:



Step two where luciferase reacts with oxygen to trigger luciferin to produce light:



Although unnecessary to fully understand the chemistry behind this reaction, the ability for light to be self-contained in each luminous organism provides evidence for the efficiency of bioluminescence. (See appendix for more information regarding this reaction)

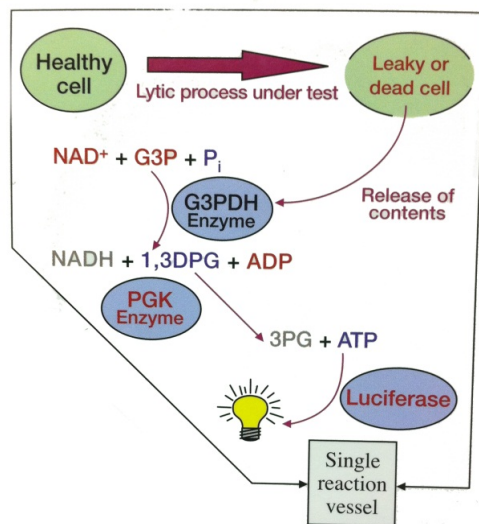


Figure 11 Basic chemical reaction in bioluminescence found in fireflies³³

³¹ Horsburgh, *Living Light: Exploring Bioluminescence*, 22

³² Chemistry of Bioluminescence, The Bioluminescence Web Page. last modified Jan. 5, 2012.
<http://www.lifesci.ucsb.edu/~biolum/chem/index.html>

³³ Source: cover image, *Coupled Bioluminescence Assays*

BIOLUMINESCENCE IN SCIENCE

Currently, bioluminescence is used by scientists around the world to test for existence of luciferin, luciferase and ATP in various types of media. Bioluminescence light provides immediate feedback as a product of chemical reactions to become an effective research tool. The following are a list of random assays of that use bioluminescence in varied experiments:

- Detection of bacterial contamination in the food industry³⁴
- Pesticide and bacterial monitoring in freshwater³⁵
- Metal and mercury detection in water sources³⁶
- Measurement analysis of biomass in living matter³⁷
- Estimation of contamination intensity in biomass³⁸
- Detection of alien life forms through NASA's Life on Mars program
- Characterization of ATP, luciferin and luciferase

Despite such widespread laboratory uses for bioluminescence today, there is unsubstantial design research proposing bioluminescence as a design material. The following section represents recent design explorations conducted by designers and researchers.

³⁴ Corey, *Coupled Bioluminescent Assays*, 3

³⁵ Corey, *Coupled Bioluminescent Assays*, 251

³⁶ LaRossa, *Bioluminescence Methods and Protocols*, 221

³⁷ Brolin and Wettermark, *Bioluminescence Analysis*, 104

³⁸ Brolin and Wettermark, *Bioluminescence Analysis*, 115

2.2 Bioluminescent Design Models

Few designers have studied bioluminescence as a design medium beginning in 2008, a recent time ago considering the thousands of years of its known existence. Thus, the design potential of the material continues to evolve.

BIOPIXELS, BIOLUMINESCENT BACTERIA (*E. coli*)

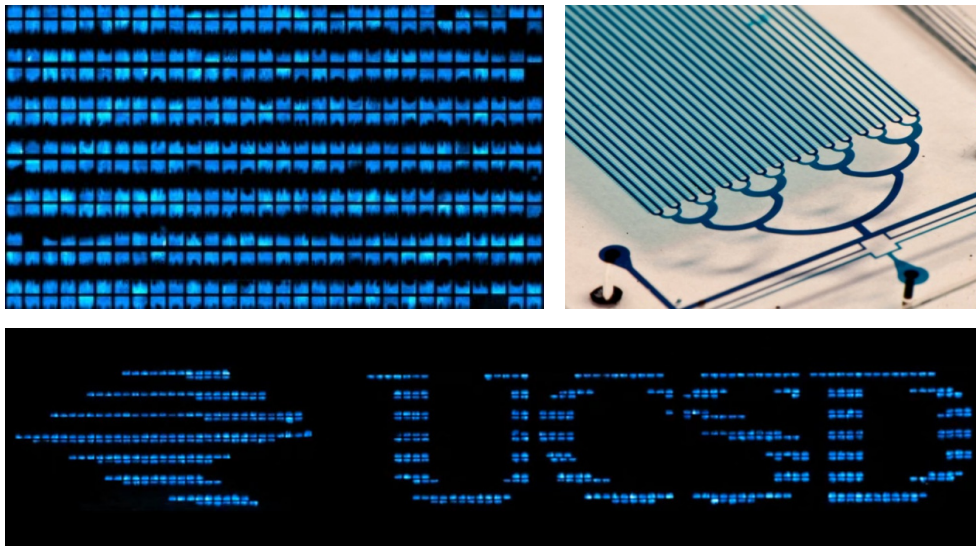


Figure 12 Biopixels, a project by UC San Diego that builds a microchip-sized billboard with luminous bacteria³⁹

At the University of California at San Diego, researchers were able to program thousands of “pixels” of bioluminescent *E. coli* on a 1cm size chip by regulating the pollutant level of each individual pixel to control light output. The *E. coli* bacterium glows 24-hours a day.

The 1cm tall luminous chip fits in a person’s palm therefore the practical use of this application as a viable light source remains unknown due to its size. However, the Biopixels project makes a huge impact in showcasing the potential properties of bioluminescent bacteria and its ability to become designed and manipulated.

³⁹ MacDonald, Kim, “Researchers Create Living ‘Neon Signs’ Composed of Millions of Glowing Bacteria,” December 18, 2011, UCSD Division of Biological Sciences, <http://biology.ucsd.edu/>.

BIO-LIGHT, BIOLUMINESCENT BACTERIA (*E. coli*)



Figure 13 The Bio-light uses luminous bacteria to produce as a potential light source⁴⁰

Royal Philips Electronics (also known as Philips) built a design concept for a light source containing gallons of bioluminescent bacteria. The design composes individual glass chambers which contain bioluminescent bacteria in liquid form; the luminescent organisms feed on compost and methane via a silicone tube for sustenance.⁴¹ Here, the design is envisioned as a stand-alone light fixture.

While the Bio-light doesn't provide powerfully bright light, the potential for bioluminescence to become a viable light source is exemplified through this project. Practical challenges in this experiment include constant maintenance of the luminescent bacteria, consistent lux output and the control of light output.

⁴⁰ Philips, "Biolight," photograph, 2011, Philips company website, http://www.design.philips.com/philips/sites/philipsdesign/about/design/designportfolio/design_futures/bio_light.page.

⁴¹ "Bio-light," Philips company website, accessed February 4, 2012, <http://www.design.philips.com>.

E. GLOWLI, BIOLUMINESCENT BACTERIA (*E. coli*)



Figure 14 Reading under bioluminescent light of *E. coli* bacteria⁴²

Students at the University of Cambridge conducted a series of experiments with bioluminescence to evaluate its potential for chemical manipulation. The project is named E glowli, similar to the bioluminescent bacteria *E. coli*. The experiments demonstrated codon optimization could increase color and brightness.⁴³

The team fabricated a bioluminescent light to showcase the improved brightness in *E. coli*. The student team also hypothesized applications of bioluminescence in urban settings, such as emergency lighting and integration in street tree canopies to replace conventional street lights.

⁴² “E.glowli Cambridge,” University of Cambridge, accessed February 3, 2012, <http://2010.igem.org/Team:Cambridge>.

⁴³ “E.glowli Cambridge,” University of Cambridge, accessed February 3, 2012, <http://2010.igem.org/Team:Cambridge>.

INSTALLATION BY NICOLA BURGGRAF, BIOLUMINESCENT ALGAE

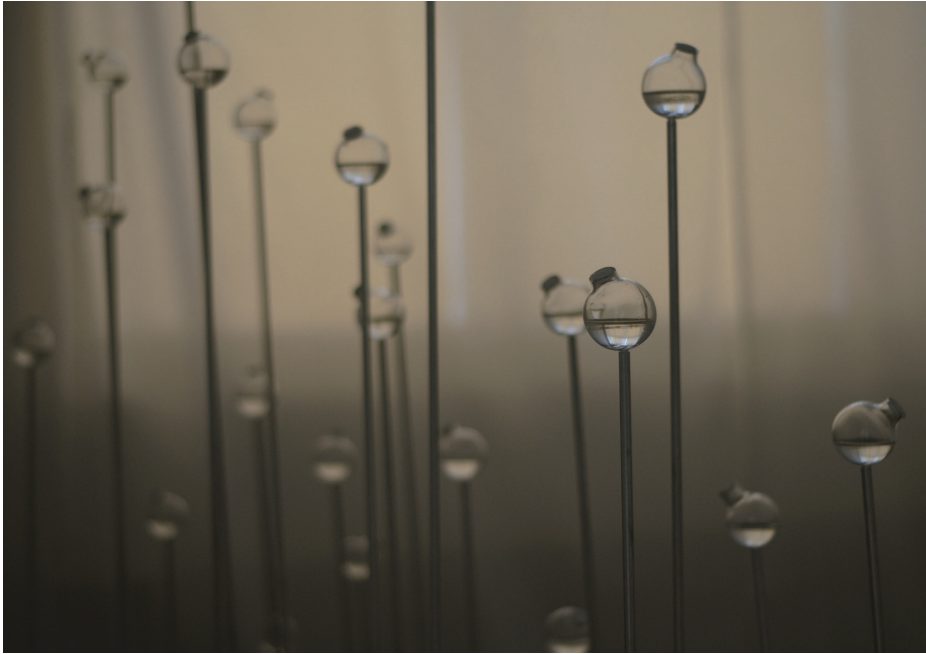


Figure 15 A bioluminescent field of lights⁴⁴

Graduate student Nicola Burggraf wrote a thesis titled “Bioluminescence: The Design of Living Light.” Her study explores setting up parameters for design research to occur in bioluminescence. The full exploration of her thesis is represented in a design installation in interior darkness.

The installation utilizes dozens of glass orbs filled with bioluminescent organisms which respond to human movement. When touched or disturbed, the luminescent liquid in the orbs exhibit luminescence in the presence of human movement.

⁴⁴ Nicola Burggraf personal website, accessed February 2, 2012, <http://www.nicolaburggraf.com>.

OVERVIEW OF DESIGN MODELS

Overall, these bioluminescent design models introduce the exciting potential of bioluminescence outside of the scientific realm. The fact that most of these installations and design experiments have been completed relatively recently (four years or less) signifies unknown potential in bioluminescence for applicability in design and architecture.

WHAT WAS GATHERED?

1. *Use of organic light*: Organic light is highlighted as an emerging design material.
2. *Bacteria vs algae*: Bacterial bioluminescence emits a constant glow while algal bioluminescence emits blue light upon stimulation.
3. *Structured environments*: All design models are set in indoor settings, providing evidence that the organisms could perform predictably in a constructed context.
4. *Darkness*: All design models display the material in dark, interior settings.

WHAT'S MISSING?

1. *Human experiences* of the material are subject to interpretation because real interactions cannot be conceived through photographic information.
2. *Levels of light* shown in the images may not be accurately depicted due to variable camera settings.
3. The *length of luminescence* is unknown.
4. *Connection* from any surrounding context is missing since these examples focus on manipulation of the light itself without a contextual relationship.

DISTINCTIVENESS OF BIOLUMINESCENT ALGAE

Algae and bacteria are the only two types of bioluminescent organisms considered for incorporation into the design models. Bioluminescent algae (or phytoplankton) demonstrate greater design potential than bacteria because:

1. Its luminescence is the result of external forces; other organisms have active control of their luminescence and are not yet understood for their design applicability.
2. The miniscule size of the phytoplankton suggests flexibility in its application as a perceivable lighting element.
3. The availability of the Pyrocystis family of bioluminescent algae from online suppliers (such as EMPCO)⁴⁵ allows the material to be studied directly.

Due to these reasons, bioluminescent algae are examined further for its design abilities as a perceivable lighting element.

⁴⁵ "Bioluminescent Algae," EMPCO Holdings, LLC, accessed February 5, 2012, <http://empco.org/edu/index.php/bioluminescent-algae.html>

2.3 Chapter Two Conclusion

Bioluminescence is an *organic* form of light in existence for millions of years. Hundreds of luminous organisms create their own light due to environmental darkness. In the field of science, bioluminescence is particularly valuable as an experimental research tool. However, the design of bioluminescence is unconventional in the built environment. Thus, recent design models lay a foundation for understanding existing design qualities of bioluminescence.

The next chapter will provide evidence of encounters, observations and experiments with bioluminescent algae (phytoplankton) from the Pyrocystis family of dinoflagellates.

3

The Unique Abilities

- 3.1 Analyzing the Material
- 3.2 Experimenting With Bioluminescent Algae
- 3.3 Overview of Experiments
- 3.4 Identifying Unique Abilities
- 3.5 Chapter Three Conclusion

Chapter Three provides a qualitative design analysis of two species of bioluminescent algae. Initial analyses observe the quality of bioluminescent light while experimentation leads to confirmation of unique abilities of these organisms. Experimentation positions the material for design applicability.

