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Sound Morphogenesis: A Theory and Methodology of Architecture and Design informed by Sound and Music

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Sound Morphogenesis:

A Theory and Methodology of Architecture and Design informed by Sound and Music

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy in Media Arts and Technology

By

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Sound Morphogenesis

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ABSTRACT

Sound Morphogenesis

by

Yin Yu

In 1958, Iannis Xenakis used a *glissandi* diagram as the *parti* for the architectural design of the Philips Pavilion. It was a pioneering example of an architectural form directly derived from the morphology of a sound object. In stark contrast, sound is usually seen as a pollutant, as something to be absorbed, blocked and diffused in current architectural design and practice. From an architectural design theory perspective, *Digital Morphogenesis* demonstrates significant theoretical implications in computational design and digital fabrication due to its natural-inspired sustainable methodologies, new forms, fabrication techniques, and multidisciplinary approaches. However, our current architectural and design field does not consider sound material from a morphological perspective in both theory and practice.

My research aims to expand the theory of digital morphogenesis by encompassing sound objects as an additional architectural material for computational design and fabrication. I introduce *Sound Morphogenesis Design* (SMD), a new design framework that uses information theory as a foundation to develop methodologies for architecture and design research. My research explores three main questions: (1) How does architectural practice change when sound is not viewed as pollution but as a design opportunity? (2) How does sound morphology expand the theory of digital morphogenesis and change the approach for architectural design research? And (3) what would be the novel design practice of sound morphogenesis design that enhances aural experiences and aesthetics? To integrate sound

morphology in design, this dissertation presents a systematic survey of musical aesthetics in architectural projects and develops two SMD methodologies: *WYHIWYW* and *SoftTectonics*. *WYHIWYW* (What You Hear Is What You Wear) investigates digital domain design techniques such as *Digital Design through the Open-Sound-Control Protocol*, *Computational Design through MIDI*, and *Computational Design through Modular Synthesizers*. Through such techniques, the listening experience enriches and expands the design process. *SoftTectonics* explores sound morphogenesis from three different approaches using physical prototyping of soft materials: *tip-grow*, *feather-flip*, and *pneumatic-cavity*. These methods provide a framework for digital architecture, wearable design, and new media artworks.

A novel analysis tool CIMT (Creative-Impact-Musicality-Technology) evaluates the developed research experiments to prove SMD's contribution as a design theory. The present dissertation paves a path to cross music and architecture for future discovery, design, and human perception.

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> Music is a matrix of ideas, of actions of energy, of mental processes, reflections in turn of the physical reality which created us and which sustains us [...]
>
> — *Iannis Xenakis*[1]

1.1 Research Background

The *Philips Pavilion* (Figure 1.1) is a pioneer multimedia architectural project for synthesizing the visual, auditory, architectural, and technical intersection of human perception capacities. Designed by Iannis Xenakis (1922-2001), the architecture of the *Philips Pavilion* is a significant work in modern architecture history because of the design *parti,*[2] the advanced construction of the shell structure, and the systems for sound and light controls. In 1954, Xenakis introduced hyperbolic paraboloid structures (below formula) through the graphic notation of his musical composition *Metastaseis*. In the score, bars 309 to 314 (Figure 1.1), Xenakis pinned two points that moved at a constant speed on two non-coplanar lines. As a result, several series of straight lines formed a doubly ruled surface for the *string glissandi*. Several years later, while designing the *Philips Pavilion*, Xenakis used the *glissandi* diagram as the architectural design *parti*. The *Philips Pavilion* is an early example of an architectural form establishing an intimate connection to the morphology of a sound object–*glissandi*.

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[1] *Musique-Architecture*, 2nd edn., Paris: Casterman,1976, p. 16.

[2] In architecture, *parti* is the decision behind an architect's design

$$z = \frac{x^2}{a^2} - \frac{y^2}{b^2}$$

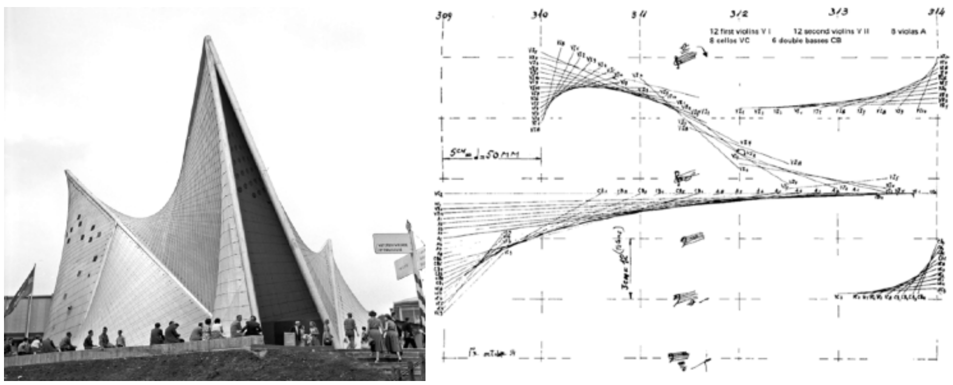

Figure 1.1 Philips Pavilion and Metastasis Score. Left: Philips Pavilion. Brussels, Belgium. 1958. (Source: https://en.wikipedia.org/wiki/Philips_Pavilion). Right: String Glissandi. Bars 309-314 of Metastasis. (Source: Xenakis, Sharon 2008)

The *Philips Pavilion* is recognized as an iconic modern architecture project of the 20th Century. As a design approach, music continues to inspire and inform architectural practitioners and design researchers. In recent years, publications related to music and architecture have sparked great interest and reached a broader audience. More importantly, the connection of these two fields opens the dialog between musicians, architects, and beyond. For example, *Music and Architecture* (2008), edited by Sharon Kanach, presents Iannis Xenakis's architectural works throughout his career from the early Le Corbusier years to his independent architectural practice. *Music, Space and Architecture* (2012), organized by the Amsterdam Academy of Architecture, offers a multidisciplinary approach covering the spatial experience in relation to architecture and music at different scales with essays, projects, and experiments. The Symposium *Music in Architecture — Architecture in Music*

(2014) holded at the University of Texas, Austin, invited musicians, architects, and scholars to exchange ideas on music and architecture. Meanwhile, at the MAXXI (Rome, Italy), the exhibition *Open Museum Open City* (2014), curated by Hou Hanru, features crucial topics of our time from the lens of sound in space. Furthermore, dissertations and theses by Saewon Yoo (2016), Rachel J. Beesen (2016), Marko Petreski (2016), Michelle M. Morimoto (2017), and Francesco Myles Sciotto (2018) also offer valuable resources on the research of music and architecture.

1.2 Problem statement

Since the discovery of architectural acoustics in the early 20th century, the applications of the field have mainly focused on sound design in concert halls, auditoria, and performance places. Unlike the invention of light bulbs, architectural acoustics mainly focus on engineering performance. Architectural lighting design, on the other hand, has developed beyond task illumination which was originally as the replacement of candlelight. Architectural lighting design has become both science and visual art and continues to explore new aesthetics and human perceptions like what we experienced in James Turrell's artwork.[3] In stark contrast, architectural acoustic is treated as a functional practice of sound control.

Yet, in architectural design and practice, sound is usually seen as a pollutant, as something to be absorbed, blocked and diffused. For example, *Gemini* (2014), designed by Neri Oxman of MIT Media Lab, aims to create a quiet environment for humans through a semi-closed wood chamber for sound cancelation and 3D printed material for sound

[3] James Turrell is an American artist known for his work within the Light and Space movement. He has been recognized for his artistic and architectural contributions to society all over the world.

absorption (Figure 1.2 Top left and right). Brady Peters, from the University of Toronto, used computer programming, parametric modeling, and simulation to design acoustic installations (Petters 2011, 2013, 2015) that reflect and control sound orientations (Figure 1.2 Middle left). Different materials have been explored using digital fabrication technologies, such as perforated wood (Figure 1.2 Middle right) for sound absorption (Foged et al, 2014), pattern tracing gypsum surface (Figure 1.2 Bottom left) for sound diffuser (Dickey, 2021), or ABS robot fabricated walls (Figure 1.2 Bottom right) for sound diffuser as well (Vomhof et al, 2014).

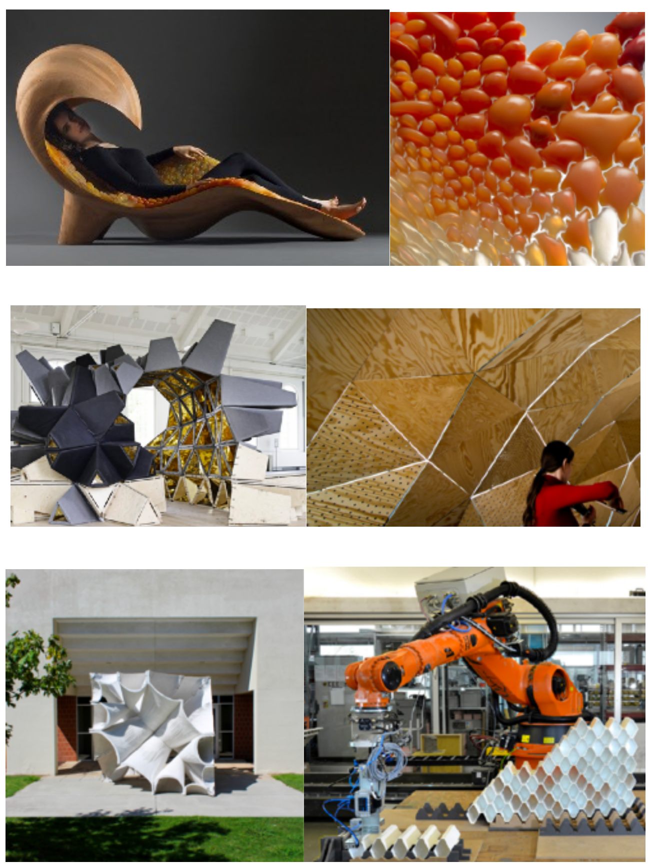

Figure 1.2 Computational Design in Architectural Acoustics. Top left: Gemini. Neri Oxman. 2014. Top right: Detail of the 3D printed material of inner lining (Source: https://neri.media.mit.edu/projects/details/gemini.html)

Middle left: Project Distortion I. Brady Peters. 2010. (Source: https://www.daniels.utoronto.ca/people/core-faculty/brady-peters)
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Bottom left: Sound Pavilion. Studio Dickey. 2021. (Source: http://studiodickey.com/sound-pavilion). Bottom right: Robotic fabrication of acoustic brick walls. ETH. 2014. (Source: http://acadia.org/papers/FYW2G2).

Figure 1.3 Representative Digital Morphogenesis Architecture Works. Left: Sendai Grin Grin Park. Matsuro Sasaki. 2005.(Source: http://architecturalmoleskine.blogspot.com/2013/03/toyo-ito-grin-grin-park-fukuoka.html) Middle: Taichung Theater. Toyo Ito and Cecil Balmond. 2016 (Source: https://archello.com/project/national-taichung-theater) Right: Pneuma. Neri Oxman. 2012. (Source: https://neri.media.mit.edu/projects/details/pneuma-2.html)

When viewed from design theory perspective, thanks to the emerging technologies, new design theories developed in the last few decades, such as *Deconstructivism*,[4] *Blobism*,[5] *Parametricism*,[6] *Architectural Tectonism*,[7] *Responsive Architecture*,[8] and *Digital*

[4] Works such as Frank Gehry's Santa Monica House 1978-1988, Daniel Libeskind's Berlin City Edge 1987-1988, Peter Eisenman's Biocenter 1987, and Zaha Hadid's The Peak 1982.

[5] Works such as Greg Lynn's Ravioli Chair 2005, Peter Cook and Colin Fournier's Kunsthaus Graz 2003.

[6] For example, the Gehry Partner's LV Foundation 2006-2014, ZHA's Kartal-Pendik Masterplan 2006, and Mark Burry's Gaudí and CAD 2006.

[7] A branch from Parametricism, works such as ZHA's 3D Printed Chair 2014, and Achim Menges's ICD/ITKE Research Pavilion 2013-14.

[8] Works such as Lars Spuybroek's Water Pavilion 1997, Mark Goulthorpe's Aegis 2003, and Philip Beesley's Hylozoic Ground 2010.

Morphogenesis.[9] In the book *Theories of the Digital in Architecture* (2014), Rivka Oxman and Robert Oxman ensembled the emerging theories and presented a foundation of transformations in design methods as well as the evolution of new forms of design thinking. Among the new theories, *Digital Morphogenesis* demonstrates significant theoretical implications due to its natural-inspired sustainable methodologies, new forms design and fabrication techniques, and multidisciplinary approaches, such as biology, computer science, materials science, and ecology, etc. Representative works (Figure 1.3) of digital morphogenesis theory are Matsuro Sasaki's *Sendai Grin Grin Park* (2005), Cecil Balmond's *Taichung Theater* (2016), and Neri Oxman's *Pneuma* (2012). However, the important dimension of sound is still absent in the digital morphogenesis theoretical framework. Overall, our current architectural and design practice does not encompass sound as an experimental and empirical building material in both theory and practice.

Since Dennis Gabor, the physics Nobel Prize winner, published his paper *Acoustical Quanta and The Theory of Hearing* in 1947, information theory has fundamentally changed how musicians approach composition in electronic music. With the rise of information theory, musicians and scientists have developed new knowledge and analytical frameworks of the science of sound over the last seven decades. Pierre Schaeffer borrowed the term *morphology* to describe the information of sound objects in his landmark work *Treatise on Musical Objects* (1966). Music is not only conceived as a combination of musical notes played by one or more instruments, but as digital information that can be shaped, sculpted, transformed by machines. My research aims to expand the theory of digital morphogenesis

[9] Representative digital morphogenesis works are Matsuro Sasaki's Sendai Grin Grin Park 2005, Cecil Balmond's Taichung Theater 2016, and Neri Oxman's Pneuma 2012.

by encompassing sound objects as the additional architectural materials for computational design and fabrication. I introduce *Sound Morphogenesis Design* (SMD), a new approach that uses information theory as a tool to develop methodologies for architecture and design practice.

My research aims to expand the theory of digital morphogenesis by encompassing sound objects as an additional architectural material for computational design and fabrication. I introduce *Sound Morphogenesis Design* (SMD), a new design approach that uses information theory as a foundation to develop methodologies for architecture and design research. The objectives of Sound Morphogenesis Design raises three main research questions:

Research Question 1: How does architectural practice change when sound is not viewed as pollution but as a design opportunity?

Research Question 2: How does sound morphology expand the theory of digital morphogenesis and change the approach for architectural design research?

Research Question 3: What would be the novel design practice of sound morphogenesis design that enhances aural experiences and aesthetics?

1.3 Methodology

This dissertation explores the research questions from two approaches: theory and practice.

From a theoretical perspective, to answer the first question, I conducted a survey of modern and contemporary architectural projects from 1939 to present. The survey shows the knowledge of architectural projects that viewed sound and music not as pollution, but as aesthetics. These musical aesthetics in architecture propose an original design philosophy. To understand the design philosophy of the SMD theory, I used a classification approach to identify critical sound and musical characteristics in architectural practice. These two main steps (a survey and classifications) answers Q1. To explore Q2, I developed a novel theoretical framework SMD based on the fundamental theory of communication–*Information Theory*.

From a practical perspective, I implemented the SMD theory to develop a series of approaches to explore the questions through design experiments. Two novel methods examined the SMD framework: *WYHIWYW* and *Soft Tectonics*. Using the method of WYHIWYW, I demonstrated two design experiments *Between the Points* and *Modulating Light* that enhance the aural perception during the design process. Through the method of Soft Tectonics, I showed three experiments *airMorphologies*, *OctoAnemone*, and *SoftVoss*. These experiments demonstrate the morphogenesis approach enhanced time-based aural experiences for a human-center architecture and design environment. I evaluated SMD experiments through a list of sound and music aesthetic criteria.

1.4 Organization

Chapter 1 introduces the research background on the musicality of architecture and the current problems in the context of digital architecture and computational design. It defines the assumptions, research issues, goals, and research questions. It presents the overall dissertation structure.

Chapter 2 presents a context of music in architecture design research. It surveyed iconic modern and contemporary architectural projects inspired by music. Selected representative architectural projects are from the 1930s to the present. This chapter presents a collection of contemporary practitioners using music as a design approach in architectural projects. It introduces a classification method for the design approach and explains the criteria of music features in architectural design. It summarizes ten important design approaches and seven design evaluation criterias.

Chapter 3 introduces the theoretical framework of Sound Morphogenesis Design. A three-axis diagram expands the design framework of SMD illustrating the intersections of music, architecture, and technology. It explains the important element in the technology axis which is the foundation of communication in the digital age–Information Theory. On the architecture axis, it introduced various morphogenesis models for design computation. Viewed from the music perspective, it introduces three important concepts: sound object, sound morphology, and music information retrieval (MIR). It presents a technical background of sound as material for design.

Chapter 4 explores a variety of digital architecture design techniques based on the framework from Chapter 3. It outlines a series of mapping strategies using Rhino, Max/MSP, and modular synthesizers. It presents and discusses the results of three experiments *Between the Points* and *Modulating Light*. In all three projects, the sound component takes precedence over the visual component throughout the design process.

Chapter 5 explores an analytic method based on the framework of SMD. It carries case studies on Xenakis's work and presents SMD as a methodology for researching musical architectural projects.

Chapter 6 presents a series of design experiments that implemented SMD techniques, summarized as *Soft Tectonics*. It presents three design outcomes: airMorphologies, *SoftVoss*, and *OctoAnemone*.

Chapter 7 turns the SMD approach to a pedagogical implementation. Several assignments, projects, and student work feature the positive contribution of SMD in design education.

Chapter 8 concludes with the contribution of the present dissertation and future directions.

2. Musical Aesthetics in Architecture

Sound is mechanical energy.

-*Curtis Roads* (2015)

Peter Zumthor’s architecture reveals a strong musical sensibility as a part of the design process. In the book, *Thinking Architecture*, Zumthor (1998) wrote the link between the two fields:

> Architecture is always concrete matter. Architecture is not abstract, but concrete. ... Music needs to be performed. Architecture needs to be executed. … To experience architecture in a concrete way means to touch, see, hear, and smell it.

Sound, the material of music, is concrete. It touches our skins, makes our bones vibrate, resonates with our souls, and oscillates across our surrounding environment. As composer Curtis Roads (2015) noted, sound penetrates rapidly to the brain in the form of electrochemical signals. Furthermore, Roads (2015) observed:

> The experience of music is a cognitive response to a perceptual reaction. Music directly touches emotions and associations; intellectualization is a side-effect.

The musical aesthetic in architecture is not merely an acoustic quality. It is performative and emotional. The fundamental aspects of music research are important to understand the musical aesthetics in architecture. This chapter presents a survey of contemporary architecture designed from the perspective of music. I will discuss each aesthetic issue and classify various music design opportunities for architectural practice. The goal of this chapter is to cover a range of topics connecting the field of architecture design.

2.1 Why Music?

> I listen. The music draws me in. It is a space. Colorful and sensual, with depth and movement. I am inside it. For a moment, nothing else exists.
>
> -*Peter Zumthor* (1998)

As mentioned earlier it is a good moment to systematically bridge the field of contemporary music into the theory of architecture design and practice. Like architecture shapes human interaction and social behavior, music affects us physically and psychologically. New music materials were introduced by electronic technology in the 1950s. For example, the introduction of the magnetic tape gave musicians a new color palette and state-of-the-art design strategies to develop unheard musical forms.

However, in architecture design and practice, designers tend to consider sound as a pollutant, as something to be absorbed, blocked, controlled, and diffused. R. Murray Schafer (1993), the renowned Canadian composer, once critiqued that the modern architect is designing for the deaf. He also emphasized that “the study of sound enters the modern architecture school only as sound reduction, isolation, and absorption”.

In recent years, the discussion on music surfaced in architectural literature and projects. As an example, a series of conferences and publications on Iannis Xenakis's work inspired many architects and designers. In particular, *Music and Architecture*, published in 2008 by Iannis Xenakis and Sharon Kanach, is an excellent resource on our field. Another example is the symposium *Music in Architecture – Architecture in Music*, organized by the University of Texas, Austin in 2011. The event brought architects and musicians together for a collaborative dialogue on music and architecture, which later resulted in a publication in 2014 with the same title.

Technologies have changed architecture and music radically. What we need is a systematic study of the subject, and further discussion of the aesthetic issues, its implications, and a potential framework for a theory covering the future of music as a design opportunity.

2.2 Music as Design Opportunities in Architecture

Architecture design needs information. A project usually starts from a client's requirements, such as program, site, budget, etc. Music information can be used to materialize a design idea by incorporating specific music information into the design process. The results can range from abstract renditions to hightail specific and detailed sound representations. Because of the long history of architecture and music, a comprehensive publication covering all the architecture projects inspired by music would be an entirely different research effort. However, I curated a selection of architectural works from the modern time and examined their design approaches. It is necessary to classify the design opportunities featured in those projects to understand their context and contribution to this research. This section explores a certain musical aesthetic design consideration in architecture from 1939 to 2021. Section 2.4 presents a table of selected projects. Two main considerations frame the elements of the musical design: *Music as Design Opportunity* (approaches) and *Musical Features in Architecture* (outcomes). The two main categories with their subtopics are listed below：

Music as Design Opportunity in Architecture

Architectural acoustics;

Musical instrument;

Pitch;

Chromesthesia;

Notation;

Music form;

Rhythmic;

Music information;

Spatialization;

Sociomusicology.

Musical Features in Architecture

Visual Musicality;

Musical Movement;

Aural Experience;

Musical Interactivity;

Sociomusicology Representation;

Time.

2.2.1 Architectural Acoustics

Acoustics, the science of sound, is a branch of physics. For Daniel R. Raichel,[10] the science of acoustics "deals with the creation of sound, sound transmission through solids, and the effects of sound on both inert and living materials." Modern acoustics contributed with a variety of applications in material science, medicine, marine navigation, communication, oceanology, animal bioacoustic, music synthesis, and noise cancellation (Raichel, 2006). The first architectural acoustic project is the lecture hall at the Fogg Art Museum in Harvard. It is considered to be the beginnings of modern acoustics. Wallace Clement Sabine published a series of papers (1900-1915) on architectural acoustics while working on the acoustic enhancement for the Fogg lecture room. His studies provided the foundation for the science of room acoustics (Katz and Ewart, 2007). Sabine established the relationship between absorption and reverberation time. He defined a reverberation time (RT) as

$$T = \frac{0.049V}{\sum_i S_i \alpha_i} \tag{2.1}$$

Here V is the room volume (cubic feet), S_i the component surface area, and α_i the corresponding absorption coefficient.

Architects often work closely with acoustic engineers in contemporary architectural practice, especially in auditoria and concert halls. A successful example is the Walt Disney Concert Hall, designed by architect Frank O. Gehry in collaboration with the acoustician Yasuhisa Toyota for the Los Angeles Philharmonic (Figure 2.1 Top left). The air volume of

[10] An expert on acoustics https://www.nytimes.com/2007/01/08/science/08raichel.html

the main concert wall was approximately 30,600 cubic meters. The room air volume for each seat is 13.5 cubic meters, close to the reasonable figure of 10 (Toyota et al., 1999). The interior finishing used natural woods, such as Douglas Fir for the ceiling and walls, Oak for the audience floor, and Alaskan yellow cedar for the stage floor. The reverberation time is approximately 2.0 seconds at 500 Hz. Considered to be a "living room" for the city, both performers and audience successfully experience the architecture design when performing or listening to the music at the Walt Disney Concert Hall.

Other common architectural acoustic issues can be found in interior public spaces. For example, a restaurant offering tasty dishes in a noisy environment could be an unpleasant dining experience. In some restaurants, people can not even hear each other at the same table. Many factors have an influence on the acoustic experience. For example, if an empty interior space has a high ceiling, people would have difficulty communicating. The *HIVE* (2017), designed by Studio Gang in the great hall at the National Building Museum (Washington, D.C.), creates acoustic chambers to improve public engagement in a dynamic sonic environment (Figure 2.1 Top right). The three acoustic chambers, made of recyclable, lightweight paper tubes, reflect or pass sound through the tubes to the great hall (Studio Gang, 2017).

Architectural acoustic is mainly concerned with an enclosed interior space. However, how do we conceive and describe an interior space? What boundaries differentiate the exterior from the interior? Concerts and public speeches in an open space could trace back to antiquity. For instance, the famous Hellenistic theater, the *Ancient Theater of Epidaurus,* was constructed during the 4th century BC. In an outdoor space, mountains, trees, land, and clouds become the natural material for sound reflections, absorption, and diffraction. A good example of architectural acoustics is the *Ruup* (2015) project (Figure 2.1 Bottom left). Three massive megaphones designed in an Estonia Võru county forest, improve the local community's engagement with sounds from nature. Designed and built by the students from the Interior Architecture Department of the Estonian Academy of Arts, *Ruup* is an installation made of larch. Each megaphone structure spanned three meters in diameter, and placed within six meters of each other, forming a large circle inside the forest. Visitors sit inside the megaphones to hear the rich amplified forest sounds, such as rustling leaves, chirping birds, and other wildlife. The project was inspired by the acoustics of the forest during a search for a lost mushroom picker (Estonia, 2017). *Ruup* is an excellent example of an architectural project that reminds people to listen to the sounds surrounding them.

A successful architectural acoustic application can enhance our musical experience and enrich our public life. Lukas Kühne, the German sculptor, created a series of architectural sculptures (2005 - 2012) that applied sound properties to the designed space. The *Tvísöngur sound sculpture* (2012), for example, is a "singing concrete" located on a mountainside above the town of Seyðisfjörður, Iceland (Figure 2.1 Bottom right). It consists of five interconnected concrete domes. The heights of the domes vary from two to four meters, and the total area is about 30 square meters. Each dome resonates a unique tone that corresponds to the Icelandic musical tradition of five-tone harmony. As a natural amplifier, the *Tvísöngur* stimulates both the visual and the auditory senses inviting the local community to sing and play music (Kühne, 2012).

As a branch of acoustical engineering, architectural acoustics is the fundamental design principle for the auditoria, concert halls, and lecture rooms. However, we can also find creative approaches in other circumstances that could help to enhance the public aural experience and promote active listening environments.