3.1 Analyzing the Material

This section documents real observations of bioluminescent algae conducted by the author of this text. Two species were obtained for analysis:

125mL of *Pyrocystis lunula* in L/2 growth medium

1000mL of *Pyrocystis fusiformis* in L/2 growth medium

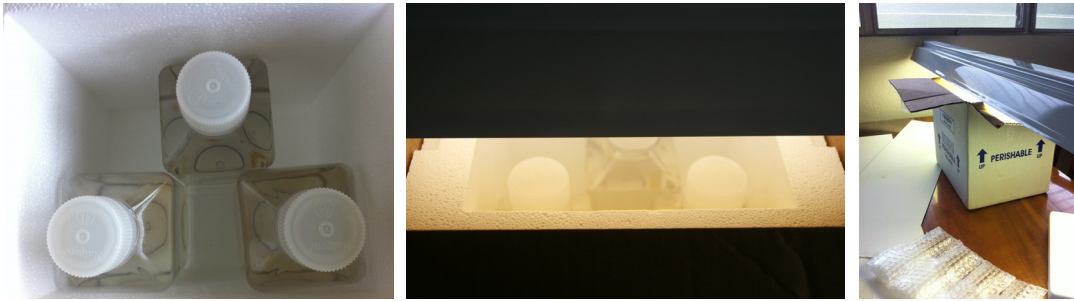


Figure 16 Growing *Pyrocystis* spp. under fluorescent light, source: author

These samples were sustained in controlled environments using direct fluorescent light and nocturnal darkness to facilitate 12 hour light/dark cycles. The dark cycle was achieved through nocturnal darkness. The containers were stored at room temperatures not exceeding 76 degrees Fahrenheit. These measures activated photosynthesis, inducing a natural circadian rhythm for the algae, and producing continued light emission. Circadian rhythm refers to an organism's natural biological cycle throughout a 24-hour period. Analysis began when a proper growth schedule of the organisms was established.

PYROCYSTIS LUNULA



Figure 17 Several hundred luminous dinoflagellates contained in a flask within a growth medium similar to seawater, source: author

P. lunula is less common than the *P. fusiformis* species but more abundant than the *P. noctiluca* species. Each of these species differs in shape and size but cannot be distinguished in apparent luminosity.

Earlier research has documented that bioluminescent algae require stimulation to catalyze bioluminescence. To induce light emission, organisms were simply shaken or swirled within the container. Initial observations:

1. In this agitated state, nearly all of the algae became activated, creating visible blue light.
2. Blue light illuminated the solution with bright luminescence and was sustained for a maximum of ten seconds upon initial stimulation.
3. Depending on which portions of liquid are most affected, some algal cells exhibited luminescence longer than others.
4. During peak hours (midnight), little or no stimulation was required for the algae to luminesce. 1 am to 3 am produced the most brilliance.

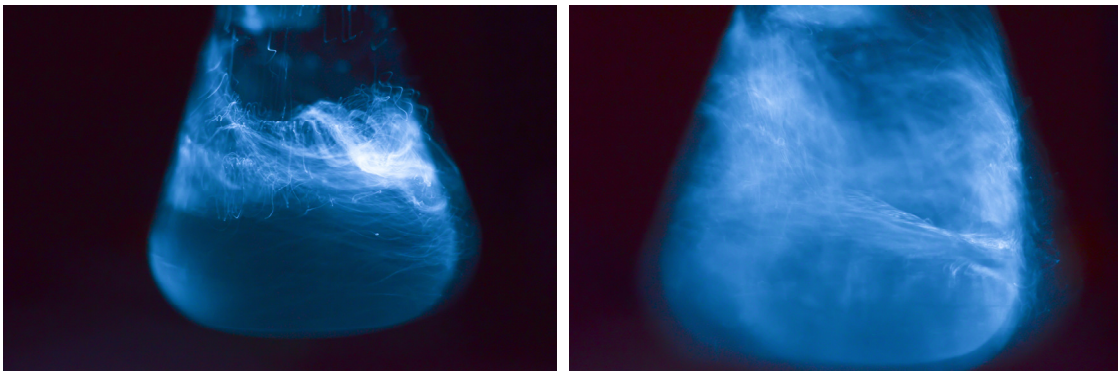


Figure 18 The agitated state of *Pyrocystis lunula*, source: author

P. lunula emitted luminescence on the entire exterior surface of each individual cell. Each cell can be clearly recognized when observed closely. This agitated state of luminescence is further referred to as *active bioluminescence*.

Luminescence was best perceived in adequate darkness. Eyes fully adjusted to darkness (light adaptation) experience increased sensitivity bioluminescence. In interior settings, residual light from exterior sources negatively affected visual perception. Examples of residual light are artificial street lighting and light leakage from under a doorway.

PYROCYSTIS FUSIFORMIS



Figure 19 Larger volumes of *P. fusiformis*, source: author

The author of this text observed another species of bioluminescent algae called *Pyrocystis fusiformis*. These organisms were contained in a 32 oz. volume to further understand the material in greater liquid volumes. This species is more common than *P. lunula* and *P. noctiluca* and is known to cause “Red Tide” in various coastal areas of the world. Red Tide is an algal bloom phenomenon that references the reddish-brown color of the algae and not the color of its bioluminescence. Again, luminescence in this species was only observed at night and photosynthesis was induced using the same method of 12 hour light/dark cycles.

The quality of light from *P. fusiformis* is undistinguished from *P. lunula*. Both emit the same blue color of light and appear to sustain a luminescence of up to ten seconds before completely fading. The clear distinction in *P. fusiformis* is that the shape of the cells, if observed closely, is more elliptical rather than the crescent shape of *P. lunula*.

This quantity of algae is useful in explaining how the algae perform when in larger volumes. The first *P. lunula* sample is contained in a small, plastic beaker whereas the newer *P. fusiformis* are contained in two larger bottles. During the day both algal species appear to sit at the bottom of all the containers with few cells floating at the surface. However, because the individual cells are extremely difficult to identify with the human eye in the daytime, the best way of detecting the cells within the volume of liquid is to watch for luminescence at night.

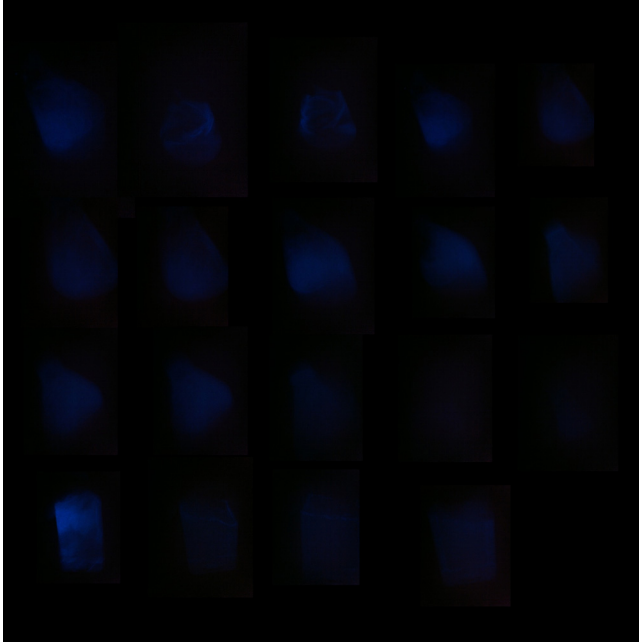


Figure 20 A collage of bioluminescent stimulation, source: author

This photo collage captures multiple displays of active bioluminescence through digital photography. Because the light emission is both dim and temporal, the images do not accurately represent the true visual quality or amount of light discharged when the photos were taken.

When *P. fusiformis* was agitated in darkness, bioluminescent organisms were perceived on the surface and at the base of the container; they did not appear anywhere in the middle of the volume. This provides clear evidence that despite the ample room in the container, algae will collect on the surface or at the bottom. Volumetrically, most of the volume did not contain bioluminescent organisms unless the containers were shaken to displace the algae. From this observation, bioluminescent algae could become further concentrated if the depth of water is dramatically reduced.

Algal cells have positive or negative buoyancy that depend on their morphology within their reproduction period. This explains the high density of reproductive algae at the bottom of the sample with newly formed or infertile cells floating at the surface.

P. LUNULA IN ADDITIONAL GROWTH MEDIUM

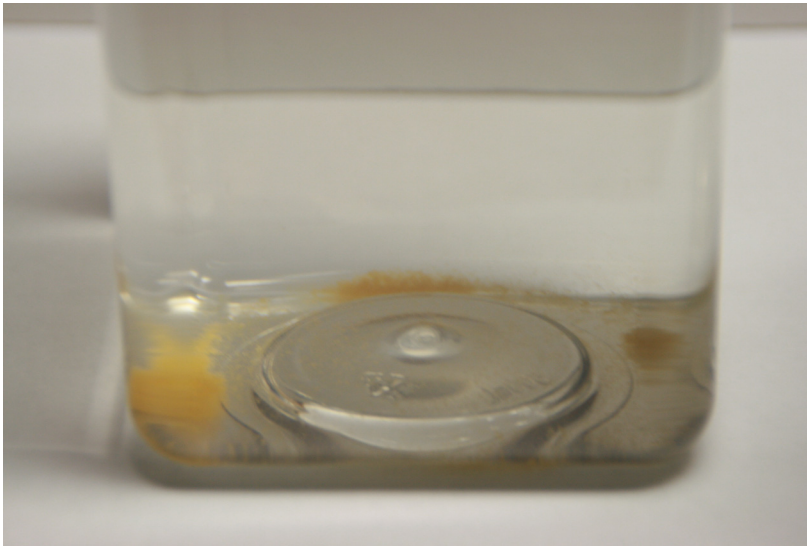


Figure 21 Cellular concentrations of *P. lunula* in fresh growth medium, source: author

To prolong the lifespan of the original 125mL sample of *P. lunula*, an additional 500mL of L/2 growth medium was added to the solution. This provides a fresh growth environment and a larger container for *P. lunula* to continue populating. In the previous observance of *P. lunula*, organisms were shaken or swirled to provoke luminescence. However in this solution, a high concentration of *P. lunula* settled on the bottom of the container in reddish orange clumps. When observed in darkness, a major discovery was made.

After a small tap on the container, concentrations of *P. lunula* blinked and sparkled at random, much like the flash of cameras in a sports arena. Roughly a few dozen cells displayed bioluminescence per second. Remarkably, the duration of luminescence continued for hours. Even though the light output was not significant, bioluminescence was sustained for a prolonged period of time, introducing a new characterization of luminescence in *P. lunula* that was not observed in *P. fusiformis*. This phenomenon of twinkling is further referred to as *passive bioluminescence*.

J. Woodlands Hastings of Harvard University has studied bioluminescence in dinoflagellates in relation to circadian rhythm and identified two forms of luminescence present in dinoflagellate algae. The first form is what's considered a "flash,"⁴⁶ where luminescence is visible to the human eye for

⁴⁶ Hastings, Schultz, Liu, "Dinoflagellate Bioluminescence and Its Circadian Regulation"

only milliseconds. The second form is a “glow” lasting for hours during the latter phase of the night period of the algal circadian rhythm. The glow that Hastings discusses may explain the series of sparkles observed in the *P. lunula* sample.

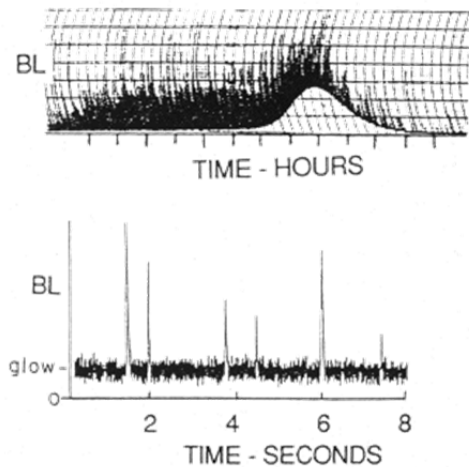


Figure 22 Charts by Hastings illustrating bioluminescence (BL) glow with flashes overlaid throughout a 12-hour period⁴⁷

This amazing display of bioluminescence has substantial potential in night time environments as a design element. Not only is the algae able to sustain light emission without stimulation, but it produces a dynamic sparkling effect not previously documented in prior design research or through observation.

⁴⁷ Hastings, Schultz, Liu, “Dinoflagellate Bioluminescence and Its Circadian Regulation,” 504

3.2 Experimenting With Bioluminescent Algae

The following experiments test bioluminescent algae (*P. fusiformis* and *P. lunula*) in controlled environments. A containing medium is required to hold the algae and therefore should be translucent to provide maximum visibility. Without translucence, bioluminescence cannot be adequately perceived.

In any observance of bioluminescence, it is imperative that maximum darkness is present followed by light adaptation, which takes about fifteen minutes. Once human eyes are fully adjusted to darkness, testing can begin.

Experimentation was aimed at determining the following:

1. Physical conditions required for bioluminescence
2. Resiliency of bioluminescent algae
3. Minimum growth medium volume required for bioluminescence
4. Efficiency of various stimulants to catalyze luminescence

OPEN AIR



Figure 23 Source: author

When purchased, bioluminescent algae were delivered in a sanitary bottle or beaker. All design precedents using bioluminescent algae utilized the organisms within a containing medium. However, no previous attempts have been made in observing bioluminescent algae removed from their liquid

habitat. To do this, a paper towel is used to soak up a portion of the growth medium containing bioluminescent specimens to answer if light emission is possible without water.

After many attempts to provoke luminescence from the paper towel, light emission was not observed in darkness even though dozens of *P. fusiformis* organisms were identified in the sample. Therefore luminescence from bioluminescent algae (*P. fusiformis*) had to occur within a liquid medium.

SEALED BAG



Figure 24 Source: author

More conclusions were required to understand the algae's response within various types of containers. The original beaker was limited in its ability to respond to certain forces because of its rigidity. Therefore to manipulate the algae in new ways, a plastic Ziploc bag became an appropriate testing container to understand the ways in which algae react to various stimuli.

To do this, bioluminescent algae (*P. fusiformis*) were poured from its original container into a sandwich-sized, plastic Ziploc bag where the liquid to air ratio within the plastic bag was 1:3. The plastic bag was sealed to prevent liquid from spilling out. Physical forces were applied to the bag to determine which force contributed to greatest luminescence.

First the liquid was shook within the bag. Luminescence occurred throughout the entirety of the liquid confirming two things; the liquid contained enough bioluminescent organisms to produce significant results and that the transfer of algae from one container to another sealed container didn't appear to have any effect on the amount of luminescence emitted.

Secondly, a light touch to the wall of the bag produced luminescence surrounding the touched area. No other areas of the bag displayed luminescence through this stimulant.

Finally, the bag was squeezed at various pressures, making sure to not inadvertently open or damage the bag. After even pressure was applied to all sides of the bag, luminescence appeared on the meniscus of the liquid but most organisms were not activated. The bag was also squeezed together quickly with enough kinetic energy to splash liquid within the bag; luminescence lit up the entire bag.

These tests indicated that there's a direct correlation between the speed and acceleration of liquid flow and luminescence. This statement is confirmed by a 2007 study at the University of California San Diego by Elisa Maldonado and Michael Latz, who examined shear-stress forces on bioluminescent dinoflagellates in relation to bioluminescence. The study cites that "dinoflagellates respond directly to the fluid force acting on the cell."⁴⁸ Maldonado and Latz conclude that acceleration of flow positively contributed to bioluminescence while deceleration of flow drastically reduced bioluminescence intensity.⁴⁹

TRANSLUCENT SHEETS

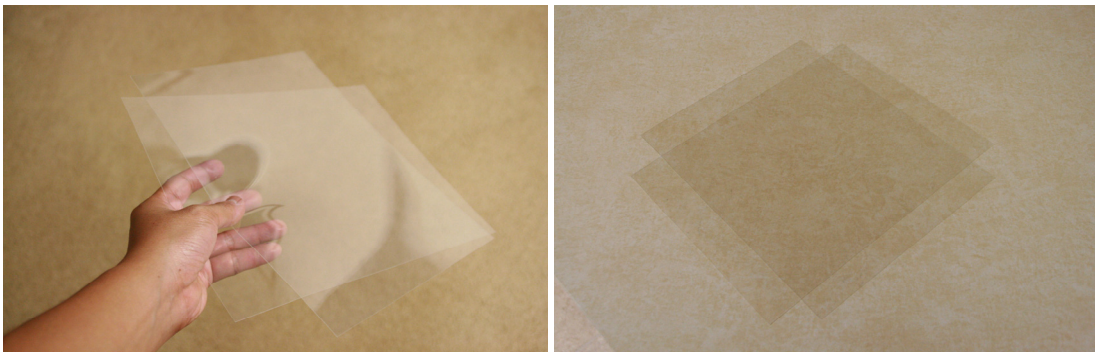


Figure 25 Two acrylic sheets transition the material into architectural applicability, source: author

Lastly, the author of this text tested the algae for its architectural applicability based on understood characteristics. The intended application involved translucent sheets towards developing a touch-responsive surface. Two letter-sized plastic sheets (0.1 mm thickness) were obtained because of their flat geometry. A small amount of *P. fusiformis* specimens was poured onto one of the plastic sheets to form a liquid bead about 3.5 inches in diameter.

⁴⁸ Maldonado and Latz, "Sheer Stress Dependence of Dinoflagellate Bioluminescence," 243

⁴⁹ Maldonado and Latz, "Sheer Stress Dependence of Dinoflagellate Bioluminescence," 245

In darkness, luminescence was immediately observed on the periphery of the bead. The second plastic sheet was then laid directly over the first sheet in order to evenly spread out the liquid between the two sheets to produce a thin (<1mm) liquid layer of bioluminescent algae. The dispersion pattern of the individual algal cells was unknown: the cells will either become evenly distributed or spread toward the periphery of the two sheets. Its reactivity to touch also needed to be tested.

Astonishingly, a light touch catalyzed luminescence of the algae in the exact location of the touch, essentially resulting in a living, touch-responsive surface. Furthermore the algal cells were evenly distributed throughout the entire surface of the plastic sheet. What's interesting about this experiment is that the volume of growth solution was significantly compromised from its original state but bioluminescence occurred without vigorous shaking or swirling. This demonstration is further known as the *sheet method*.

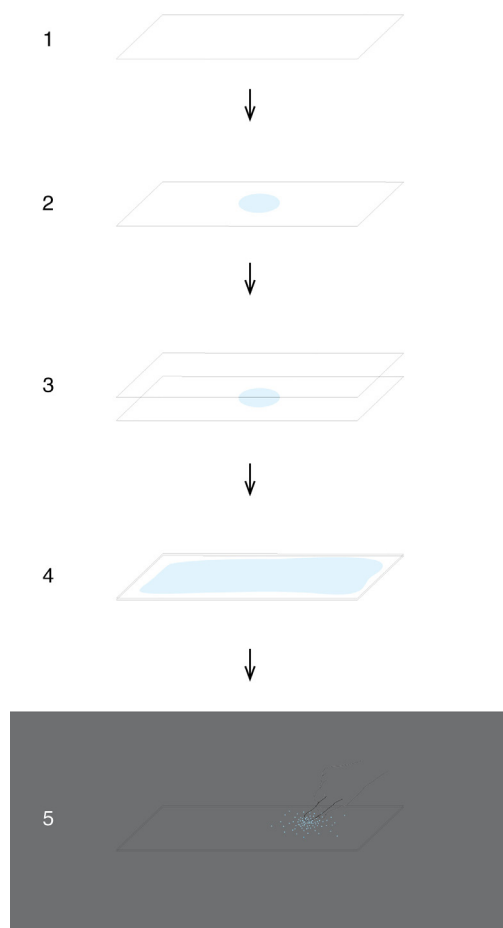


Figure 26 The sheet method process, source: author

There are two reasons to explain the results of the sheet method. First, any change in growth medium volume to facilitate the flow of liquid will encourage luminescence. Slight pressure on the plastic sheets compresses the liquid, causing volumetric changes. This minimal volume of liquid demonstrates that facilitating liquid flow requires little energy. If *P. fusiformis* concentrate at the bottom or top of liquid, then this test further concentrates the density of algae to generate maximum bioluminescence.

Lastly, this demonstration shows the resiliency of the algae. After 72 hours of dormancy between the two plastic sheets, *P. fusiformis* continued to show signs of bioluminescence during its night cycle. This sample underwent evaporation and temperature instability due to lack of growth medium but still survived.

3.3 Overview of Experiments

These simple experiments were examined and confirmed the capability and limitations of bioluminescent algae for potential design utilization. The following results are collected from the experiments:

1. Bioluminescent algae produce light within liquid; the amount of liquid is irrelevant. They are resilient and will survive when transferred to new media.
2. Flow of liquid is the primary stimulant for catalyzing bioluminescence in *Pyrocystis* dinoflagellates. Acceleration of flow increases intensity of bioluminescence.
3. The *sheet method* demonstrates an interactive lighting surface with high efficiency of luminosity per amount of effort.
4. Bioluminescence is best perceived in very dark settings.

TECHNICAL CONSIDERATIONS

Dealing with a living material reveals challenges:

1. *A Containing Device* -Bioluminescent phytoplankton, due to their marine origin, should be contained and preserved in liquid. The optimal quality of bioluminescent light depends on the method and translucence of the containing media.

Beyond plastic bottles, bags and plastic film, other materials such as glass and ETFE (ethylene tetrafluoroethylene) haven't been explored as a containing media. Further methods may exist beyond those described in this text.

2. *Maintenance of A Living Material* -Proper and constant maintenance of the material should be practiced for consistent growth and luminescence. Correct temperature and light/dark cycles are easily attained in all architectural environments, but there are thermal limitations that disqualify certain climatic regions from sustaining bioluminescence. Additionally, it is necessary to sterilize all containers and liquids prior to occupancy of bioluminescent organisms to assure complete independence from undetectable microorganisms such as bacteria.

Adequate Darkness -A major challenge of designing with bioluminescent light is assuring adequate darkness. Today artificial night lighting levels are exponentially higher than they were a century ago.⁵⁰ Therefore measures should be taken to limit the presence of competing lights.

VARIABLE CONSIDERATIONS

Additional considerations regarding bioluminescent algae arose after experimentation.

1. The experiments described in this chapter utilize less than a gallon of the algae and therefore do not accurately reflect the performance of an overall algal population of several million gallons in a natural habitat. Also, testing with larger media could alter the outcome of the experiments. For example, a larger surface area of acrylic material could have led to new conclusions on the efficiency of catalyzing luminescence.
2. The survival process implemented is synthetic. Fluorescent light is used to encourage photosynthesis in the test samples while natural Pyrocystis organisms capture sunlight in expansive marine environments utilizing sunlight for photosynthesis.
3. Consideration should be given to the climatic limitations of bioluminescence. Although bioluminescent dinoflagellates occur naturally in various climatic zones around the world from subtropical to arctic regions,⁵¹ a thermal range for acceptable performance should be established regardless of known habitable regions.
4. A colored containing media was not considered; therefore materials such as colored polyethylene films could potentially create various new colors such as green or purple using blue bioluminescent light as a base color.
5. Testing the material in various locations in the presence of street lighting or other artificial lighting sources could have yielded different results since the tests were conducted in interior darkness.

⁵⁰ Bogard, Let there be Night, ?

⁵¹ Rhyther, *Luminescence of Biological Systems*, 387

3.4 Confirming Unique Abilities

Unique abilities of *Pyrocystis spp.* are confirmed through experimentation and previous documentation. Other characteristics are also acknowledged but are not unique.

1. REACTIVE



Figure 27 Reactivity of phytoplankton⁵²

Bioluminescent dinoflagellate algae react to external stimuli by emitting their own form of light. Therefore the direct and predictable manipulation of algae signifies its strong design potential; larger bioluminescent organisms are not currently understood for their predictable performance in design.

The duration of luminescence differs from species to species but depending on the concentration of organisms, the *Lunula* variety will luminesce undisturbed for hours (passive bioluminescence).

Bioluminescence's reactive ability has potential to communicate the presence of activity in natural and manmade environments. These activities include vibration, wind, people, rain, cars or other variables. Therefore *kinetic occurrences are transformed into visible light*.

Wireless sensors and transmitters are part of architectural constructs as mechanisms for catalyzing dynamic design effects but bioluminescent algae have non-electrical, sensory capabilities, which eliminate any need for supplementary devices to produce light.

⁵² "Bioluminescent Splashes," photograph, image reproduced courtesy of Phil Hart, <http://redbubble.com>.

2. NOCTURNAL

The expression of light at night due to circadian rhythm is one of the most unique properties of bioluminescent algae. *Pyrocystis spp.* follow a light/dark cycle which governs the time frame for light emission. Light absorption occurs in the day and energy is released at night due to the photosynthetic nature of the algae.

Although its lighting function is limited to the night, bioluminescence is highly perceivable in nocturnal conditions once light adaption occurs. As mentioned earlier in the text, our eyes become hundreds of times more sensitive to light at night and allow for greater perceptibility within the nocturnal time period. Any difficulty to perceive bioluminescent light in the day is negated by its usefulness in diurnal conditions. Artificial electrical lighting can be turned on at any time of the day. However, the limited time frame of bioluminescent light is an opportunity to set up creative design requirements.

When *Pyrocystis spp.* is modified, there is no differentiation between natural and artificial light to generate photosynthesis. Therefore the circadian rhythm of bioluminescent algae can be easily modified.

(See appendix for more information regarding human circadian rhythms)

3. ORGANIC *(Refer to Chapter Two for more information)*

As a living light, bioluminescence is organic and reproduces constantly. The photosynthetic and reproductive properties of bioluminescent algae confirm that it's a renewable resource. In design professions, material renewability is desirable from a financial and sustainable perspective. Contrasting most lighting practices, bioluminescent light can be grown and sustained.

The design opportunity of bioluminescence is its ability to emit visible light without electrical or structural support, as long as its growth requirements are satisfied. In addition to urban areas, natural areas such as forests and beaches can host bioluminescent light. As a non-conductor of electricity, oceanic and wetland areas are also suitable for bioluminescence, especially since the algae come from marine habitats. Isolated rural areas without electricity are also potential settings for this living light.

Since bioluminescent algae produce oxygen and remove atmospheric carbon dioxide, they provide added benefits in urban settings. In fact, bioluminescent algae are one of the most productive sources

of oxygen on our planet.⁵³ Similar interventions like green walls and roofs share this characteristic of oxygen generation and carbon absorption.

In addition to the unique qualities identified, bioluminescent algae have other notable qualities.