Figure 2.1 Architectural Acoustic Projects. Top left: Gehry Partners and Yasuhisa Toyota, Walt Disney Concert Hall, 2003 (Source:https://www.archdaily.com/441358/ad-classics-walt-disney-concert-hall-frank-gehry?ad_medium=gallery) Top right: Studio Gang, HIVE, 2017 (Source: https://studiogang.com/project/hive). Bottom left: Interior Architecture students at the Estonian Academy of Arts, Ruup, 2015 (Source: https://www.tonutunnel.com/projects/ruup-in-the-pahni-forest) Bottom right: Lukas Kühne, Tvísöngur sound sculpture, 2012 (Source: http://www.lukaskuehne.com/)

2.2.2 Musical Instrument

The shape of a musical instrument often becomes a visual inspiration for architectural design. Spanish architect and structural engineer Santiago Calatrava designed a series of bridges between 1999 and 2004 in Hoofddorp, Netherlands, where residents named the bridges as the Lyre, the Harp, and the Lute (Calatrava, 2004). The musical image and the sequence of the vertical bridge cables added a new aesthetic to the urban landscape (Figure 2.2 Top left).

The physical model of a musical instrument is another source for design. For example, the sound sculpture, *Aeolus* (2009), was an architectural instrument played by the wind (Figure 2.2 Top right). Designed by artist Luke Jerram, *Aeolus* is a large-scale Aeolian harp. Blown by the wind, the strings move up and down. The strings resonate at a harmonic frequency when the wind blows faster, and the sculpture generates sounds with musical attributes.

However, the translation between musical instruments to architectural design requires skillful selection, abstraction, techniques, and articulation. Enlarged scales or plain realistically translations might result in a failed design outcome, such as the piano-shaped *Rajanagarindra Institute of Child Development* (2014) in Chiang Mai, Thailand (Figure 2.2 Middle left), the piano-violin-shaped building (2007) in Huainan, China, and the keyboard pattern façade at the Musicians Hall of Fame and Museum (2008) in Nashville, TN (Figure 2.2 Middle right). We have seen a similar design approach in other projects, such as the *Big Duck* (1930) in New York and the *Big Basket* (1997) in Ohio. The *Big Basket*, for example, cost $30 million to build in 1997 and sold for $1.2 million in 2018. A non-artful translation could damage the value of an architectural project.

A good translation of a musical instrument to an architectural design does not necessarily need to be seen, but to be heard. The *Sea Organ* (2015) in Zadar, Croatia is a landscape architecture project based on the organ musical instrument—flue pipe (Figure 2.2 Bottom). Designed by the architect Nikola Bašić, the acoustician Ivan Stamać, and organ pipe designer Tomislav Faullend Heferer, 35 organ pipes are built-in underneath the staircases at the seashore. Visitors listen to the random sounds that come out from the organ pipes. The pipes designed follow the physical model of the flue pipe. Each pipe consists of mouth, foot pipe, lip, and resonator (Stamac, 2005). The ocean wave moves the water inside the tube, and the air inside of the pipe is pushed out through the lip. In the following sections, I will discuss more about the detailed design of the *Sea Organ*.

2.2.3 Pitch

Pitch can bring a sense of musicality and harmonic qualities to an architectural project. In the *Sea Organ*, for example, 35 pipes are arranged into seven sections at a total length of 70 meters stairy promenade. Each of the five pipes in one section has a space of 1.5 meter between each other. From the north side to the south end, each section is one step shorter. The far north section has eight steps and the far south section has two steps. This design is based on traditional Croatian traditional Klapa music with melodies and chords conformed to the diatonic major scale (Stamac, 2005). In each section, the five pipes are tuned to one chord. The chord contains tones out of the major scale. The lower and higher pitches (frequencies between 65 Hz and 250 Hz) were chosen for allocation of tones to the pipes. The pipes are tuned to chord tones as follows: D, G, d, g, h (odd sections) and C, G, c, e, a (even sections), respectively (Stamac, 2005).

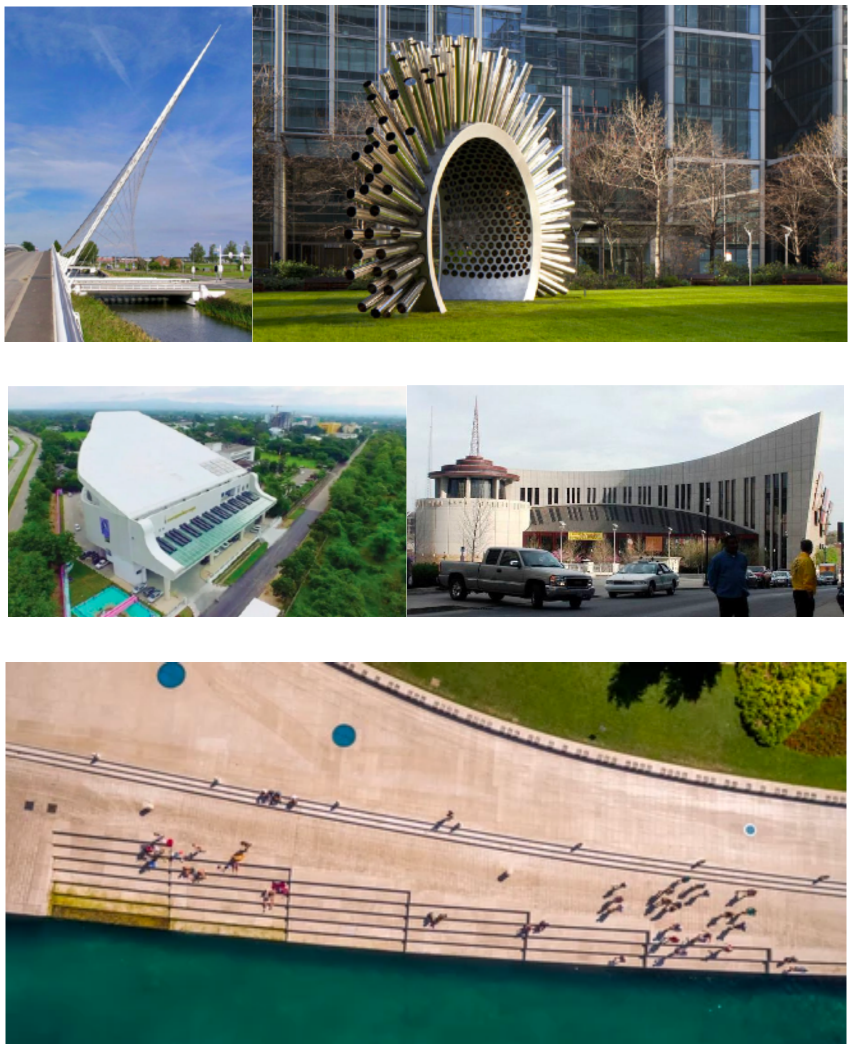


Figure 2.2 Musical Instrument Projects. Top left: Santiago Calatrava, The Harp-Nieuw Viennep Bridge, 1992 (Source: https://www.wikiwand.com/en/Haarlemmermeer). Top right: Aeolus - Acoustic Wind Pavilion. (Source:https://www.lukejerram.com/aeolus/) Middle left: Rajanagarindra Institute of Child Development (2014) (Source: https://wp.stolaf.edu/news/where-are-they-now)
Middle right: Country Music Hall of Fame, Nashville (Source: https://en.wikipedia.org/wiki/Country_Music_Hall_of_Fame_and_Museum)
Bottom: Nikola Bašić and Ivan Stamać dipl. inž, Sea Organ, 2015 (Source: https://www.shutterstock.com/search/zadar+sea+organ)

2.2.4 Chromesthesia

Synesthesia is a phenomenon of perception (Block, 1983). Chromesthesia, or "color-hearing", is a type of synesthesia in which stimuli color by aural experience (Haack and Rudolf 1981, Block 1983, Rogers 1987). Studies show sounds that are loud and of high pitch tend to evoke bright colors, whereas sounds that are soft and lowered-pitched tend to evoke darker colors (Polzella and Hassen, 1997). Some musicians use color to direct, play, or compose music. For example, Olivier Messiaen, the French composer, was influenced by the color of musical keys (Bernard 1986, Ward 2013).

Steve Roden, a sound artist, used colors from a glockenspiel (a percussion instrument) for the pavilion score during a performance at the 2005 Serpentine Gallery Pavilion (Roden, 2005). The pavilion was designed by architects Eduardo Souto de Moura and Álvaro Siza, and the structure engineer Cecil Balmond. Although the architectural design didn't apply colors or musical attributes, the site specific performance is an example of a live event using colors to execute sounds in a building environment (Figure 2.3 Left).

The Academie MWD (2012) in Dilbeek, Belgium, features a musical design through its colorful lenticular façade (Figure 2.3 Right). Designed by Carlos Arroyo, the academie offers education in music, theater, and dance. The colorful façade was inspired by postmodern Belgium architect Alfons Hoppenbrouwers's painting. In the late 1990s, Hoppenbrouwers turned music into visual art in his *Ockeghem* and *Bach* series paintings. Using mathematics and color, Hoppenbrouwers transformed music into lines with different proportions, geometry, and color. The façade is a visual representation of musical color interpretations.

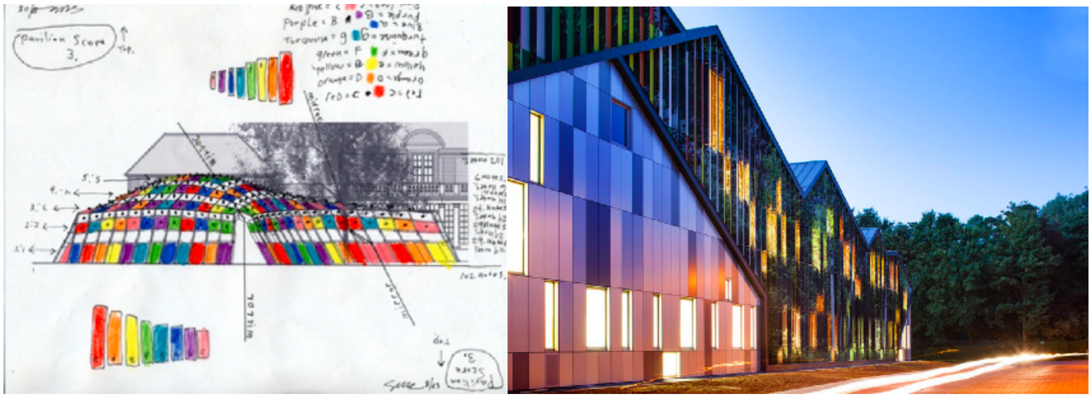


Figure 2.3 Chromesthesia Projects Left: Steve Roden, Pavilion score, 2005 (Source: http://www.inbetweennoise.com/works/sounding-architecture-and-pavilion-scores/) Right: Carlos Arroyo, Academia MWD Belgium, 2012. (Source: https://www.carlosarroyo.net/)

2.2.5 Notation

Music notation and graphic scores are visual representations of sound that designers can use as inspiration. The spatial composition of the *Therme Vals* (1996), for example, shows a dynamic arrangement of spaces. Designed by Peter Zumthor, the winner of the 2009 Pritzker Prize, the design process of the *Therme Vals* started with block diagram studies–the geometric abstractions for spatial organization. Zumthor wanted to create an experience of a sequence of spaces. The spaces in the block diagram resembled part of a score by John Cage (Hauser, 2007). The architectural space experience mimics reading John Cage's score: rhythms, compression, and intensities of the sound event moving along the temporal axis of the notation.

Steven Holl, a New York-based American architect, has been exploring the relationship between music and architecture in his practice since the 1990s. He offered a series of experimental studios at the Columbia GSAPP (Graduate School of Architecture, Planning and Preservation) in relevant topics, such as studio *Architectonics of Music*. The *Daeyang*

Gallery and House (2012) used Istvan Anhalt's graphic score "*Symphony of Modules*" (1967) for the architectural design. Anhalt composed three modules on the score, each module has a contour. Holl used these three contours for the profiles of the three buildings. He also abstracted the music notes into 55 skylights on the ceilings. Holl brings the language of graphic notations from the 1960s into contemporary architecture discourse.

The famous *Philips Pavilion* (1958) belongs to the notation approach we are describing. In his composition *Metastaseis* (1954), Xenakis drew the graphic score of *string glissandi* between the Bars 309 to 314, which only lasted a few seconds during the performance. As mentioned earlier, the *glissandi* is generated by a series of straight lines to achieve the doubly ruled surfaces. Four years later, when working on the *Philips Pavilion*, Xenakis used this double ruled surface for the hyperbolic paraboloid structure of the pavilion. The *Philips Pavilion* is an early example of an architectural form that brings the visual language of a graphic score into its design–*glissandi*.

Figure 2.4 Notational Projects. Left: Peter Zumthor, Therme Vals, 1996. Middle: Steven Holl, Daeyang Gallery and House, 2012. (Source: https://www.stevenholl.com/project/daeyang-gallery-and-house/).
Right: Iannis Xenakis at Le Corbusier Studio, Philips Pavilion, 1958. (Source: https://en.wikipedia.org/wiki/Philips_Pavilion).

2.2.6 Music Form

Modern technology influenced music composition during the 20th century. The definition of form also evolved. Music form could refer to the result of organized sound, or the structure of a piece. In electronic music, a heterogeneous collection of macro morphologies would classify as “free forms” in traditional theory (Roads, 2015). As Roads observed:

> The form of a work contextualizes the internal materials and structures, articulating their structural roles, rendering them recognizable.

The design process of a music form could be articulated into an architecture spatial composition. For example, Johann Sebastian Bach’s mastery of counterpoint in his compositions created new forms of musical expression (Forkel, 1920). Bach’s harmony is not a single line of melody but an interweaving of several independent melodies. This style of musical form inspired Zaha Hadid’s *JS Bach Concert Hall* (2009). The structure is a circular chamber music hall that utilizes a single continuous ribbon of fabric, continually stretching, compressing, and interweaving through the space. Like Bach’s work, the fabric moves up and down, touches the floor, emerges in air, and reaches to the ceiling. Hadid’s continued fluidity of space design resonates with Bach’s endless flowing and movement.

Steven Holl’s *Stretto House* (1992) used four sections of the building to represent the four movements of Béla Bartók’s *Music for Strings, Percussion and Celesta* (1937). The name was derived from the musical term *stretto*, meaning the overlapping of musical themes, and became the main synthetic tool of the design process, the overlapping of spaces. (Martin, 1994). The concrete block symbolizes the heavy percussion in the performance, whereas the glass and metal tubes represent the light strings.

Moses und Aron (1932), the masterpiece of the Jewish composer Arnold Schönberg, is a three-act opera with a third unfinished act. The whole musical structure grounding to a halt inspired the Jewish architect Daniel Libeskind's design in the Jewish Museum Berlin (2001). As Libeskind observed, at the end of the opera, words were spoken not sung, there was a nonmusical expression. The architect understood the void as part of Schönberg's original composition. In the design of the Jewish Museum Berlin, the diagonal windows on the facade and the intertwined structures in the interior are Libeskind's ideas of separated lines. The space created in between becomes Libeskind's "void" (Libeskind, 1992).

Alvar Aalto's *Finnish Pavilion* (1939) for the New York World's Fair is a great example of the musical form design approach in interior architecture with a societal and a cultural impact. The interior walls naturally grow throughout the space. Some areas stretch and some others contract. The pavilion was analyzed by scholars Sarah Menin and Gilbert Decouvreur. For them, Aalto's works were influenced by the Finnish composer, Jean Sibelius, whose music helped Finland develop a national identity during a critical time of a young post-war nation state. In contrast with his early works, Sibelius removed the traditional sonata form and focused on evolving musical ideas in a single continuous movement. As a result, a sense of unbroken, organic form emerged in Sibelius' works (Pike, 1978). This is a great example of an architect influenced by a contemporary composer both sharing a deep love to their land.

2.2.7 Rhythmic

Rhythm is the most fundamental element in all forms of musical expression (Roads, 2015). As Edgard Varèse observed, "Rhythm is the element in music that gives life to work and holds it together" (Varese, 1959). Erwin Schrödinger, the Nobel Prize-winning physicist, introduced the concept of "negentropy" in his *What is life* (1944)? He describes life as producing orderliness, and "organization maintained by extracting 'order' from the environment" (Schrodinger, 1944). Life is negentropy. Rhythm is the negentropy for music.

How to give life to architecture? Frank Lloyd Wright gave life to the house *Fallingwater* (1939) by designing the dynamic cascaded space on the top of a flowing waterfall. Le Corbusier gave life to the southwall of the *Notre-Dame du Haut* (1955) by designing a lively interior wall with varying degrees of opening angles, alternating depths, and colorful stained glass windows.

However, rhythm in architecture can no longer be viewed merely as a pattern of solid and void composition. Rhythm can influence our perception of the musical experience over time. Rhythm in architecture should also consider the time dimension. One of the most iconic rhythmic architectural projects is the west façade at the *Convent of La Tourette* (1961) due to its scale, proportion, and musical movement. Designed by Iannis Xenakis in collaboration with Le Corbusier, the density and continuity in the "undulating glass panes" became his musical expression in architecture. Facing the northwest, the natural light illuminates the interior space. Selective direct and indirect light grows into the interior space through the glazing. At about 3.66 meters floor-to-ceiling height, light and shade perform a musical gesture inside. While walking at a constant speed, one can perceive dramatic light movements thanks to the continuous change of the concrete frames' density. The rhythmic experience is a continuity of several light transformations. A new architectural aesthetic emerges through Xenakis's music composition, intellectual contemplation, and mathematical abstraction.

2.2.8 Music Information

Music can be carried, stored, and retrieved by computers in the digital age. Designers can access digital information and use them for creative and practical applications, such as music visualization, voice recognition, etc. The *Pavilion 21 MINI Opera Space* (Figure 2.5), designed by Wolf D. Prix/COOP HIMMELBLAU, is an early attempt of a digital architectural model using selected music information to shape the pavilion's façade. During the design process, the spectral information of the song *Purple Haze* by Jimi Hendrix and a passage from *Don Giovanni* by Mozart were obtained through information processing (Prix, 2010). The color-coded frequency was mapped on the digital model of the architectural block. Although the final result is not a direct translation from the music information to the architectural information, the analysis process demonstrates a potential digital design strategy using music information.

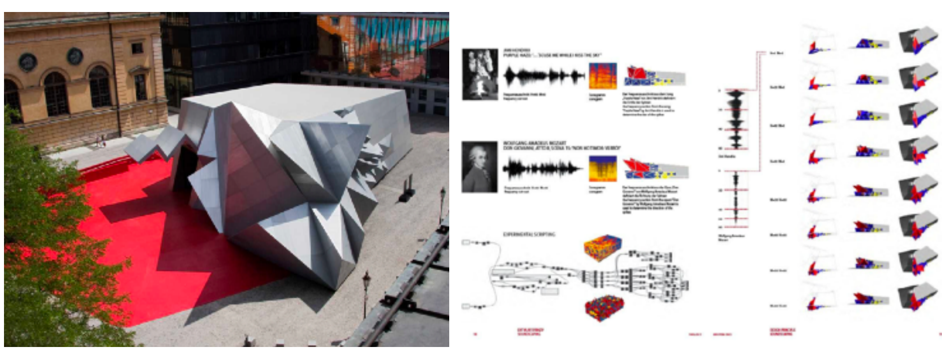


Figure 2.5 Music Information Projects. Left: COOP HIMMELB(L)AU. Pavilion 21 MINI Opera Space. 2010. (Source: https://archello.com/project/pavilion-21-mini-opera-space) Right: Process in Generation of 3D Model (Source: http://www.coop-himmelblau.at/architecture/publications/pavillon-21-mini-opera-space)

2.2.9 Spatialization

Another sound attribute is direction. Sound waves in air tend to radiate spherically in three dimensions from a source (Roads, 2015). In recent multimedia architectural projects, designers bring sound into the spatial design practice. By placing wired speakers at different locations, visitors are able to experience fully immersive sound environments, such as *Son-O-House* (2004), *NASA's Orbit Pavilion* (2015), and *Ekko* (2012). An analog example would be the *Swiss Sound Box* (2000), the Swiss Pavilion for the World EXPO Hanover, Germany, designed by Peter Zumthor. The *Swiss Sound Box* was made mostly of wood—lumber from Switzerland. Zumthor took this opportunity to turn the building into a culinary, musical, and performative experience. The architectural box has a dimension of 50 by 50 meters with a height of 9 meters. Corridors and spaces were created with a series of 118 individual stacks of large lumber (Zumthor, 2000). The sound of music, talks, performances, and walking steps travels throughout the wood and the gaps in between. In *Thinking Architecture* (2010), Zumthor said:

> "There is disharmony and broken rhythm, fragments, and clusters of sound, and there is also the purely functional sound that we call noise. Contemporary music works with these elements. Contemporary architecture should be just as radical as contemporary music."

No high-tech element was used in the pavilion. Not even a single screw, nail, or glue was used in this project. The beams that form the walls are separated and stacked with wood. The walls are connected with tension rods and steel springs. The whole structure works by the resulting compression and friction of the stacked beams. Zumthor uses simple architectural principles to evoke the visitor's senses. “It is a sentiment of feeling,” he said. Visitors can enter the pavilion from the different paths they take. The *Swiss Sound Box* is a performance space that is constantly changing by visitors, nature (wind or rain), and the curated music program. Zumthor found a harmonious resonance between the building, its inhabitants, and the surrounding natural world. The architecture responds to the sound harmonically from different directions in the space.

2.2.10 Sociomusicology

In the 1960s, musical scholars adopted the term *Sociomusicology* to describe research on music from the perspective of any social science field (Hebert, 2019). From a social perspective, music interacts with the community and affects social and individual behavior. As Roads (2022) noted:

> Xenakis said that he composed in order to feel less miserable. This is an excellent reason to compose. But the effect of music goes beyond one’s self. Composition is a service to humanity. Through music, a composer can also make other people feel less miserable.

Architectural design could be more socially engaged and aurally healthy if we consider it from a sociomusicology perspective. The Melbourne Conservatorium *Ian Potter Southbank Center* (Figure 2.6) took the inspiration from Willian Hogarth’s 1741 etching the *Enraged Musician* to rethink the interaction between the musician and their community. Designed by John Wardle Architects, the *Ian Potter Southbank Center* is the new home for music rehearsal and practice. Unlike the annoyed violinist distracted by the cacophony outside his window in Hogarth's etching, the *Ian Potter Southbank Center* opens several huge and deep windows on the street level inviting pedestrians to engage with the music.

Figure 2.6 Sociomusicology Projects. Left: Enraged Musician. William Hogarth. 1741. (Source: https://en.wikipedia.org/wiki/The_Enraged_Musician). Right: Ian Potter Southbank Center. John Wardle Architects. 2019. (Source: https://www.johnwardlearchitects.com/projects/ian-potter-southbank-centre/)

2.3 Musical Features in Architecture

We should be able to "hear" music if an architecture possesses musical qualities in its design. The listening act goes beyond our ears and reaches other human senses.

2.3.1 Visual Musicality

Patterns are commonly associated with music. Universal patterns have developed over the years. As Cecil Balmond (2013) observed:

> Seeing and perceiving set up entry gates to emotion and memory, they link a universe of fleeting connection. … Pattern exists in all modes of how a particular material shapes, proportions and joins to itself, or other elements.

For example, a visual element, such as stairs or windows arranged in a sequence of piano keys, could be associated with music. The *Musicians Hall of Fame and Museum* (2008) in Nashville (TN) is an example of visual musicality that applied a keyboard pattern for the window openings on the walls. Each window is narrow and vertically arranged as a set of two and a set of three one by one, just like the black keys on the piano. The *Schmitt Music Mural* in Minneapolis is another example of a painted score on the wall to suggest its visual musicality.

2.3.2 Musical Movement

We experience space in motion. A space possessing musical movement encourages us to move because we perceive a musical experience embodied in the architecture. As Metzger (2018) observed:

> Movements leave traces and are inscribed in memories which are actually stored in the limbs.

Our musical memory could be triggered through an experience of physical movement. For example, when driving through the bridges (the Lyre, the Harp, and the Lute) in Hoofddorp, Netherlands, one could perceive the movements of the steel cables. While running in the Ekko (2012) designed by Thilo Frank (Figure. 2.7 Left), a child could experience the dynamic movement of the wood frames and the continuous lines of the stainless steel wire moving up and down in a big circle. Inside of *Son-O-House* (2004) by NOX Architects (Figure 2.7 Right), one could interact with the dynamic stretched body and shell structure.

The pavilion invites its visitors to navigate the space by moving and experiencing the different scales and proportions.

Figure 2.7 Musical Movement Projects. Left: Ekko. Thilo Frank. 2012. (Source: https://www.thilofrank.net/ekko) Right: Son-O-House. NOX. 2004. (Source: https://parametric-architecture.com/son-o-house-by-nox-lars-spuybroek/)

2.3.3 Aural Experience

Architecture is not silent. As Lukas Kühne demonstrated in his sculptures, even concrete has unique sound characteristics. The *Chapel of Sound* (Figure 2.8), designed by OPEN architecture, is another example that promotes aural experiences by amplifying its surrounding sound ecology. If a space possesses or encourages an active listening experience, we can study such designs by analyzing their aural features. Other examples discussed in the previous section, such as the *Swiss Sound Box* and the *Sea Organ*, also have such qualities.

Figure 2.8 Chapel of Sound. OPEN architecture. 2021. (Source: http://www.openarch.com/task/387)

2.3.4 Musical Interactivity

A musical instrument generates sound when played. In architectural terms, sound will be generated as we interact with a design that embodies musical interactivity. Harry Bertoia's *Sonambient Barn* (Figure 2.9) is a metal sculpture designed for interaction. If we touch the sculpture, beautiful sounds will play. In contemporary architectural design, if we could integrate musical interactivity into our design practice, we might achieve a new dimension of interaction with our living environments and sound experience.