BLUE LIGHT

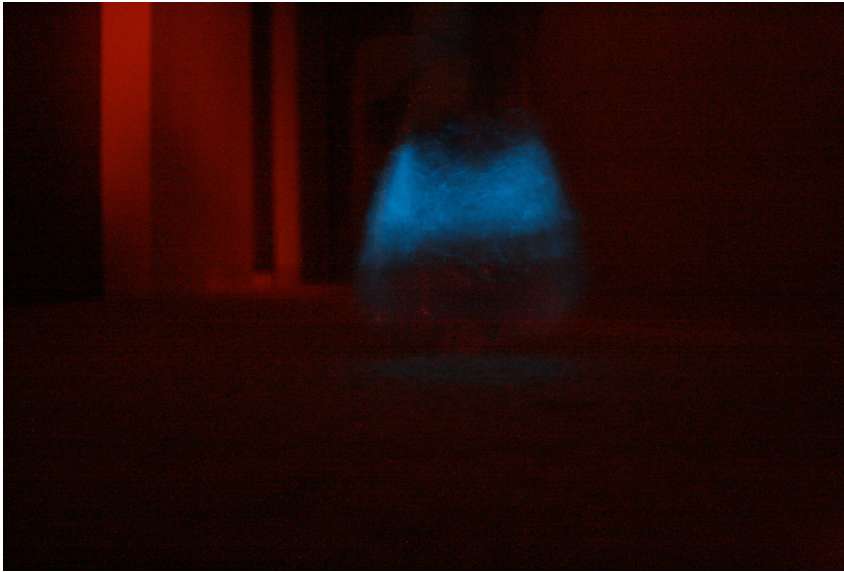


Figure 28 Blue light from stimulated dinoflagellates, source: author

Algal bioluminescent organisms emit blue light; this color cannot be changed or manipulated. Blue is the wavelength color that travels furthest in water. Terrestrial bioluminescent organisms, such as fungi produce green light, the most visible wavelength color on land.

According to Deborah Sharpe, who studied color and psychology, the color blue is associated with traits such as dignity, poise and reserve.⁵⁴ In American culture, Sharpe notes that the uniforms of police officers, sailors, and the US flag use blue to represent these traits.

Frank and Rudolph Mahrke have written about the effects of light and color in architectural environments. They clarify that blue decreases human blood pressure and has a “transparent and wet” character,⁵⁵ which coincidentally describes bioluminescent algae.

⁵³ Roach, John, “Source of Half Earth’s Oxygen Gets Little Credit.”

⁵⁴ Sharpe, *The Psychology of Color and Design*, 91

⁵⁵ Mahrke and Mahrke, *Color and Light in Man-Made Environments*, 15

LOW-LUMINOSITY

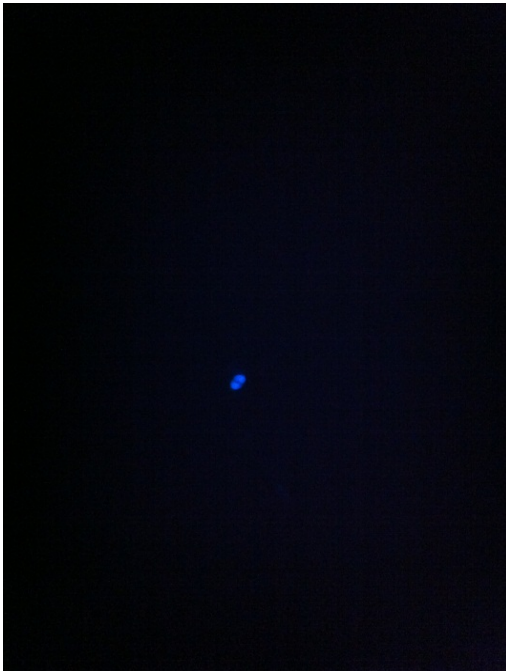


Figure 29 Light emission of a single dinoflagellate at night, source: author

The low-intensity light of by luminous algae is difficult to perceive in apparent brightness. However, *Pyrocystis spp.* provides a unique design opportunity to be observed independently from its context in the dark. Most artificial lights have a brighter lumen output than bioluminescence. However bioluminescence can be considered a catalyst for comprehending how much light is really necessary at night. If bioluminescent design becomes an established lighting practice, we should evaluate what appropriate amount of darkness in nocturnal environments today is acceptable.

3.5 Chapter Three Conclusion

At the beginning of the chapter, bioluminescent algae were perceived to possess unique qualities established by previous design models and by scientists. These qualities are confirmed throughout the chapter. The first set of tests observed the material while the second set of tests manipulated the material through various media. Gathering biological research of bioluminescence and the results of these tests, the unique qualities of the material are identified as:

Reactive -Response to stimulation suggesting dynamic interactivity of the material

Nocturnal -Natural circadian rhythm to control the nocturnal emission of light

Organic -Living and regenerative light with limitless physical applicability

The combination of these three abilities distinguishes bioluminescence as a unique lighting practice from other known lighting practices. The next chapter will visualize the experience of bioluminescence by representing the abilities of the light in selected settings.

4

Visualizing the Experience

4.1 Overview of Design Potential

4.2 Analysis of Context

4.3 Simulation of the Experience

4.4 Overview of Simulations

4.5 Chapter Four Conclusion

Chapter Four visually demonstrates the unique abilities of the bioluminescent algae by introducing its light in proposed nocturnal environments to project an experience that broadens perceptions of each setting.

4.1 Overview of Design Potential

Bioluminescent algae have distinct abilities of being respondent to stimuli, nocturnal with light exclusively at night, and organic. It's important to understand how these properties transition the material into a design setting.

(1) *Response to stimuli* -A stimuli should be considered to facilitate the movement of the material to trigger its luminescence. The stimuli can be in the form of physical movement such as wind, tide, trees, pedestrians, cars, vibrations, etc. Thus, any bioluminescence exhibited will likely be a consequence of a physical activity at night, whether natural or fabricated.

(2) *Nocturnal* -Due to a natural circadian rhythm, the nocturnal light emission of the material makes its purpose entirely suited for the night. Therefore the light will be applied in a dark, nocturnal context.

(3) *Organic* -Bioluminescent algae can be integrated into virtually any nocturnal setting because the light is self-contained. It should be kept in mind that this living material should also receive routine maintenance.

Two distinct displays of bioluminescent are known:

(1) *Active bioluminescence* -a bright flash as a result of agitation; the luminosity of the flash decreases exponentially if no further stimulation is applied.

(2) *Passive bioluminescence* -a constant but faint twinkle upon light agitation (when algae are highly concentrated)

These abilities inform programmatic design requirements. Experimentation confirms two strategies of employing bioluminescent light:

(1) The *container method* -Bioluminescent organisms contained in sealed, transparent containers. Generating bioluminescence with this method requires a substantial stimulus.

(2) The *sheet method* -Bioluminescent algae captured between translucent sheets producing a touch-responsive surface. This method requires subtle stimuli to induce luminescence.

THE EXPERIENCE OF THE LIGHT

When the author of this text asked fourteen different people of varying backgrounds whether or not they had heard of bioluminescent algae or phytoplankton, only two had said yes. When the bioluminescent light of *Pyrocystis lunula* was presented to the same fourteen people, none had claimed to have witnessed this light firsthand. The reactions to the light were consistently similar:

-*Curiosity* of an unfamiliar light

-*Fascination* of a microscopic organism and its reactivity to stimuli

-*Care* of a living material

These reactions suggest the emotional perceptions of bioluminescent light.

AN INITIAL SIMULATION OF THE LIGHT

Simple visualizations clarify the envisioned aesthetic and potential experience that bioluminescent light communicates. A black background represents apparent darkness to simulate a truthful luminosity of light produced by bioluminescent dinoflagellates. It is important to note that these visualizations are not intended to produce a desired effect. Rather they are tools for analyzing and understanding the effectual quality of the light.

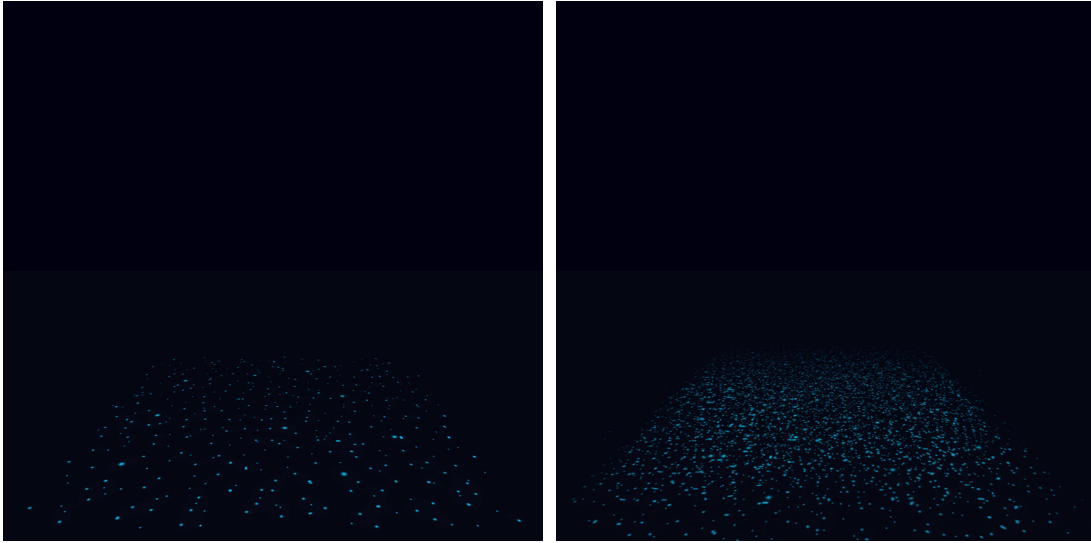


Figure 30 A bioluminescent floor, source: author

The first set of images introduces the light of bioluminescent algae as a floor material. The image on the left describes the material as it might exist during passive bioluminescence. The image on the right illustrates a stimulated condition in active bioluminescence. This goes for the following images in this series. By theoretically employing the sheet method, this scenario is pragmatic due to the even distribution of algae caused by gravity in horizontal uses.

Here, luminescence is scattered due to the minimal amount of liquid envisioned in the fabrication of this idea. Because this application is based on an confirmed method of utilizing bioluminescent algae, these images visualize the light in small quantities rather than projecting greater utilizations of bioluminescence that haven't been confirmed in this text.

Mahnke and Mahnke described the color of blue and its experiential effect in floor applications as “inspiring feelings of effortless movement if light,” but “substantial if dark.”⁵⁶ As a floor element, blue bioluminescent could represent expansive water. Therefore, this application might simulate the experience of gliding over water.

⁵⁶ Mahnke and Mahnke, *Light and Color in Man-Made Environments*, 15.

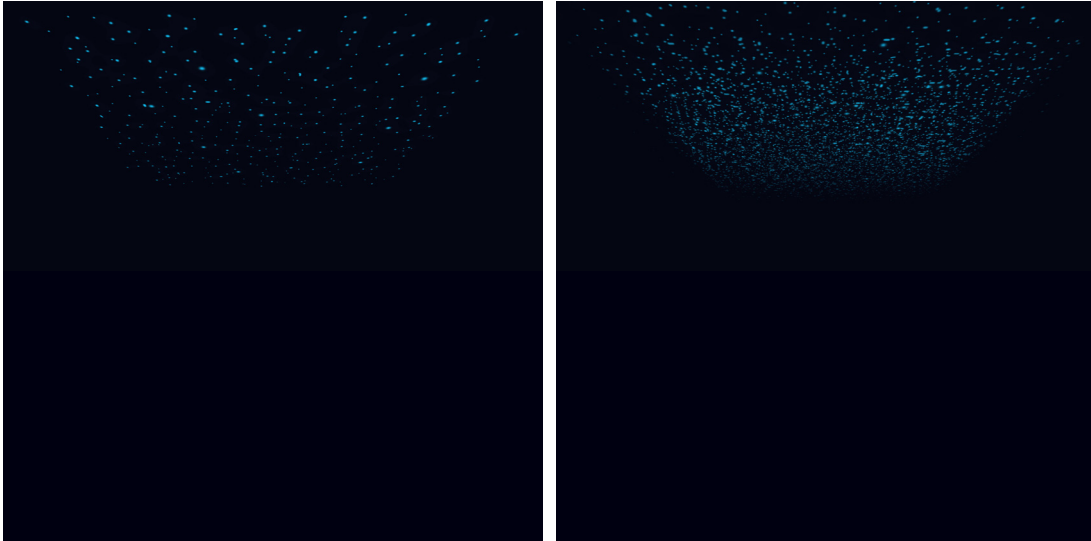


Figure 31 A bioluminescent ceiling, source: author

These images suggest the material imagined as a ceiling. Again, Manhke and Mahnke claim that for ceiling applications, the effect is “celestial, cool, tangibly advancing if light” and “heavy and oppressing if dark.”⁵⁷ As an overhead design element, bioluminescence provides an experience similar to observing the night sky. If used liberally, bioluminescence might mimic the experience of being underwater.

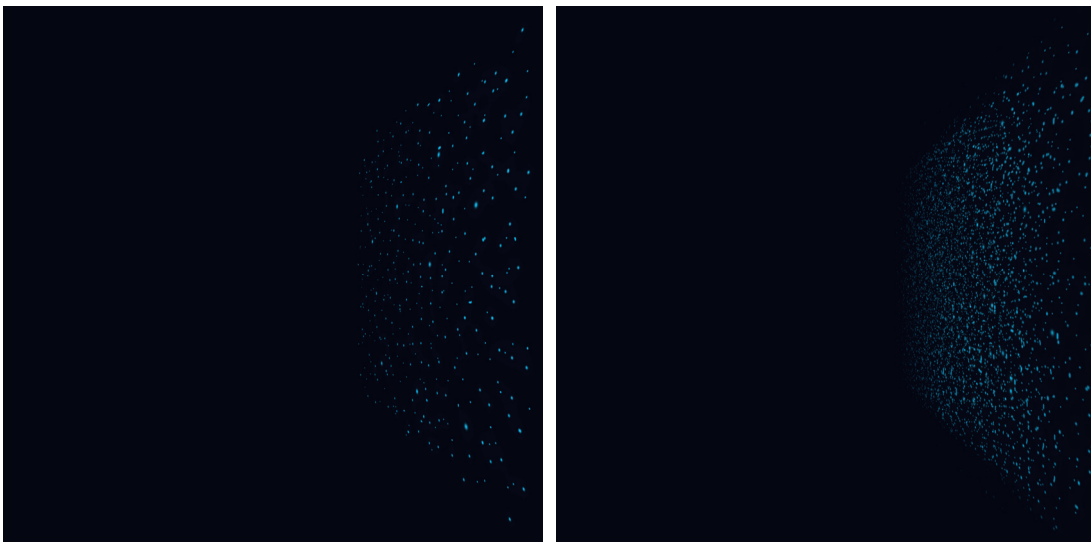


Figure 32 A bioluminescent wall, source: author

As a wall element, evenly distributed luminescence is questionable because bioluminescent cells tend to float or sink. Blue light for wall applications is “cool and distant if light,” encouraging and “space-

⁵⁷ Mahnke and Mahnke, *Light and Color in Man-Made Environments*, pg. 15.

deepening if dark.”⁵⁸ The experiential effect of this application is similar to the observance of stars from outer space.