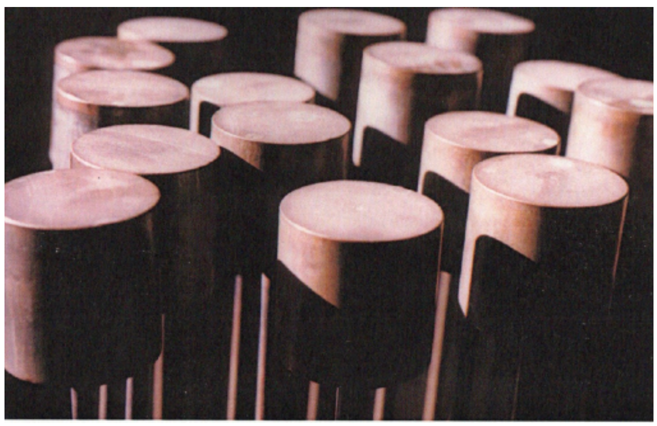


Figure 2.9 Sonambient Barn. Harry Bertoia. 1960. (Source: https://medium.com/@jeffrey_head/bertoia-sound-sculptures-seeing-what-i-hear-6c77d1b45d62)

2.3.5 Sociomusicology Meaning

The sociomusicology meaning in architecture work could potentially impact society and culture significantly. With formal analysis, scholars could associate the composer's musical expression with an architectural piece. As mentioned earlier, one iconic project is the *Fininish Pavilion* by Alvar Aalto (Figure 2.10 Left), in which the form of the interior walls was connected with the Jean Sibelius' Finnish national epic. The *Jewish Museum Berlin* is another example that embodied Schönberg's sociomusicology influence in the building

(Figure 2.10 Right). Arnold Schönberg, composed the opera's first two acts, *Moses und Aron,* from 1930 to 32. As a Berliner, Schönberg expressed his own "Jewish identity" crisis, and *Moses und Aron* roots his early response in dramatic form to the growing anti-Jewish movements. Sociomusicology representation in architecture would allow us to open up much-needed conversations in a contemporary social context.

Figure 2.10 Sociomusicology Representation Projects. Finnish Pavilion.Alvar Aalto. 1939. (Source: https://archipelvzw.be/en/agenda/654/aalto-sibelius) Left: Jewish Museum Berlin. Daniel Libeskind. 2001. (Source: https://www.jmberlin.de/en/libeskind-building#media-18101)

2.3.6 Energy Perception

Like the heat map of solar analysis in architecture, sound energy exists in our living environment. In acoustic design, acoustic energy constitutes the time-dependent reverberant field (Raichel, 2006). The aesthetics in architecture not only lies in its form and material, but also its sensuousness. With advanced material science, humans' experience of sensation and emotion could be changed by the embodied rhythmic pattern of sound energy. *Project*

Distortion I (Figure 2.11) by Brady Peters demonstrates a parametric approach exploring the relationships between material, geometry, and acoustic performance.

Figure 2.11 Project Distortion I. Brady Peters. 2010. (Source: http://www.bradypeters.com/project-distortion-i.html)

2.3.7 Time in Architecture

Music is inconceivable without time. But how about architecture? Arata Isozaki, the 2019 Pritzker Prize Laureate, once said in an interview,[11] "No time then no space. An architecture as a solution, every time is different." In *the Timeless Way of Building*, Christopher Alexander introduced the concept of the "quality without a name", and gave an example of such quality as "a corner of an English country garden, where a peach tree grows against a wall" (Alexander, 1979). Calling a work of architecture timeless suggests that it is independent of time. However, Alexander's "quality" refers to the tree which is dependent on time.

[11] Arata Isozaki — TIME SPACE EXISTENCE

In the article *Inhabiting Time*, Juhani Pallasmaa points out that "in recent architecture, design has prioritized an engagement with time through its creation of temporary and highly flexible structures. … but less focus on how the design of buildings might impact the experience of time…" (Pallasmaa, 2016). Indeed, we can find many architectural experiments dealing with growing material, biology synthesis, or generative design. For example, the Center Pompidou's 2019 exhibition *The Fabric of the Living* (*La Fabrique du Vivant*) features living sculptures investigating life in a digital age, and furniture and building materials made of living fungus.

Human perception of time varies in different contexts. Balmond pointed out when time is experienced as not linear, duration bends into qualities. His graph of time mixed two moments, body time with emotional time. Balmond's "emotional time" suggests a psythocology way to see time. In Zumthor's view on sensations of beauty, he described " the intensity of a brief experience, the feeling of being utterly suspended in time, beyond past and future" (Zumthor, 2010). Time is an aesthetic factor for architectural design. Kengo Kuma in an interview[12] advocated to "merge our building into time." Xenakis's "undulating glass panes" are an example of an architectural element designed with consideration of time and speed. The density and continuity in the "undulating glass panes" became another of Xenakis's musical expressions in architecture.

[12] Kengo Kuma – TIME SPACE EXISTENCE.

2.4 Sound and musical aesthetics in Architecture (1939 to 2021)

Since WWI, modern technology has shaped architectural design. In this survey, I focus on architecture that was built during the modern period. I selected representative architectural projects from the 1930s to the present. Two important criteria were used: (1) it must be related to music, either design inspired or informed by music; (2) it must have been built—conceptual work, unbuilt project, or digital architecture is not included. Table 2.1 presents 26 architecture projects that have been discussed in section 2.2 and 2.3.

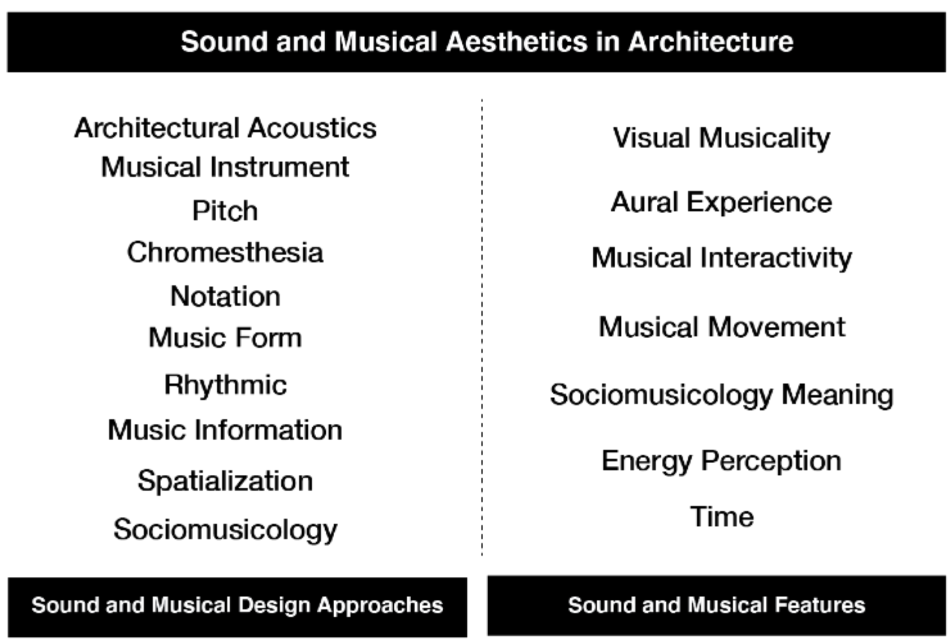


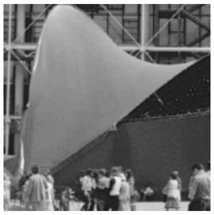
Figure 2.12 A Diagram of Elements of Sound Musical Aesthetics in Architecture. Yin Yu. May 2022.

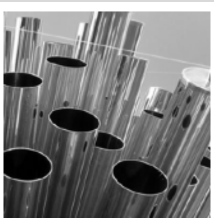
2.5 Summary

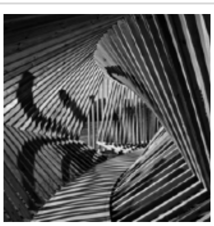
In this chapter, we discussed the musicality in architectural projects from two perspectives: music as design approach and musical features in architecture. Focusing on contemporary architecture history from the 20-21th century, I introduced a classification system of musical aesthetics in architecture (Figure 2.12). This classification system analyzes the musicality in an architectural project from the design process to the design outcome. With this classification system, I conclude that in architectural design, the practice of musical aesthetics could be achieved and studied through the elements and criteria presented here.

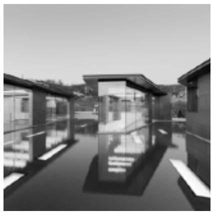
Table 2.1 Sound and Music as Design Opportunity in Architecture

Project Name	Designers	Location	Sound and Musical Design Approach	Sound and Musical Features
 Finnish Pavilion (1939)	Alvar Aalto	The New York World Exhibition	Music Form	Visual Musicality Musical Movement Sociomusicology Meaning
 EXPO 58' Philips Pavilion (1958)	Iannis Xenakis, Le Corbusier	Brussels Belgium	Notation	Visual Musicality Aural Experience Sociomusicology Meaning
 The Convent of La Tourette (1961)	Iannis Xenakis, Le Corbusier	Éveux, France	Rhythmic	Visual Musicality Time

Project Name	Designers	Location	Sound and Musical Design Approach	Sound and Musical Features
 Diatope (1978)	Iannis Xenakis	Centre Pompidou, Paris, France	Morphology	Time
 Stretto House (1991)	Steven Holl	Dallas, Texas, US	Music Form	Visual Musicality Musical Movement
 Therme Vals (1996)	Peter Zumthor	Vals, Switzerland	Notation	Visual Musicality Musical Movement
 Swiss Sound Box (2000)	Peter Zumthor	Hanover, Germany	Architectural Acoustics	Aural Experience
 Jewish Museum Berlin (2001)	Daniel Libeskind	Berlin, Germany	Music Form	Visual Musicality Sociomusicology Meaning

Project Name	Designers	Location	Sound and Musical Design Approach	Sound and Musical Features
 Son-O-House (2004)	NOX Architects, Edwin van der Heide	Son en Breugel, Netherlands	Music Information	Aural Experience Musical Interactivity
 Sea Organ (2005)	Nikola Bašić (architect) with Ivan Stamać dipl. inž. (sound)	Zadar, Croatia	Musical Instrument Pitch	Aural Experience Sociomusicology Meaning
 JS Bach Concert Hall (2009)	Zaha Hadid	Manchester, UK	Music Form	Visual Musicality Musical Movement
 Aeolus (2009)	Luke Jerram	various locations	Pitch Musical Instrument	Visual Musicality Aural Experience
 Soundscaping Pavilion MINI Opera Space (2010)	Coop Himmelb(l) au	Munich, Germany	Music Information	Visual Musicality

Project Name	**Designers**	**Location**	**Sound and Musical Design Approach**	**Sound and Musical Features**
 Project Distortion I (2010)	Brady Peters	Copenhagen, Denmark	Music Information	Visual Musicality, Musical Interactivity Aural Experience Energy Perception
 Cromatico (2011)	Lukas Kühne	The Tallinn Song Festival Grounds, Tallinn, Estonia	Architectural Acoustic Music Scale	Aural Experience Musical Movement
 Tvísöngur sound sculpture (2012)	Lukas Kühne	Seyðisfjörður, Iceland	Architectural Acoustics Musical Scale	Visual, Spatial Aural
 Academia MWD Belgium (2012)	Carlos Arroyo	Dilbeek, Belgium	Chromesthesia	Visual Musicality
 Ekko (2012)	Thilo Frank	Hjallerup, Denmark	Spatialization	Musical Interactivity Aural Experience

Project Name	Designers	Location	Sound and Musical Design Approach	Sound and Musical Features
 Daeyang Gallery and House (2012)	Steven Holl	Seoul, South Korea	Notation	Musical Movement Time
 Chimes House (2014)	David Sheppard	Exeter, England	Music Composition	Musical Movement
 NASA's Orbit Pavilion (2015)	NASA / StudioKCA	NYU/ Huntington Garden	Spatialization Sound Ecology	Musical movement
 Ruup (2015)	Interior Architectur e students at the Estonian Academy of Arts	Forest megaphones, Estonia	Architectural Acoustics	Aural Experience Sociomusicology Meaning
 HIVE (2017)	Studio Gang	National Building Museum, Washington, D.C.	Architectural Acoustics	Aural Experience

Project Name	Designers	Location	Sound and Musical Design Approach	Sound and Musical Features
 80Hz: Sound Lab (2018)	Thomas Wing-Evans	Sydney, Australia	Music information	Musical Interactivity
 Ian Potter Southbank Center (2019)	John Wardle Architects	Southbank, Melbourne	Sociomusicology Notation	Sociomusicology Meaning
 Chapel of Sound (2021)	OPEN Architecture	Chengde, China	Sound Ecology	Aural Experience Musical Movement

3. Sound Morphogenesis: A Design Framework

> Cell and tissue, shell and bone, leaf and flower, are so many portions of matter, and it is in obedience to the laws of physics that their particles have been moved, moulded and conformed.
>
> *- D'Arcy Wentworth Thompson (1942)*

> Electronic music introduced the notion that the design of sound morphology–on every timescale–is part of the composition process.
>
> *-Curtis Roads (2015)*

3.1 Technology as the Bridge between Music and Architecture

In this chapter, I introduce the fundamental concepts and the design framework of Sound Morphogenesis Design (SMD). Given the interdisciplinarity of the work, information theory provides a relevant background for my research. From a perspective of digital morphogenesis, it is important to cover the definition of key concepts, terminologies, and current research work in both the music and the architecture fields. A theoretical diagram of Sound Morphogenesis Design presents as a visual tool to guid throughout the rest of the dissertation.

3.2 Research Questions

As mentioned in Chapter 1, the following questions guide this research framework of SMD:

> *Research Question 1:* How does architectural practice change when sound is not viewed as pollution but as a design opportunity?
>
> *Research Question 2:* How does sound morphology expand the theory of digital morphogenesis and change the approach for architectural design research?
>
> *Research Question 3:* What would be the novel design practice of sound morphogenesis design that augments aural experiences and aesthetics?

3.3 ***ArMuTe*** Framework: An Intersection of Architecture, Music, and Technology

3.3.1 Interdisciplinary Design Research

A research diagram, or research framework, is commonly used in the system analysis or as a visual presentation of a workflow. For the current interdisciplinary research, a framework is necessary to guide the diverse nature of the studies. In architecture school, one of the most influential diagrams is the *Bauhaus curriculum diagram* from 1923 (Figure 3.1). The circular diagram encompasses several rings of curriculum years. Each ring has a series of course blocks, such as theory courses of color and form, principles of composition, etc. The Getty Research Institute introduced the 100th anniversary celebrations for the Bauhaus in the following way:

> The singularity of the circle suggests the holistic nature of a Bauhaus education, in which individual students representing diverse disciplinary backgrounds were to

come together in pursuit of a shared mission to reform art, design, and society (Casciato, et al. 2019).

The circular diagram is a great tool for multidisciplinary research. For example, Frederick Kiesler sketched a diagram of "*Time-Space-Architecutre*" for his *Space House* (Figure 3.2) the only house he built (Phillips, 2017). Neri Oxman designed the *Krebs Cycle of Creativity* in 2016 to describe four modalities of human creativity–Science, Engineering, Design and Art (Figure 3.3). She proposed a map to represent the antidisciplinary hypothesis: that knowledge can no longer be produced within disciplinary boundaries (Oxman, 2016).

After studying the precedents of the design framework, I developed early versions of the research map for this dissertation. Figure 3.4 is a matrix approach of an 8-by-8 grid. Each column or row has one research field. The eight research fields are architecture, music, mathematics, philosophy, science, engineering, technology, and media arts. At the intersection, there is a square that joins two fields. This diagram is available on my website with clickable links. This diagram collected and classified the literature review during my early Ph.D. research stage. However, I soon realized that the topic is too broad for each field, and the two joint fields are limited. Interdisciplinary research often crosses more than two fields.

Meanwhile, I developed a circular version of the research framework (Figure 3.5) called *A map of theory and practice illustrating the interdisciplinary nature of research on Architecture and Music.* This diagram contains an architecture and music research wheel (Figure 3.6) and an interdisciplinary research framework (Figure 3.7). I added some detailed information to this map, such as my early experiments, research questions, and references.

This map reflects my research idea, which I aim to develop a design philosophy based on theory and practice.

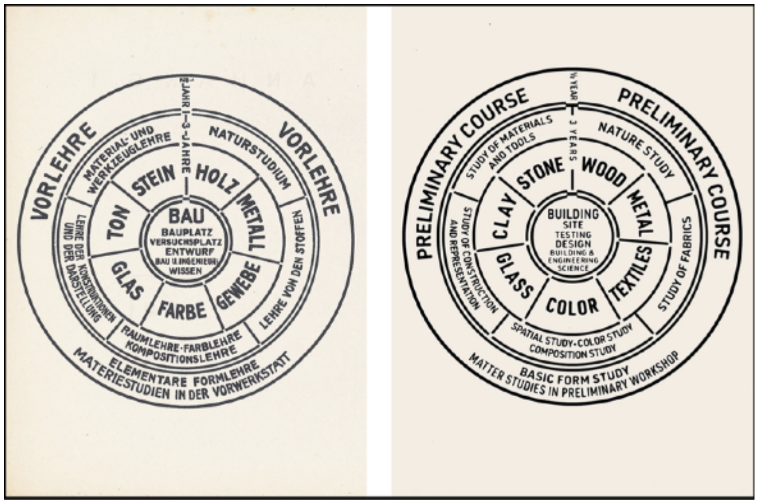


Figure 3.1 Diagram of the Bauhaus curriculum (adapted, right), Walter Gropius, 1922. Lithograph. 20.2 x 29.3 cm. From Walter Gropius, *Satzungen Staatliches Bauhaus in Weimar* (Statutes of the State Bauhaus in Weimar), July 1922. Bauhaus Typography Collection, 1919–1937. The Getty Research Institute, 850513. © 2019 Artists Rights Society (ARS), New York / VG Bild-Kunst, Bonn

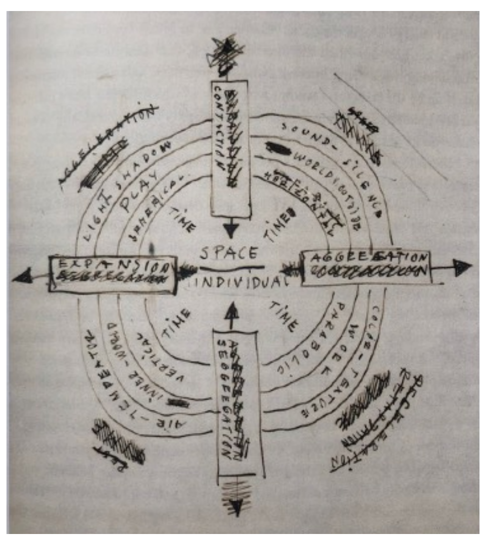


Figure 3.2 Time-Space-Architecture. Frederick Kiesler, 1933-1934. Space House sketch diagram. © 2017 Austrian Frederick and Lillian Kiesler Private Foundation, Vienna.

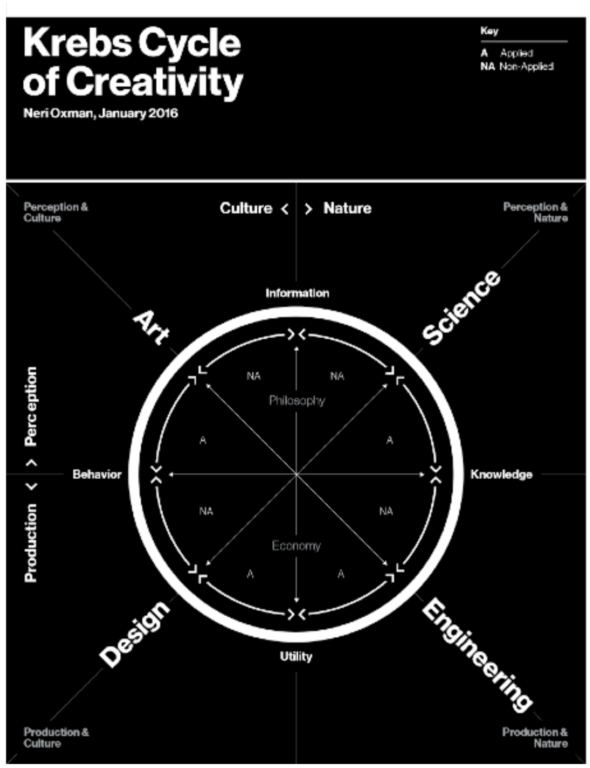


Figure 3.3 Krebs Cycle of Creativity. Neri Oxman. The Age of Entanglement. Jan 13, 2016. https://jods.mitpress.mit.edu/pub/ageofentanglement/release/1

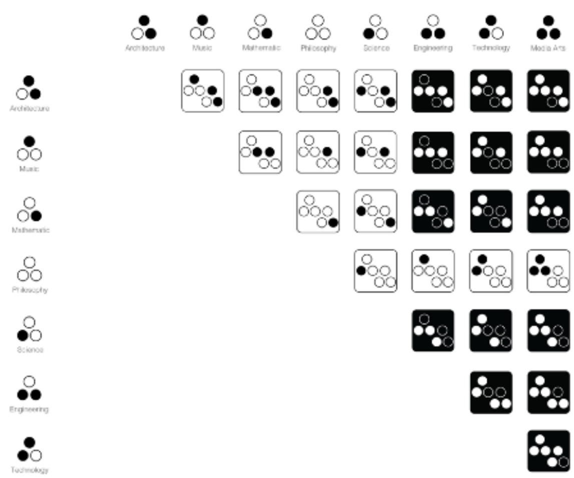


Figure 3.4 Music and architecture research metric. Yin Yu. 2018 http://yinyudesign.com/research-metric

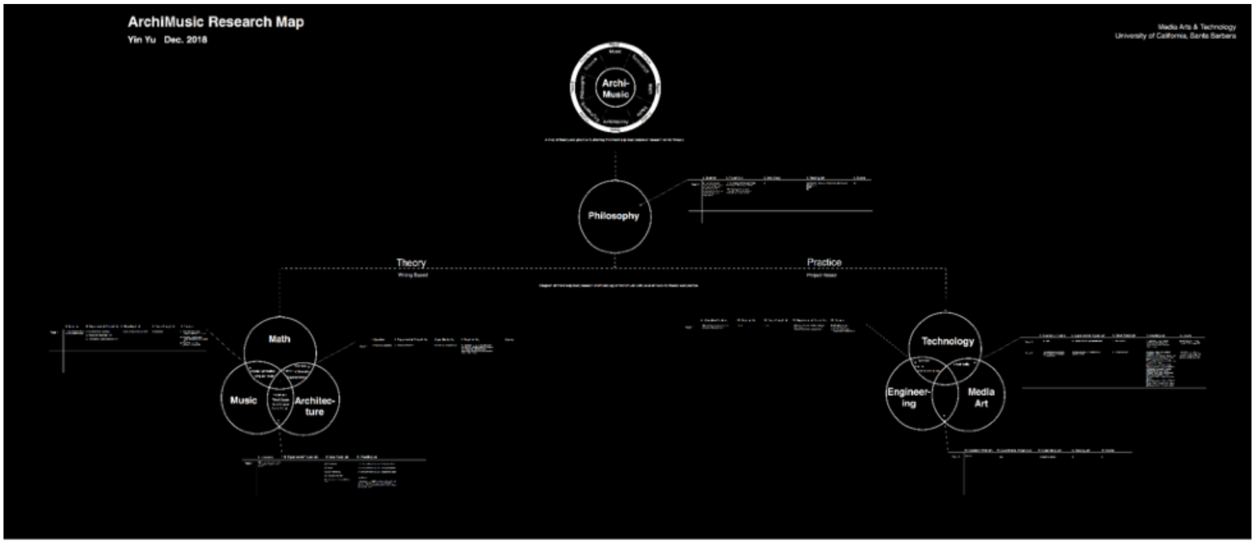


Figure 3.5 A map of theory and practice illustrating the interdisciplinary nature of research on Architecture and Music (2018)

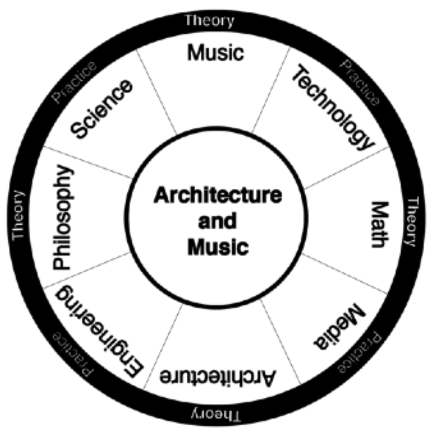


Figure 3.6 Detail of the map of theory and practice illustrating the interdisciplinary nature of research on Architecture and Music (2018)

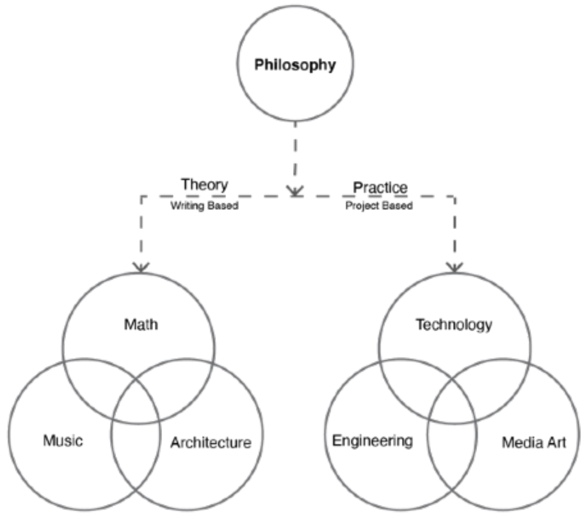


Figure 3.7 Diagram of interdisciplinary research methodology of Archimusic with parallel tracks for theory and practice (2018)

3.3.2 Diagram of ArMuTe Research Framework

As my early research map became more complicated, I decided to simplify the framework. Thus, *ArMuTe* framework has been developed (Figure 3.8). ArMuTe stands for Architecture, Music, and Technology. This diagram works great for my research because it represents important elements of what I have been working on and what I plan to continue to research. Furthermore, ArMuTe has a great flexibility and adaptability to evolve for research, study and analysis, design projects, and even pedagogical applications. For example, in Chapter 5, I use an ArMuTe based framework to analyze and study Iannis Xenakis's work to understand how he composes light using natural light and artificial light. In Chapter 7, I use this framework to develop interdisciplinary research courses for students which demonstrate great course outcomes.