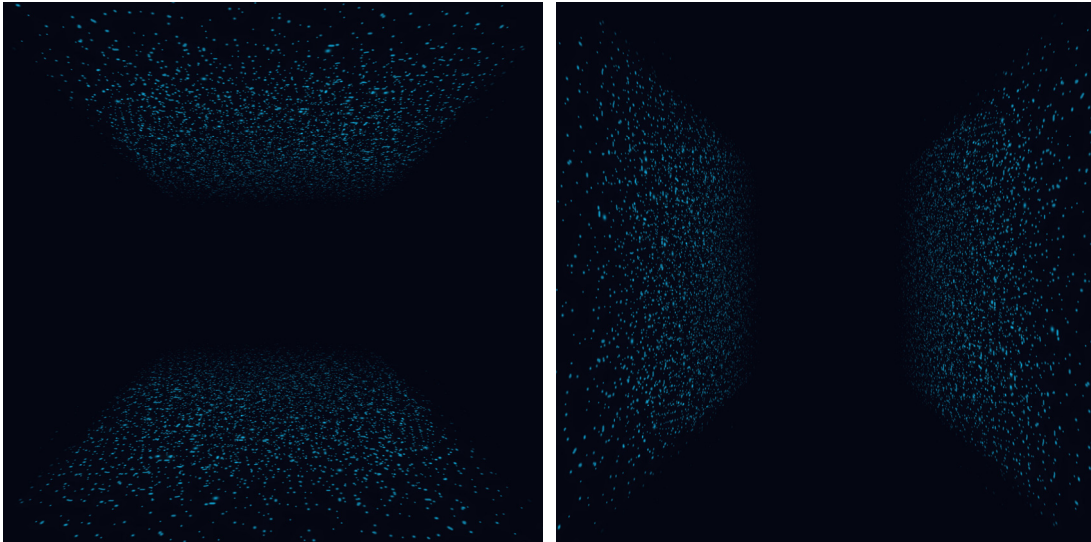


Figure 33 Bioluminescence as spatial form-givers, source: author

These images combine two applications of previous images. A floor and ceiling create a feeling of horizontal expansiveness. Whether or not the effect combines perceiving both the stars and the ocean is at the discretion of one's perception. The image on the right shows walls that form a processional or corridor to provide a limitless sky and even a feeling of freefalling through space.

Overall, these effects do suggest that blue is an appropriate color for nighttime to evoke a nocturnal atmosphere.

These images do not represent, by any means, the entirety of potential applications of the light in any setting. Rather, they suggest the light as a planar element that conforms to the geometric elements of a cube. Also, the light pictured does not identify a reactor for the algae; therefore it may be unlikely that all of the surfaces depicted will display active luminesce simultaneously. Also, the images are missing a context because the light becomes a space defining element itself. Therefore these images assume that bioluminescence is envisioned as a surface material rather than a new element in three-dimensional space.

⁵⁸ Mahnke and Mahnke, *Light and Color in Man-Made Environments*, 15.

4.2 Analysis of Context

After understanding the abilities and constraints of bioluminescent light, several potential nocturnal environments are appropriate for its application.

1. EXISTING URBAN ENVIRONMENTS

Certain settings within urban environments allow bioluminescent light to be perceived or be fully demonstrative of the material's full design capability and experiential quality. Prominence of street lighting in public urban areas is not conducive to visibility of bioluminescence. Thus, the use of bioluminescence is most effective in completely dark space and is not recommended in areas saturated with artificial light. These areas could be existing alleyways, parking lots and urban environments with relative darkness.

2. FUTURE URBAN ENVIRONMENTS

Due to limited visibility of bioluminescence in bright urban environments today, a darker city may allow for greater perception of bioluminescence.

Don Pettit, an active NASA astronaut, believes that one day in the future, the wealth of a city will be judged by the darkness of a city while still providing enough visible light to meet its needs.⁵⁹ He argues that today, artificial light is a measure of prestige for societies. In pursuit of a dark night sky, a contributor in the book *Let There Be Night* has projected ways in which darkness can be achieved to contribute to spiritual and natural connections. He proposes that all forms of artificial light at night be directed towards the ground while street lighting should be reduced to 50% power.⁶⁰

If these predictions are correct, drastic changes will occur in the way lighting is designed in the urban nightscape of cities tomorrow. As a result, a darker urban environment is achieved.

⁵⁹ *The City Dark*, directed by Ian Cheney (2011; New York: Wicked Delicate Films, 2011), DVD.

⁶⁰ Bogard, *Let There Be Night*, 204

3. NATURAL ENVIRONMENTS

Most exterior natural environments at night provide greater relative darkness than urban areas at night. Natural exterior environments are the most conducive to visibility of bioluminescence at night because bioluminescence evolved within this context. Therefore its luminescence and experiential qualities will be perceived better in this environment due to natural darkness and isolation from brighter, artificial light forms.

In most natural outdoor environments at night, appropriate darkness is achieved without the modification of existing conditions. Bioluminescence's ability to exist virtually anywhere due to its portability as a non-electrical, organic light corresponds well with this environment.

4.3 Simulation of the Experience

The following simulations represent the quality and experience of bioluminescent light by taking into account its unique abilities. It is through these renderings that we ask, “What’s an additional experience of an existing setting that we could not have perceived beforehand?”

By using these renderings to communicate bioluminescence’s effectual presence, these simulations do not intend to provide a definitive or conclusive end or resolution when employing this lighting strategy. Instead these renderings are visual clarifications of the possibilities of design with the properties of bioluminescent algae and represent the imaginative ideas of the author.

1. AN EXISTING URBAN ENVIRONMENT



Figure 34 An existing dark alley in an urban context⁶¹

An existing dark alley is commonly perceived to be uninviting and dark. This specific setting was chosen to represent urban areas at night based on relative darkness compared to existing areas due to lack of bright illumination. Therefore this urban darkness is an opportunity for the clear perception of bioluminescent light to change our assumptions of the space. The following image presents bioluminescent light added to the same setting.

⁶¹ “Alley,” Otake Town, accessed April 4, 2012. Courtesy of <http://otake-town.webs.com/alley.htm>.



Figure 35 A dark alley with the addition of bioluminescence

Pictured above is the same dark alley transformed by the visible luminescence of millions of bioluminescent phytoplankton. The proposed addition of this soft, blue light into an uninviting area such as this alleyway attempts to convey human curiosity and interest in the light itself. Through the perceptual process, we first consider what an alleyway means to us then question its altered character in this simulated application. The effect provokes an inviting atmosphere compared to its original condition without bioluminescent light.

Functionally, passive bioluminescence will be complimented by active bioluminescence stimulated by the movement of wind. Although premature to determine the technicality of this proposal, the organisms and growth medium envisioned here utilize the sheet method, where the “sheet” would be thin enough to be manipulated by airstream movement.

Luminance would be perceived at night but become undetected during the day. Due to the translucence of the material as well as the liquid media, the brown color of the algae itself would only be visible during diurnal conditions and would hardly impact the aesthetic of the daytime atmosphere. This is due to its similarity in relative brightness of its context and competing contextual elements.

Structurally, this application is simple to achieve, through methods proposed earlier in the text. Consequently, an alternate perception of the alleyway is conceived with a minimal amount of architectural alteration to existing conditions.

2. A FUTURE URBAN ENVIRONMENT



Figure 36 An existing urban environment at night

This nighttime urban environment as shown above illustrates the apparent brightness of the setting with typical lighting practices. Due to the potential of a darker city in the future, low pressure sodium street lighting would be reduced by 50% and the practice of up-lighting would be eliminated. As a result of darker urban environments mentioned earlier in the text, bioluminescence will have increased visibility in a darker city environment.



Figure 37 A darker urban environment with the addition of bioluminescence

Pictured above is a city environment utilizing bioluminescent floors that respond to pedestrian activity. This idea is derived from the natural, tactical function of the algae, where it's "burglar alarm theory" illuminates predators as a direct response to their movement; it's also a form of biomimicry. This simulation is not a design solution but instead an image representation of how an increased perceptibility of this environment takes place when bioluminescent algae are introduced to this future context.

The result is an interactive environment that engages pedestrians and increases their perception of the experience as a pedestrian. At night, the bioluminescent medium has an optimal experiential effect due to its nocturnality and reactivity at night. Diurnal conditions would render the bioluminescent media imperceptible due to presence of sunlight (lack of visual contrast).

The apparent luminance of the city is unknown in this future setting whether or not this scenario is imminent in the future. Overall, this example provides an accurate representation of the potential experience that might occur in this scenario drawing from the reactivity of the algae and visual subtlety of its light.



Figure 38 A closer look at the delicacy of the light

There are technical challenges in this scenario. The organisms may need to be integrated in ways that are not outlined in this text. Sustenance of the living organisms would require a continuous flow of growth medium (seawater) embedded in the architectural framework.

Additional research into non-algal bioluminescent organisms might also affect this future setting. By the time this future setting is possible, additional bioluminescent organisms will likely be documented in design research. As a result, a greater palate of colors, luminosities and interactions may become available beyond the single algal variety explored in this text.

3. A NATURAL ENVIRONMENT #1



Figure 39 A natural shoreline setting at night⁶²

An unassuming shoreline setting is an appropriate natural setting for the infusion of bioluminescence because luminous algae thrive in these environments. Existing physical stimulants in this setting such as waves may potentially cause bioluminescent algae to react to the movement of the ocean.

⁶² Night Beach, July 26, 2010. Courtesy of deviantart.com



Figure 40 A shoreline with the infusion of bioluminescent light

This simulation demonstrates the experiential effect of bioluminescent light. Several key points aid in understanding this composition.

First, water movement catalyzes active bioluminescence using the container method. This action not only produces perceivable light but also communicates the constant physical changes in the environment, such as the rising of tides or consistent movement of waves.

Next, the living light is presented in an unconstructed setting and functions without electricity. Furthermore, the bioluminescent organisms here are set in their natural habitat of ocean water, making their sustenance unquestionable.

The effect is a broader understanding of nature, an increased perception of the context and a curiosity of the light itself. Overall, this composition conveys that these effects are accomplished through the exclusive abilities of bioluminescent algae.

3. A NATURAL ENVIRONMENT #2



Figure 41 A dark forest trail⁶³

To broaden the potential effects of bioluminescent light in natural environments, a dark forest setting contrasts the previous example. This setting is characterized by tall trees and a gravel pathway, but the infusion of bioluminescent light into this setting allows us to consider what we want to learn from this environment that we cannot perceive in its current state. If it was assumed that these trees sway slightly and its leaves fall continuously, bioluminescent light may potentially take advantage of these physical stimuli.

⁶³ Journey to the mystical forest path, June 27, 2011. Courtesy of howtogeek.com.



Figure 42 Bioluminescent light amongst tree canopies in a natural setting

This image envisions bioluminescent light suspended amongst tree canopies to evoke a deeper understanding of this natural environment. A myriad of bioluminescent translucent sheets connect the trunks of three trees to form triangular planar elements that luminesce when (1) trees sway and warp the shape of the sheets, (2) leaves and twigs fall on the sheets and slide off and (3) when wind blows across the sheets. Through these three strategies of inducing active bioluminescence through nature, we build an awareness of the subtleties of this environment that were not originally perceived.

To execute this scenario, the sheet method is used, where its performance and responsiveness has been confirmed. Although the lifespan of luminous algae in this environment is questionable, the algae have demonstrated resiliency for up to three days in earlier testing of similar, isolated condition. Photosynthesis and appropriate thermal requirements are not issues of concern due to adequate shade and diffused natural lighting.

Overall the experience communicated by this image is a curiosity in the light and a broadened perception of the surrounding environment. By utilizing an understood method of displaying bioluminescence, the effect of this setting gains credibility in its pragmatism. Furthermore, it's an ethereal intervention that's imposed onto the setting without harm to the natural habitat.

4.4 Overview of Simulations

Each of these rendering exercises is carried out to explore the visual and perceptual experience (that we could not have perceived beforehand) of bioluminescent light within nocturnal environments.

The resulting effect is similar throughout the exercises:

- (1) A *subtle, delicate* quality of light is emanated through active and passive bioluminescence.
- (2) A *renewed interpretation* of the environment is conceived.
- (3) A *visual dialogue* is formed between man / light and nature / light.

These visual exercises clarify the potential of the unique abilities of bioluminescence. However, they are not design solutions. They are exercises to express the abilities of the algae, its applicability and the experience it composes through the subjective ideas of the author of this text.