As this research aims to expand the theory of digital morphogenesis in architecture design, I focus on the topics related to morphogenesis on the Architecture axis. On the axis of Technology, information theory offers fundamental principles in this research. From a music perspective, I will focus on sound as design material by introducing topics related to sound objects and sound morphology. A research diagram based on ArMuTe for this research called Sound Morphogenesis Design (SMD) is presented (Figure 3.9). In the follow sections, I will discuss SMD in detail.

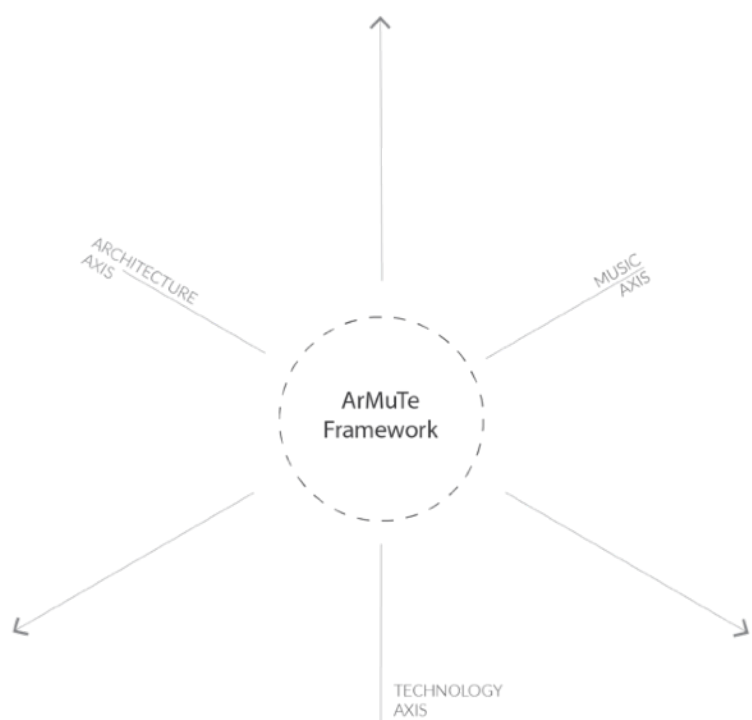


Figure 3.8 The diagram of ArMuTe framework (2021)

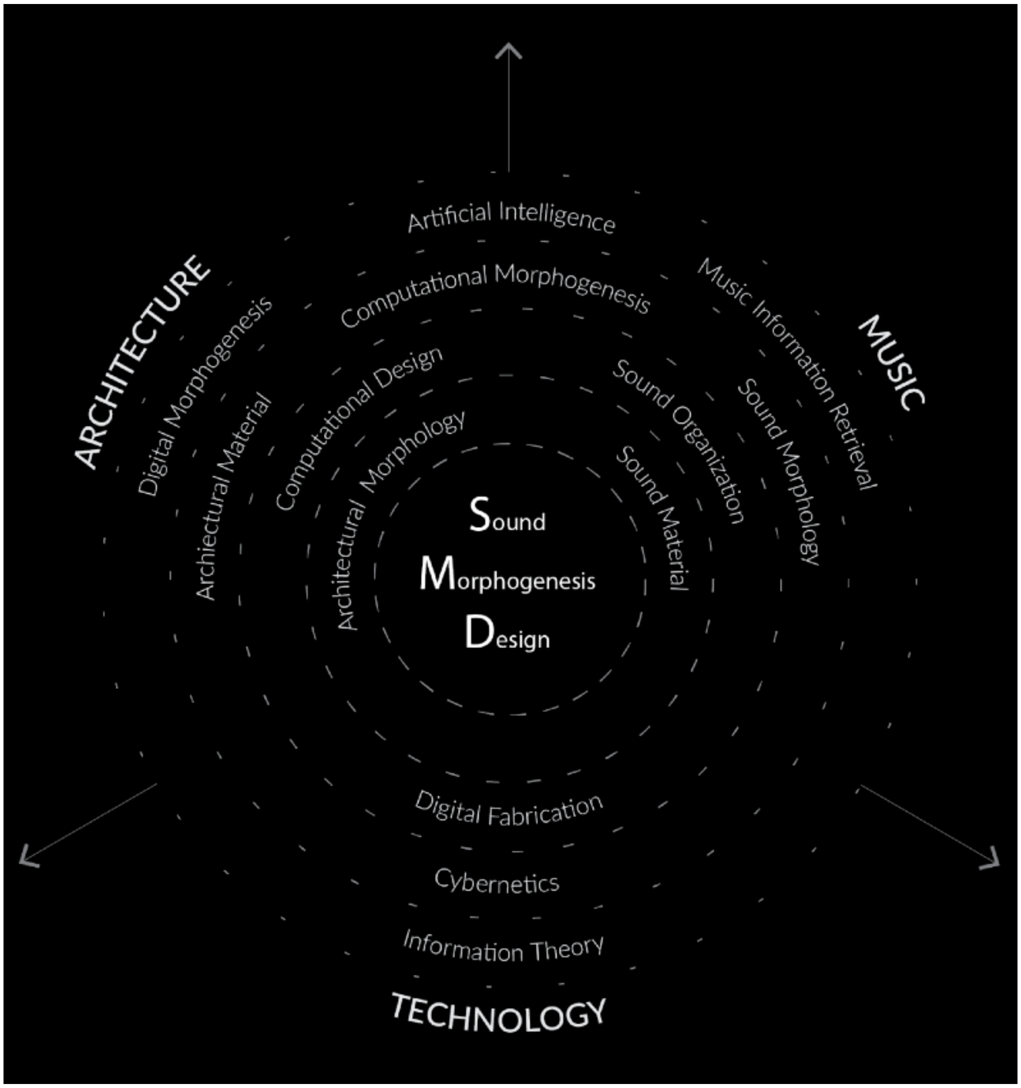


Figure 3.9 The System of Sound-based Morphogenesis for Design (April 2021)

3.4 On the Technology Axis

Information is the resolution of uncertainty.

- Claude Shannon (1948)

Information is information, not matter or energy.

- Norbert Wiener (1948)

3.4.1 Technology in Creative Domains

Technology has changed the way we design, make art, and compose music. The development of recent electronic music composition is interconnected with the evolution of computer science. Pioneer artists started to use computers in art making in the 1960s, such as Frieder Nake and Philip Peterson. In recent years, computational design software and digital fabrication technology enabled the maker movement to blossom globally in the art, design, and architecture communities and beyond.

3.4.2 Information Theory

In 1948, Claude Shannon, the father of the digital age, published the groundbreaking paper—*A mathematical theory of communication* in the Bell Systems Technical Journal. In the paper, Shannon's discovery of the fundamental laws of data compression and transmission marked the birth of Information Theory (Verdu, 1998). Like concrete to architects, information[13] is the material that pioneer architects and musicians work within the digital age. For example, electronic musicians today can compose music with data that is carried by electricity. Architects design buildings using machines and complex software to process information.

[13] sometimes called signale, message, or data in different research fields.

Information is carried, stored, retrieved and processed by machines, whether they are electronic computers or living organisms.

A digital signal in information theory depends on the efficiency of its representation. As Shannon observed:

> (The) semantic aspects of communication are irrelevant to the engineering problem. The significant aspect is that the actual message is one selected from a set of possible messages.

The source of information could be compressed through a random process. Let us use architectural digital information as an example. In a 3D model, the output of the information source is an architectural digital model. This information source contains a number N symbols. In a simple architectural system, for instance, we can find eight architectural elements: floor, wall, ceiling, door, stair, column, roof, and window (Figure 3.10). Therefore, the number of the symbols in this model is eight, $N = 8$. The digital signal is represented as a "0" and "1" in the information channel. In mathematics, the binary logarithm ($log_2 n$) can be used to calculate the length of the representation of a number in the binary numeral system. Thus the amount of information can be measured by the logarithm of the number 2. In this architectural example, the information is 3 bits ($log_2 8 = 3$). The logarithm base 2 is based on the unit of information called bit or binary digital.

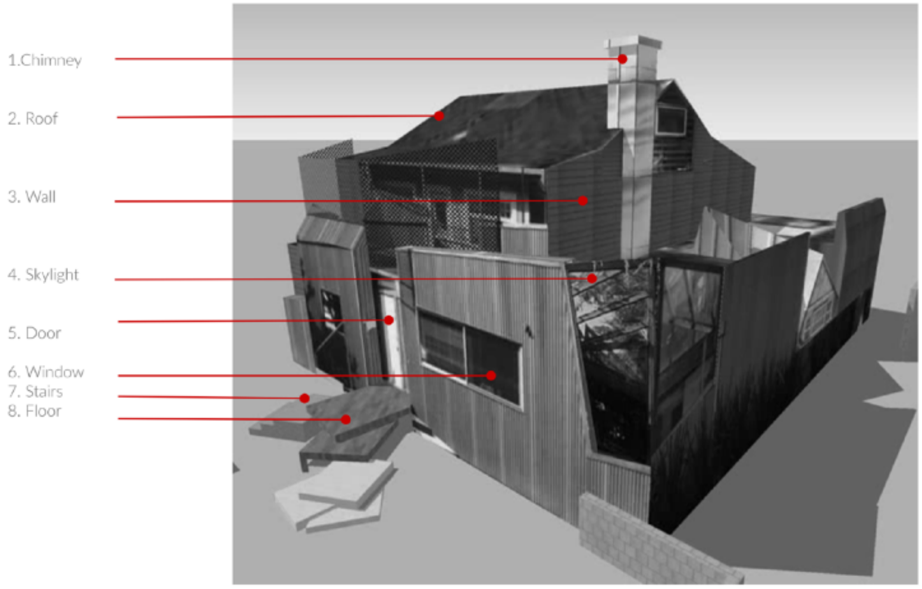


Figure 3.10 Information in digital architecture model (Image source: Frank Gehry House 1978, from 3D Warehouse)

The information sources do not select the symbols with equal frequency. For example, in a simple architectural model, the roof occurs at the rate of once while the door occurs at the rate of three. The frequency of occurrence of source symbols is a set of probabilities $\{p_1, p_2, \ldots, p_n\}$. Then the mathematical expression for the information (*H*) is

$$H = -[p_1 log p_1 + p_2 log\, p_2 + \ldots + p_n log p_n] = -\sum_{i=1}^{N} p_i Log p_i$$

Shannon defines this information *H* as entropy. He demonstrated that the relevance of the concept of entropy as a measure of information was not restricted to thermodynamics, but could be used in any context where probabilities can be defined. In our example, if the window's probability p_1 is 0.2, the entropy of the model is larger than when $p_1$is 0.8. In other words, if the window's probability is 0.2, the architectural system is uncertain or disordered. On the facade of *La Tourette* (Figure 3.11), the modular windows on the top two levels have a higher frequency compared to the undulating glass panels on the bottom two levels. Thus, the value of information H on the top two levels is less than the one of the bottom two levels. The undulating glass panel facade has more architectural information because each size of the window has a lower frequency. It is worth noting that the selection of a symbol in a message is influenced by a previous selection; symbols in a message are not statistically independent, instead there are intersymbol dependencies or correlations. For instance, it is most likely to see windows on the walls rather than on the floors.

$$p_1 > p_{2,}$$

$$H_1 < H_2$$

Entropy in Shannon's theory is a measure of uncertainty about a symbols' identity in a message; in our example, entropy measures architectural elements in a digital model. Shannon's great contribution was that it is possible to associate entropy within any set of probabilities.

Figure 3.11 The probability of Convent of La Tourette's north-west facade partial. (Photo: Neil Poole, 2011. https://www.flickriver.com/photos/29727266@N02/6101173488/)

We can explore information theory from another perspective. Humans perceive environmental information from multiple sensations, such as smell, temperature, or taste. Architect Peter Zumthor, wrote in 1988:

> I used to take hold of it when I went into my aunt's garden. That door handle still seems to me like a special sign of entry into a world of different moods and smells. I remember the sound of the gravel under my feet, the soft gleam of the waxed oak staircase, I can hear the heavy front door closing behind me as I walk along the dark corridor and veneer the kitchen, the only really brightly lit room in the house.

In his *Information Theory and Esthetic Perception*, information science pioneer Abraham Moles observed (1966):

> The individual receives messages from this environment through various channels: visual, aural, tactile, etc. The term "channel" is applied to any material system which conveys a message from a transmitter to a receiver.

Just like the natural channels, in the digital world, the messages are transmitted through an artificial channel called *information channel*. The channel, as Shannon indicates, may be a pair of wires, a coaxial cable, a band of radio frequencies, or a beam of light, etc. In Figure 3.12, he illustrates the schematic diagram of a general communication system. It shows the basic architecture and design principles of a communication system which includes an information source, a transmitter, a noise source, a receiver, and a destination. As Shannon himself later realized, this model had "applications not only in communication theory, but also in the theory of computing machines, the design of telephone exchanges and other fields." (Shannon, 1948). He demonstrated that any communication system contains independent components that can be designed separately. For example, a musical information source can be designed with a different mathematical model from the transmitter; and on the receiver end, a 2D drawing model can translate the information into colors. Shannon's diagram is the blueprint for communication design in the digital age.