WHAT'S MISSING?

To reiterate, the technical challenges presented in these images are not entirely addressed in this study. The length of sustenance, the survivability of the organisms, the apparent luminosity of the light and the method in which the light is controlled are all unknown variables.

There may be unexplored ways to catalyze and visually represent the material. Vibrations from stereos could likely stimulate the algae to respond. Mirrors could reflect the luminance and increase luminosity. The liquid nature of the organisms could serve as a thermal stabilization element in architecture. Also, the potential for bioluminescence to be designed and implemented in natural habitats without being contained is not explored in this text.

Earlier chapters of this text explain additional characteristics of bioluminescence that were not employed through these exercises. The sensory properties are not implemented because they are too similar to applications in the field of science (this sensory ability is linked to the detection of toxins and pollutants in natural environments as a biosensor). Also, large volumes of bioluminescent material were not imagined in the rendered environments. These additional characteristics could have an impact on the perceivable character of the light and the overall experience of the space.

4.5 Chapter Four Conclusion

The unique abilities of bioluminescent light are considered to select potential design scenarios with bioluminescent light. Bioluminescence is visualized in specific nocturnal settings to achieve a symbiosis between bioluminescent light and the architecture of the setting.

Since the rendering exercise is a subjective visual representation, it is most important to understand that the renderings were guided by the unique capabilities of bioluminescent light. The renderings are visual evidence of the experience of the light to communicate a curious and delicate experiential effect while highlighting its ease of applicability in a variety of scenarios.

To conclude, bioluminescent light is suggestive and delicate; it's also an unconventional lighting practice so it conveys a curiosity to those who have not witnessed the light firsthand. The amount of natural, human or man-made interaction with the bioluminescent media correlates the visibility and experience of the light. Thus, the distinct abilities of bioluminescent light expand interpretations of nocturnal environments while enduring as a self-contained lighting practice.

5

FUTURE PROJECTIONS

2.1 Abundance of Bioluminescence

2.2 Algal Design

2.3 Chapter Five Conclusion

Chapter Five projects the future of algae by (1) explaining its current and prospective supply in our atmosphere and as a cultivated resource and (2) demonstrating its utilization as an emerging design material.

5.1 Abundance of Bioluminescence

ALGAL BLOOMS

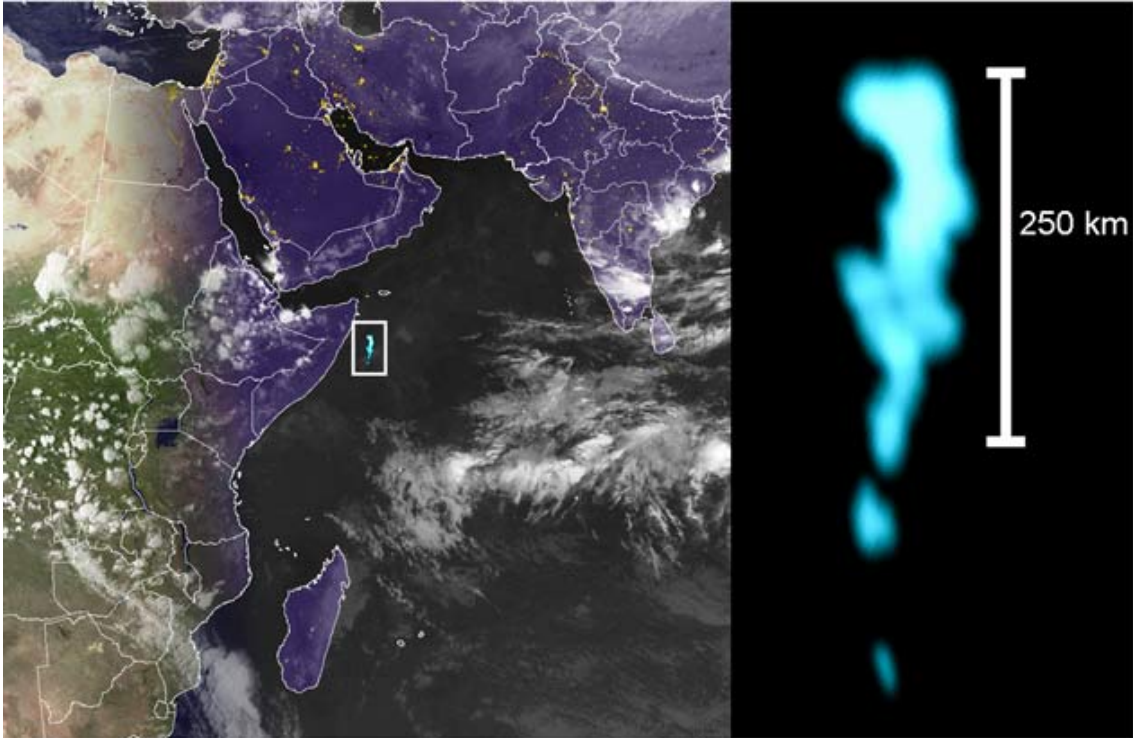


Figure 43 The Milk Sea phenomenon showing vast quantities of bioluminescent bacteria⁶⁴

Bioluminescent organisms are becoming plentiful in the world today. Satellite images show evidence of hundreds of square miles of bioluminescence in open water. More than 200 incidents of this “Milky Sea” phenomenon have been reported, mostly occurring in the Indian Ocean.⁶⁵ The bioluminescent substance in the photograph above was identified as *Vibrio harveyi*, a luminous bacterium, in which the luminescence lasted over three days.

⁶⁴ Miller, Steven, “Milky Seas from Space,” Photograph. *Bioluminescence Info Page*, <http://www.lifesci.ucsb.edu/~biolum/organism/milkysea.html> (accessed February 16, 2012).

⁶⁵ Elvidge, Haddock and Miller, “Detection of a Bioluminescent Milky Sea.”

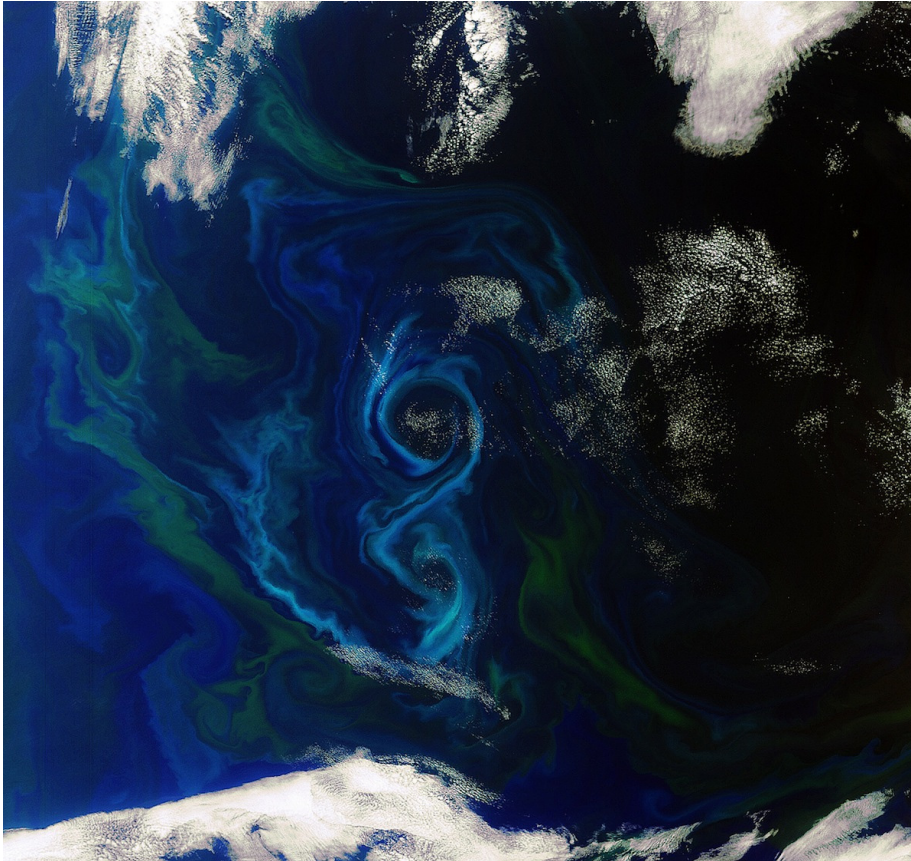


Figure 44 A figure eight algal bloom⁶⁶

This algal bloom in the southern Atlantic Ocean occurred in December of 2011. Although the species of phytoplankton in this photograph is unknown, algal blooms like these are becoming more common today because of increase temperatures due to climate change.⁶⁷

Some algal blooms are known as the phenomenon called Red Tide.⁶⁸ Red Tide is named after the reddish-brown color of non-toxic phytoplankton or algae. Not all Red Tides are made up of bioluminescent organisms but the coast of California is known to host several bioluminescent Red Tides annually.

⁶⁶ ESA, "Satellite Snaps Brilliant Figure 8 Algal Bloom," Photograph. 2011. Space.com, <http://www.space.com/14369-satellite-captures-brilliant-figure-8-algae-bloom-image.html>

⁶⁷ Climate Change and Harmful Algal Blooms, Center for Sponsored Coastal Ocean Research, last modified February 16, 2011, http://www.cop.noaa.gov/stressors/extremeevents/hab/current/CC_habs.aspx

⁶⁸ Dinoflagellates and Red Tides, Scripps Institution of Oceanography, accessed March 1, 2012, http://siobiolum.ucsd.edu/dino_intro.html

ALGAL FARMS

One day bioluminescent algae may become cultivated in large volumes. While the price of oil continues to rise, researchers have identified oil extraction properties in certain species of algae as an alternative fuel resource. Several companies around the world have developed technology to cultivate algae as an efficient, renewable resource where oil from algae is repurposed into valuable products.⁶⁹

Companies like Solazyme, Inc., which began in 2003, have identified microalgae as an opportunistic resource to supply food, fuel, and health products. Solazyme uses biotechnology to feed microalgae with plant-based sugars in order to produce diesel and jet fuel.⁷⁰ Algenol Biofuels, one of the largest companies to produce algae for fuel, is aiming for an annual production of 1 billion gallons in 2012.⁷¹ This number is an indication of the massive volume of algae artificially cultivated from a single company, as well as the investment in algae as a resource.

This algae farm by Nutrex in Kona, which is part of NELHA (Natural Energy Lab Hawai'i) is already using nearby ocean water to cultivate its microalgae.⁷² Coastal algal farms such as this one in Kona are potentially hospitable for bioluminescent algae and phytoplankton because they are easily sustained in this environment.



Figure 45 Algae cultivation in Kona, Hawai'i⁷³

⁶⁹ Bienfang, "Oil From Algae Lecture."

⁷⁰ "Solazyme Reports Fourth Quarter and Fiscal Year 2011 Results."

⁷¹ Jacquot, "5 Companies Making Fuel From Algae Now."

⁷² "About Us," Nutrex Hawaii Inc., accessed March 14, 2012, <http://www.nutrex-hawaii.com/about>

⁷³ Nutrex Hawaii. "About Us," Photograph. *Nutrex-Hawaii.com*, <http://www.nutrex-hawaii.com/about> (accessed March 14, 2012)

Bioluminescent algae do not require much maintenance to thrive. The difference between the microalgae grown for oil and the bioluminescent is that bioluminescent species such as *Pyrocystis fusiformis* do not require sugars for sustenance but instead need seawater and sunlight to survive and reproduce.

Whether or not certain species of bioluminescent algae or bacteria are truly adaptive for growth in most existing algal farms. However, the ease in which luminous algae (such as *Pyrocystis spp.*) can be grown at home at virtually any scale greatly suggests that future cultivation of bioluminescent light is highly possible by algal farms and individuals alike.

More research should be done on the material use of luminous algae beyond its lifespan. After these organisms are expired as a light source, they should be evaluated as a viable food source or as a biofuel. If one day *Pyrocystis spp.* becomes confirmed as viable resource in this respect then it is a recyclable resource with increased usefulness.

It's clear that algae may gradually become an important, fundamental resource for the future due to natural algal abundance and the global cultivation of algae. The next section will validate algae as a future design resource.

5.2 Algal Design

In the past few years, algae have been experimented with as an integral design element. The following projects indicate the current and future possibilities of urban algae production and farming. Not only has algae become a proven source of oil, but it's an emerging design material. The following projects utilize algae in design.

H.O.R.T.U.S (Hydro Organism Response to Urban Stimuli), 2012



Figure 46 H.O.R.T.U.S installation⁷⁴

H.O.R.T.U.S is an installation by the Architectural Association School of Architecture in the U.K to introduce students to urban bio-gardening.⁷⁵ Hundreds of clear pouches are filled with various types of algae where participants are encouraged to blow into each pouch to provide necessary carbon dioxide to the algae. QR codes help to identify each species of algae.

The installation allows for easy incorporation of bioluminescent algae. As a small scale interior installation of algae production, H.O.R.T.U.S. is a precedent for controlled algae growth in interior environments. More importantly this project combines biology and architecture to demonstrate the potential for algae in design.

⁷⁴ Sue Barr, untitled, photograph, 2012, *we-make-money-not-art.com*, <http://we-make-money-not-art.com/archives/2012/01/hortus-hydro-organisms-respons.php> (accessed February 20, 2012)

⁷⁵ "Current Exhibitions"

HYDRO-NET SF 2108, 2008

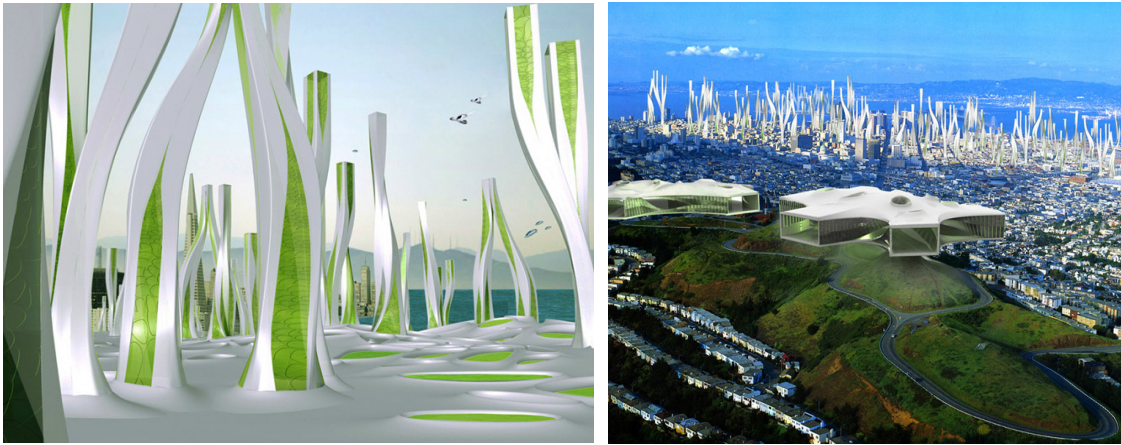


Figure 47 Hydro-Net as a proposal for San Francisco in 2108⁷⁶

Hydro-Net is a master plan vision of San Francisco for the year 2108 by architectural firm Iwamoto Scott.⁷⁷ The project is the winner of a competition hosted by the History Channel called “City of the Future” and features algae as a main design component. The main significance of this precedent is its flexibility in incorporating algae into the design while also providing insight to the possible future of our cities.

The project, conceived in 2008, embraces existing and future resources of the Bay Area linking the city through a series of “hydro-nets” and dispersing resources throughout the city. The technologies envisioned include fog capturing devices, algal ponds, urban algae farms, aquaculture zones, and fuel storage using nanotechnology. All of these technologies are meant to become interconnected and shared through the Hydro-Net.

The potential for algae production illustrated through this project strongly suggests that algae are compelling resources necessary in the future for fuel, medicine and food. In particular, bioluminescent algae can be implemented as one of many types of algae grown in this project. Here, the large quantity of algae envisioned is seamlessly integrated into urban design, demonstrating a compelling urban future with algae.

⁷⁶ Iwamoto Scott, “Hydro-net SF2108,” image rendering, 2008, iwamotoscott.com (accessed February 20, 2012)

⁷⁷ “Hydro-Net SF2108”

5.3 Chapter Five Conclusion

Algae are continuing to thrive in natural and domestic environments. The occurrences of Red Tides and algal blooms suggest future abundance of bioluminescent organisms. With current trends in algae production, bioluminescent algae such as *Pyrocystis spp.* have promising adaptability for future cultivation. Bioluminescent algal cultivation or farming is practical if integrated into existing algal farms or in small-scale residential settings.

Design models have demonstrated how algae are incorporated into design. An interior installation highlights human interaction with algae while a futuristic city plan is supported by algae as a resource. Both projects highlight that algae are an opportunistic design material and that bioluminescent varieties can be incorporated into these design models.

The attention given to algae today is a strong sign of its future prominence not only as a resource but as a design element of the future.

6

CONCLUSION

6.1 Project Conclusion

6.2 Personal Conclusion

6.1 Project Conclusion

Bioluminescence, as a phenomenon and lighting practice, lays a foundation for the design creativity in nocturnal environments in new and additional ways. Through bioluminescence, we are led to reevaluate how environments at night are engaged and experienced.

As a starting point to a limitless range of topics, this text presents ideas that require further research to extract the full potential of bioluminescent light. Various other bioluminescent organisms in addition to algae are recommended to be investigated for their design applicability. Thus the additional investigation into bioluminescence could lead to new and unforeseen visual and architectural experiences.

Not only has bioluminescence demonstrated its abilities in nocturnal settings, but it is an important resource of the future. Urban darkness could exist one day while algae could become an overwhelmingly abundant resource. Designers of the future should embrace these circumstances as potential design opportunities towards an innovative future.

Lastly, we should consider how much light is really necessary in the world today. Do we really need illumination to compose a functional architectural nightscape? How much darkness is enough to maintain a connection with the stars and sky above? Are we meant to live, instead, under natural lights such as fire, moon and stars? These questions are part of a larger picture which poses a challenge not only for architects and lighting designers but for humanity. If explored further, bioluminescence may not only address issues in design and sustainability, but the real significance that light has in our lives.

6.2 Personal Conclusion

This dissertation represents the largest academic challenge I have faced up until this point in life. It also represents the culmination of literally hundreds of discussions, countless hours of pondering and producing the document itself. I cannot thank those involved enough for their support, advice and encouragement during this endeavor.

This entire doctoral process has led me to research a wide range of topics, leading to unanticipated links in various fields of study. I'm grateful to have met many people and visit places beyond my expectation during this study. The correspondence with committee members, various experts, professors and classmates has greatly improved my communication skills and allowed me to develop meaningful relationships. The depth of research covered during the last year and a half has taught me about persistence and what's possible if we think, create and believe.

The rigor and length of the doctoral process has shown me that focused critical thinking was necessary in accurately conveying and expressing my thoughts. Due to the steady pace required for such an arduous process, I realized that good health was vital for my focus and completion of the D.Arch process. Now, I am more critical about the choices I make in life today.

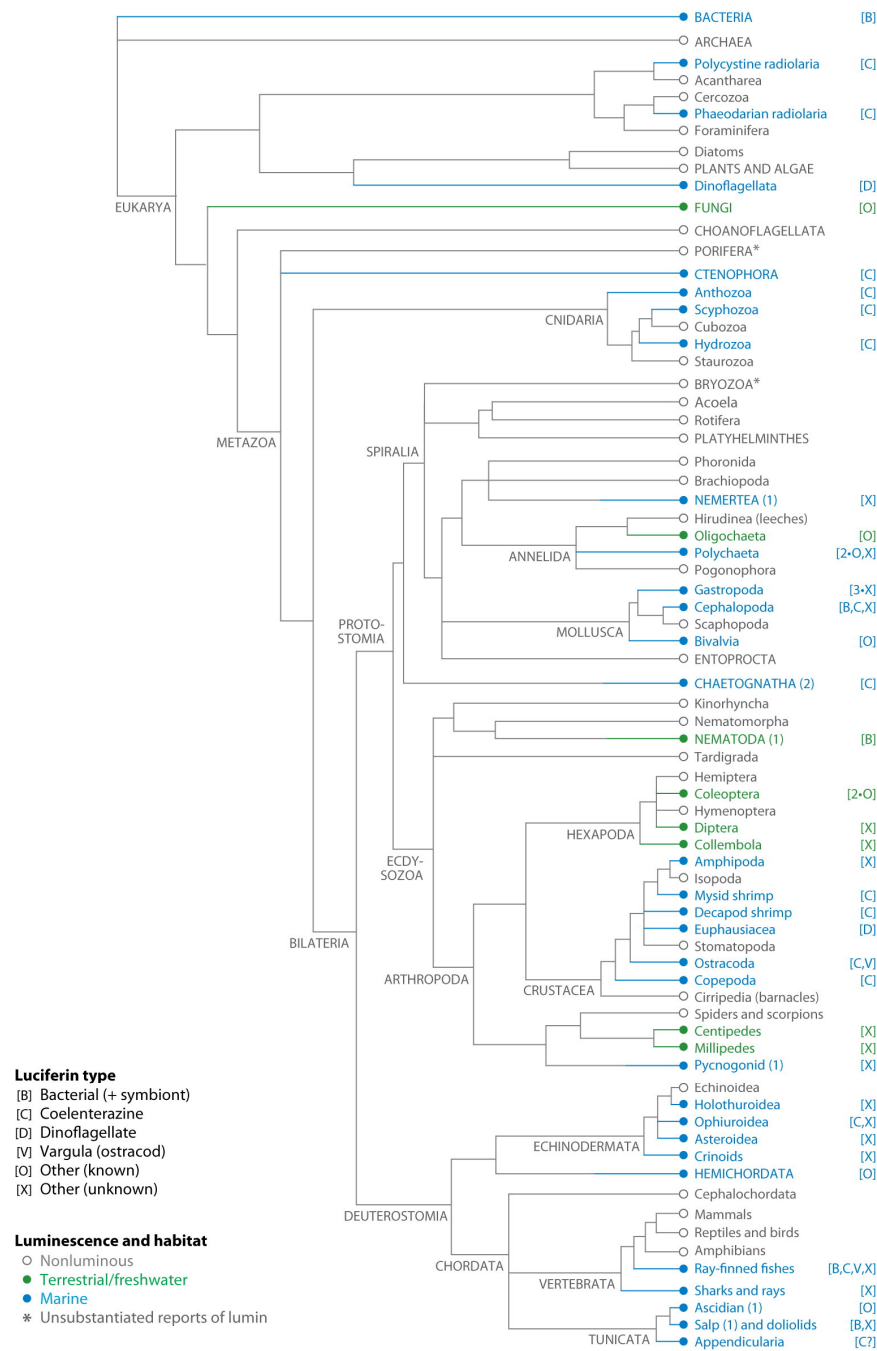
Although completing this dissertation has been very honest in challenging my persistence and character, I appreciate the ways in which this experience has taught me about myself. Again, I'm grateful to all who have contributed and supported me throughout this process and throughout my education. This is just a beginning as I continue to challenge myself along a difficult road ahead and I look forward to these challenges as opportunities to grow mentally, physically and emotionally.

Appendix

This appendix provides additional information gathered during the duration of this study which helped to inform many decisions throughout the research process. The information found here supplements the understanding of ideas and concepts presented in the text.

- A. List of Bioluminescent Organisms
- B. Biological Uses of Bioluminescent Light
- C. Additional Information on Bioluminescence
- D. Study of *Vibrio Fischeri*
- E. Human Circadian Rhythm Study
- F. Study of Shift Workers

A. LIST OF BIOLUMINESCENT ORGANISMS



A Haddock SHD, et al. 2010.
Annu. Rev. Mar. Sci. 2:443–93

Figure 48 A comprehensive list of identified bioluminescent organisms⁷⁸

⁷⁸ Source: Haddock, Moline and Case, "Bioluminescence in the Sea," 445

B. BIOLOGICAL USES OF BIOLUMINESCENT LIGHT


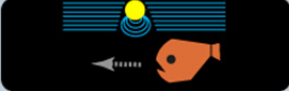





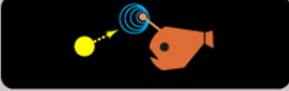
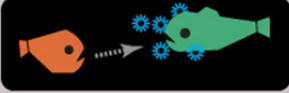



DEFENSE		startle	dinoflagellates, squid, stern-chaser myctophid
		counterillumination	many: crustaceans, fish, squid
		misdirection: smoke screen	many: crustaceans, polychaetes scyphozoans, chaetognaths, squids, tube-shoulder fishes, ctenophores, siphonophores, larvaceans?
		distractive body parts	<i>Octopoteuthis</i> squid, brittle stars, polychaetes, siphonophores
		burglar alarm	dinoflagellates, jellies, other?
		sacrificial tag	pelagic sea cucumbers, jellies, polychaetes
		warning coloration (deter settlers)	jellies, brittle stars? (tube worms, clam)
OFFENSE		lure prey attract host: bacteria)	anglerfishes, siphonophores, cookie cutter shark, squid?
		lure with external light (evaluate habitat?)	sperm whale? megamouth shark?
		stun or confuse prey	squid, headlamp myctophid?
		illuminate prey	flashlight fish, dragonfishes
		mate attraction/ recognition (swarming cue)	ostracods, <i>Japetella</i> octopus? lanternfish, flashlight fish, anglerfish? syllid polychaetes, others?

Figure 49 Biological uses of bioluminescent light⁷⁹

⁷⁹ Source: Haddock, Moline and Case, "Bioluminescence in the Sea," 464

C. ADDITIONAL INFORMATION ON BIOLUMINESCENCE

SCIENTIFIC UTILIZATIONS

The flexibility of bioluminescence in the field of science is demonstrated through random assays such as its use as a biosensor; biosensors can assess levels of various bacteria, toxins, chemicals, metals and other substances in various conditions. Dr. Edith Widder, a leading researcher on bioluminescence, is currently experimenting with *V. fischeri* as a catalyst for determining pollution levels in Floridian waters.⁸⁰ Her discovery of metals and pollutants in sediment tests were instrumental in hypothesizing algal growth and a limited oxygen supply to fish in the ecosystem.

Bioluminescence can also help identify foods that are unsafe to consume. Bioluminescent strains of the salmonella bacteria have been created by scientists for easy identification within foods to detect food poisoning. M.W. Griffiths has explored various assays of bioluminescence in the manufacturing of dairy products, which evaluated ATP as an indicator of bacterial contamination to detect pathogens and test for shelf-life of pasteurized dairy products.⁸¹

As an advanced application of bioluminescence, University of Florida Professor Rob Ferl predicts that a bioluminescent mustard plant, *Arabidopsis thaliana*, on Mars could visually transmit data back to Earth based on soil conditions, oxygen levels and other variables. Implanted with genes from a Pacific jellyfish, *Aequorea victoria*, the mustard plant would emit light in troubled conditions.

CHEMICAL REACTION

Raphael Dubois discovered that through switching the luciferin and luciferase between different species of luminous organisms, light could not be produced. This proved that each bioluminescent species produces its own unique set of chemicals.

Another component of the bioluminescence chemical process is ATP. ATP, adenosine triphosphate, is a molecule responsible for storing energy and directly responsible for brightness levels of bioluminescent light. Dr. William McElroy experimented with the tail lights of thousands of fireflies in order to test for the catalytic mechanism that made them glow. By isolating the luciferin and luciferase components from the firefly tail along with magnesium sulfate and oxygen, McElroy

⁸⁰ Olsen, "Illuminating the Perils of Pollution"

⁸¹ Griffiths, M.W., "Applications of Bioluminescence"

introduced ATP and found that ATP levels corresponded to brightness levels in the mixture.⁸² This experiment represented the first artificial creation of bioluminescence. Some organisms like jellyfish can do without ATP, using a photoprotein instead.⁸³ The photoprotein provides stored energy that can adapt to certain needs.

Most importantly, bioluminescence requires the presence of oxygen.⁸⁴ Scientist Robert Boyle (1667) discovered the necessity of air in “shining wood,” which was the term coined for luminous decaying wood. Boyle’s experiment compared shining wood to burning coal. Though drastically different in temperature and origin, luminous wood and coal, according to Boyle, had a very similar aesthetic at night. Boyle compared the effect that air and liquid had on burning coal and shining wood. At the time, oxygen wasn’t yet identified but Boyle successfully concluded that oxygen was a fundamental requirement of any bioluminescent light. In response to liquid, both shining wood and burning coal were able to recover themselves after being brief moments of liquid contact.⁸⁵

⁸² Horsburgh, *Living Light: Exploring Bioluminescence*, 24

⁸³ Pepling, “Bioluminescence provides practical applications.”

⁸⁴ Harvey, *Living Light*, 123

⁸⁵ Harvey, *Living Light*, 38

D. STUDY OF VIBRIO FISHERI

V. fischeri is one of the most popular bioluminescent bacteria species studied in microbiology. It is well-known for its symbiotic relationship with squid in Hawaiian waters. Although several other bacterial species luminesce, the *V. fischeri* species was most available for purchase and is one of the most widely studied for its bioluminescent properties.

Unlike the water solution of bioluminescent algae, bacterial forms of luminescence can thrive in open air. They also need a growth medium such as agar to continue to live, keeping in mind that they are naturally adapted for symbiosis with other marine organisms. For this reason, topical applications are most practical for bioluminescent bacteria.



Figure 50 Bacterial bioluminescence contained in agar, source: author

Real bioluminescent bacteria were purchased so that assumptions of its design abilities could be confirmed. The author of this text obtained a bioluminescent bacterium kit and several *V. fischeri* plates in agar were obtained from Carolina Biological.

The luminescence emitted from the bacteria was a soft, greenish blue glow similar to glow-in-the-dark paint. In fact, it was difficult to differentiate the quality of light from chemiluminescence. Although constant, luminosity from the bacteria was less than the algae. *V. fischeri* also lack a circadian rhythm, which bioluminescent algae have.

One difficulty with bioluminescent bacteria is that although it survives longer than bioluminescent algae, it requires more maintenance and care for sustenance. Fresh agar needs to be provided to the bacteria every four to five days. This extends the lifetime of the bacteria but limits potential design applications because it needs to be renewed constantly and the replenishing of the agar medium does not make for a sustainable system.

E. HUMAN CIRCADIAN RHYTHM STUDY

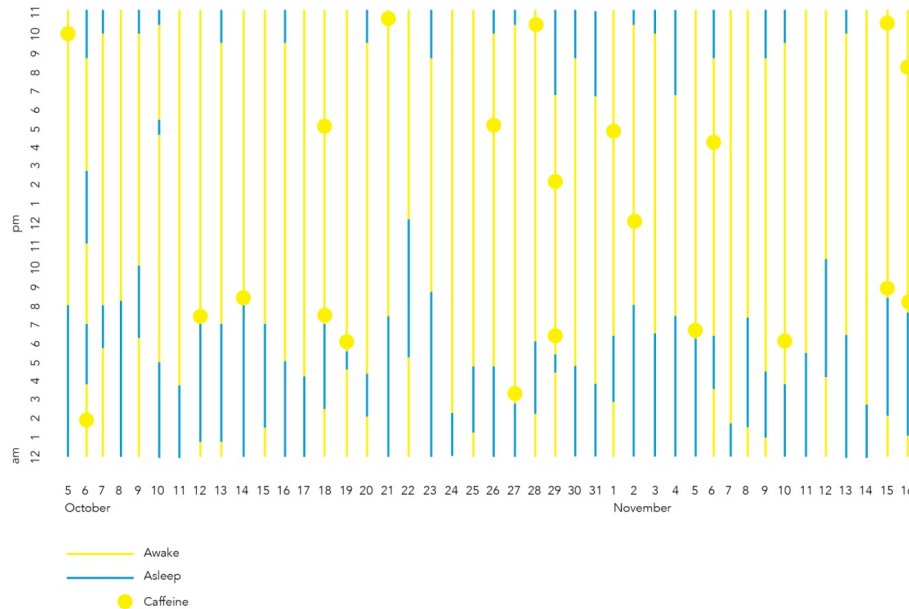


Figure 51 A sleep study conducted by the author

The author of this text charted his personal sleep schedule over the course of forty days. The results indicate a tendency to be awake late into the night while waking up in mid-morning. Overall, 259 hours of sleep and 773 hours of time awake made up the forty-three days of the study creating a 33.5% sleep to 66.5% wakefulness ratio. Despite the numerous bedtimes beyond midnight, the total sleep amounted to an average of eight hours per day. A circadian pattern also developed, despite the perception of an inconsistent sleep schedule. The author woke up between 6 and 8 am on most days and slept around midnight but was rarely awake between the hours of 2 and 5 am.

When staying up late at night was required, caffeine was considered as a remedy for sleepiness. While caffeine provided a boost in energy and concentration, the effect was temporary. Days where caffeine was taken in the morning often resulted in early nights to bed or an additional dose of caffeine. The chart also illustrates that nights when sleep occurred past midnight were followed by the consumption of caffeine in the morning. This study demonstrates that people have a natural inclination to be awake during specific hours of the day and are influenced by individual lifestyles. Regardless of long periods of wakefulness to avoid sleep, sleep was compensated for eventually. This clearly highlights that our bodies require a healthy and balanced amount of sleep.

F. STUDY OF SHIFT WORKERS

Three people who did shift work or had nocturnal sleep patterns were interviewed. These interviews were conducted to understand physical and social experiences of working at night.

TRADITIONAL NIGHT SHIFT

Don Takeuchi - Postal manager

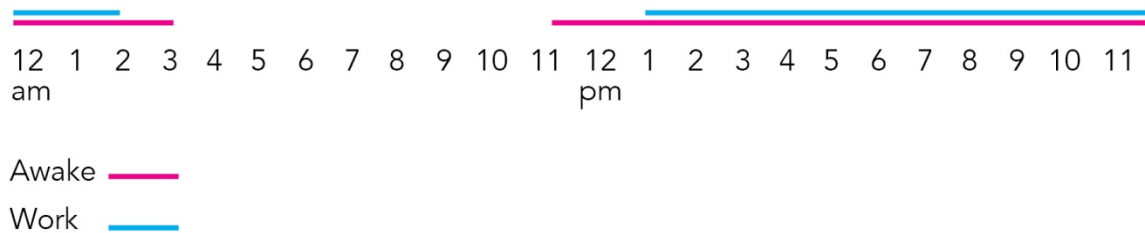


Figure 52 Daily work/sleep schedule of Don Takeuchi, source: author

Mr. Takeuchi works during the hours of 1 pm-2 am. He is the manager of postal operations at the Honolulu Main Post Office near the Honolulu International Airport. Takeuchi manages 370 employees during this shift and claims that it is a “life changing shift” due to the lifestyle changes required for the job.⁸⁶

Takeuchi wakes up at around 11 am to get ready for his 1 pm shift. He rarely drinks coffee on the job, acknowledging that most of the shift involves manual labor which allows him to stay awake for the duration of the shift. In fact, the employees on his shift do not suffer from fatigue not only because they are used to the work hours but also because of constant working and moving. Lights inside of the building are turned on 24-7 with no distinction between night and day unless one ventures outside. Because the time of day or night within the post office workplace cannot be distinguished due to constant artificial lighting, time can be estimated due to the different processes that occur throughout the shift. Takeuchi’s work hours were chosen by outside socioeconomic drivers of the present postal market. He is not immune to social complications as a shift worker. Takeuchi was asked whether or not his family was content with his work schedule. He replied that he would not consider a night shift immediately after marriage and only believes it is possible now because of his established marriage and having grown children.

⁸⁶ Takeuchi, Don, interview with author, 18 October 2010.

GLOBAL TRADING SHIFT

Mike Shimasaki - Japan Trade Industry

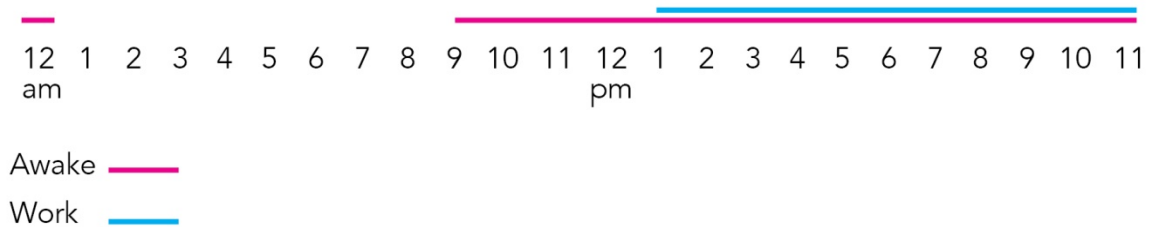


Figure 53 Daily work/sleep schedule of Mike Shimasaki, source: author

Global business sometimes equates to work hours adjusted to a different time zones. Mike Shimasaki works during the hours of 1-11 PM at a Japanese proprietary trading company. Because the company he works for operates during Japan's business hours of 8AM-6PM, this nineteen hour time difference requires a shift in his schedule. Shimasaki's office is located in Downtown, Honolulu. Despite the density of the area, he arrives having eaten lunch with reserved parking. His office often caters food for dinner since restaurants are not open for dinner in the Downtown area.

"I do most things before work, like watch television, work out and take care of bills. When I get home I sleep," says Shimasaki, whose daily routine is unlike common Downtown workers.⁸⁷

Shimasaki claims that the transition from a day job to an afternoon/night job was easy because his girlfriend enrolls in night courses and is awake during similar hours of the day. He also claims that he finds no restrictions in his ability to work during his 1-11PM shift. The light levels in his office were also bright enough to simulate daytime environments, which can create a shift in his daily circadian rhythm due to light exposure.

⁸⁷ Shimasaki, Michael, interview with author, 29 October 2010.

LATE NIGHT STUDENT SCHEDULE

Noryn Lau – Candidate, Doctor of Architecture Degree at University of Hawai‘i at Manoa

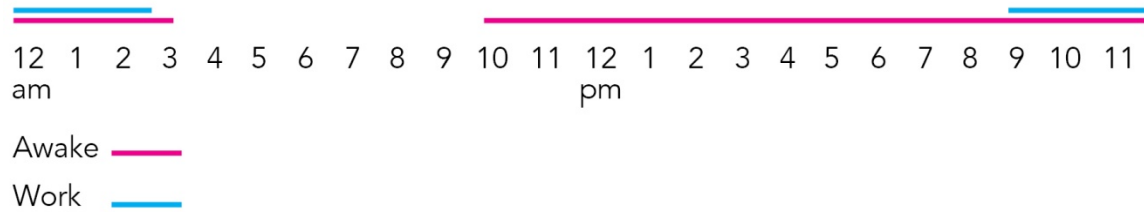


Figure 54 Daily work/sleep schedule of Noryn Lau, source: author

Noryn Lau is a candidate for the Doctor of Architecture Degree at the University of Hawai‘i at Manoa. She has developed a late circadian rhythm since she was a child, often staying up until 11 pm in elementary school.⁸⁸ Currently, she has a flexible school schedule and chooses to wake up around 10 am each morning but sometimes wakes up at 5 am for ice skating practice. She prepares lunch in the mid-afternoon, where she then takes a nap to be able to prepare for a late night of studying. Dinner comes around 8 pm and then schoolwork consumes most of Lau’s time from 9 pm to 2 am.

Lau finds herself having a difficult time waking up for early morning practices on the weekend. Her circadian rhythm tells her she should be sleeping while she’s at practice and ends up feeling sluggish because she tries to revert back to her usual weekday sleep pattern. Lau is familiar with the lack of productive workspace at night, relying on architectural studio space or a library desk to do schoolwork away from home. The fluorescent light she is exposed to in her study environment is enough to slow her melatonin secretion and temporarily halt sleepiness. Few windows exist in her study space, causing little awareness of exterior darkness or light.

INTERVIEW CONCLUSIONS

Shift work can result in life-changing consequences, both physical and social. If stimulated with the right amount of light, sound and activity, a circadian shift can occur. However natural biological patterns in our bodies tend to make shift work unnatural and difficult despite temporary increases in productivity.

⁸⁸ Lau, Noryn, interview with author, 23 November 2010.

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