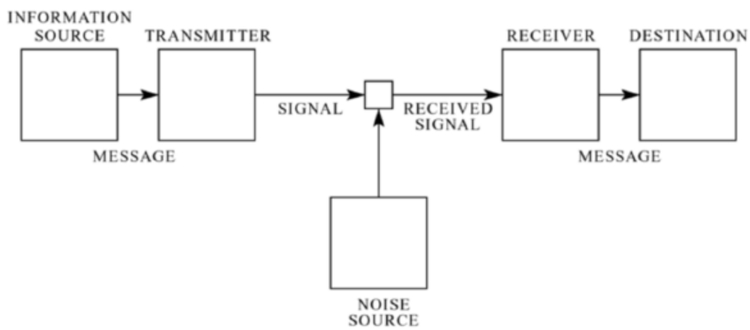


Figure 3.12 Schematic diagram of a general communication system (Shannon, 1948, pg.3)

After completing his schematic diagram, Shannon observed that the information channel has limitations; it is measured in binary digits per second. Such limitation is referred to as the *Channel Capacity* (*C*). For example, if a signal represents s bits of information, and the channel can transmit w signals per second, then the capacity of the channel is $C = ws$ bits per second. In other words, if one message exceeds the channel's limits, the message will be partially transmitted through the channel. We could use Moles' channel "dimensions" to explain the capacity. Moles use dimensions to categorize types of messages. For instance, music is one temporal dimension, motion pictures is one temporal dimension plus two spatial dimensions, and architecture is three spatial dimensions, etc. (Moles 1966, p9). If a channel has two dimensions, then one can only transmit some dimensions of a motion picture's message. These principles apply to SMD design and implement. Designers would need to carefully select which information would be the most valuable for their own practice.

3.4.3 Digital Information in Music

According to Dennis Gabor,[14] any message can be divided into elementary signals with their representative rectangles covering the whole time-frequency area (Figure 3.13) (Gabor, 1946). The Gabor's matrix is the analysis produced by the short-time Fourier transform and the wavelet transform (Roads, 2001). These transformations create a two-dimensional matrix of sound information.

$$\psi(t) = e^{-\alpha^2(t-t_0)^2} cis(2\pi f_0 t + \phi) \qquad \text{(Gabor 1946, 1.27)}$$

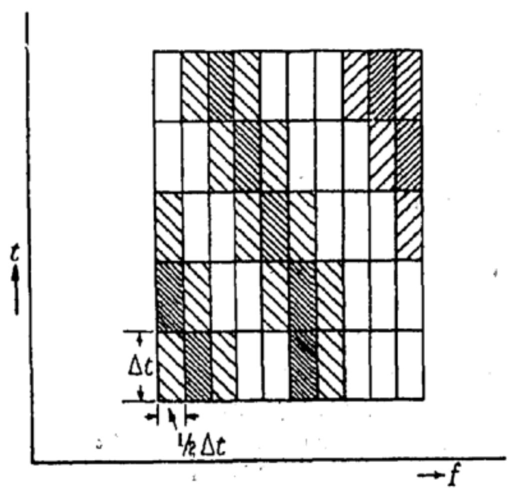


Figure 3.13 Representation of signal by logons (Source: Gabor, 1946).

The Sound Description Interchange Format[15] (SDIF) is a well-established standard format for sound description data storage (Wright et al., 1999). SDIF represents all sound

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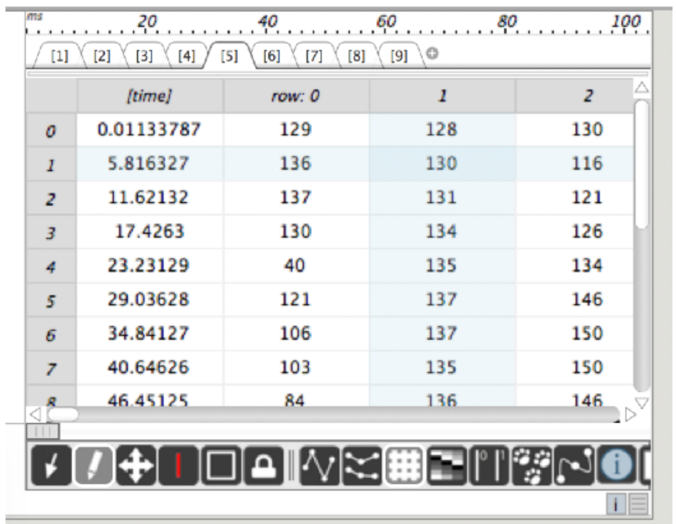
[14] A Hungarian-British electrical engineer and physicist.

[15] Developed by IRCAM (Centre G. Pompidou, France) and CNMAT (Berkeley, US).

descriptions as "streams" of "frames" over time. Each frame consists of matrices of numerical or text data. SDIF contains a variety of sound descriptions, including spectral, time-domain, and higher-level models. Many applications developed nowadays integrate an SDIF reader/writer, such as Max/MSP, PureData, Csound9, AudioSculpt6, OpenMusic, amongst others (Burred et al.,2008). Figure 4.4 is a partial view of one stream of a sound object in Max/MSP environment.



	[time]	row: 0	1	2
0	0.01133787	129	128	130
1	5.816327	136	130	116
2	11.62132	137	131	121
3	17.4263	130	134	126
4	23.23129	40	135	134
5	29.03628	121	137	146
6	34.84127	106	137	150
7	40.64626	103	135	150
8	46.45125	84	136	146

Figure 3.14 Read a SDIF file in Max/MSP (screen capture, 2021)

There are various tools that we can use to work with the morphology of the sound object. For example, *SDIF-Edit,*[16] software that uses SDIF files as objects, can edit (sculpt) the sound object graphically in a three-dimensional environment (Figure 3.15) (Bresson and Carlos, 2004). In OpenMusic,[17] the *Morphology2* library is used to analyze, classify, recognize patterns and the reconstruction of profiles and sequences (Schilingi 1999). From a

[16] A software developed by Jean Bresson.

[17] A software developed by IRCAM.

technical point of view, these applications facilitate the extraction of sound data, an important step to translate the number into a different medium.

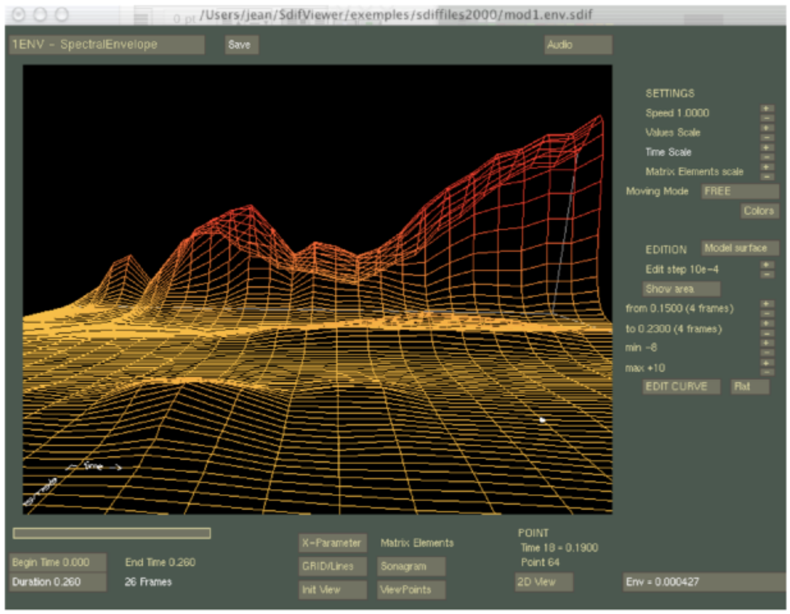


Figure 3.15 SDIF-Edit: 3D SDIF file editor (Source: Bresson and Carlos, 2004).

3.4.4 Digital Information in Architecture

A digital architectural model, or BIM (Building Information Model), contains several layers of information, from stakeholder requirements to the delivery time during the construction from each manufacturer. For our purpose, we will focus on the information specifically related to 3D digital models, which hold the spatial information (scalars, vectors), the material information (size), fabrication information (machines, axes), the physical information (tensors), geometric information, the real time information, the environmental information, and the behavior information. Some pioneer research works related to digital morphogenesis have been done in the last decade, such as *Granular Morphologies* by Achim

Menges from the ICD (Institute for Computational Design and Construction) Stuttgart, and *Material Ecology* by Neri Oxman from the MIT Media Lab. We will discuss these works in more detail in future chapters.

3.4.5 Cybernetic Design

The study of digital morphogenesis should be, first and foremost, the study of a relationship between the morphology of sound objects and the morphology of architectural materials. Due to its multidisciplinary nature, Cybernetics is a perfect tool for cross-disciplinary design. Cybernetics, according to Norbert Wiener,[18] is "the theory of communications and control in living beings, as well as in societies and machines" (Wiener, 1951). Since the late 1950s, Cybernetics has influenced the art and design fields in western societies. Design schools started to implement Cybernetics in their design pedagogy, such as the Architecture Machine Group[19] at MIT, and the Architectural Association (AA) in London. Cybernetics arts spanned more than half a century—from the early pioneer work *Colloquy of Mobiles* (1968) by Gordon Pask to the recent art installation *Hylozoic Series* (2010) by Philip Beesley studio—are continuing to influence artists and designers. Cybernetic design establishes a conversation between objects to objects, or objects to environments, and vice versa. The feedback looping system allows the machine to steer, learn, and evolve.

[18] The founder of Cybernetics.

[19] Founded by Nicholas Negroponte, later became the MIT Media Lab.

3.4.6 Computational Design and Digital Fabrication

Artists, architects, and designers continuously embrace new digital technologies. Emergent computational tools open novel possibilities. The *Kunsthaus Graz* building (2003) was made possible with the NURBS-based[20] 3D modeling software *Rhinoceros 3D*. Designed by Colin Foumier and Peter Cook, *Kunsthaus Graz* is a contemporary art museum in Graz, Austria. The façade is an organic geometry consisting of 1300 double-curved translucent acrylic panels. Each panel has its unique dimension and curvature. The complexity of this double-curved geometry cannot be achieved by the traditional plans/sections/elevations of 2D architectural drawings. The 3D model in Rhinoceros 3D is in a 1:1 scale, which means after dividing the organic surface into 1300 individual panels, they can use CAD-CAM[21] to manufacture the acrylic pieces. Without a digital computer modeling program, the geometry of the facade wouldn't be possible to accomplish. Further examples can be found in the peer-reviewed series *Fabricate* (2011, 2014, 2017, 2020), published by UCL Press, featuring excellent collections of computational design and digital fabrication projects.

3.4.7 Artificial Intelligence

François Bayle[22] mentioned in an interview, "for Schaeffer (Pierre), technology was always evolving, and he felt that one must work with its limitations. […] Artists must exploit their

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[20] NURBS: Non-uniform rational B-spline

[21] Computer-aided design / Computer-aided manufacturing

[22] A composer of electronic music. Bayle talked about sound morphology at UCSB's Corwin Chair Series Lecture, January, 2021.

medium's limitations as well as its capabilities" (Desantos and Bayle 1997). Current technologies such as Artificial Intelligence (AI) and Machine Learning (ML) play a forefront role in contemporary art and creative practices. For example, *Magenta*,[23] a Google AI project, is a python library for music generation using cutting-edge machine learning techniques. *RunwayML*[24] is another example. It offers a friendly interface for artists and designers to create artworks using ML approaches.

One of the first researchers who applied computational methods on morphogenesis was the father of AI–Alan Turing. In his paper *The Chemical basis of Morphogenesis* (1952), Turing explained morphogenesis through chemistry using mathematics in his reaction-diffusion (RD) model. The RD model presents a theoretical mechanism on how spatial patterns form autonomously in an organism. Turing examined the behavior of a system in which two diffusible substances interact with each other and found that such a system can generate a spatially periodic pattern even from a random or almost uniform initial condition (Kondo 2017). The computation research in morphogenesis not only helps the study of chemistry and biology development, how similar patterns emerge in nature, but also materials science. Turing's model could help us research soft matter, soft materials, and soft robotics with specific patterns and shapes. Machine Learning is an exciting tool for a future computational morphology—Digital Morphogenesis.

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23 https://magenta.tensorflow.org/

24 https://runwayml.com/

3.5 On the Architecture Axis

3.5.1 Morphology in Nature

The term morphology derives from the Ancient Greek *morphḗ*, which means "form" and lógos means "study." Dating back to the classical period in Ancient Greece, Aristotle's biology works[25] was the first attempt to describe the appearance of animals and plants, mainly for taxonomic reasons. In 1790, Johann Wolfgang von Goethe introduced the first main formal principle to studying morphology–*The Metamorphosis of Plants*. His work laid out the foundations of the field of Morphology as the science of organic forms and formative forces aimed at discovering underlying unity in the vast diversity of plants and animals (Goethe, Miller, 2009).

3.5.2 Morphogenesis in Nature

Based on Goethe's work, D'Arcy Wentworth Thompson, the Scottish biologist, and mathematician, published On Growth and Form in 1917. Combining biology, science, and mathematics, Thompson developed his theory of transformation in nature–morphogenesis. In a literal sense, morphogenesis means the generation of form (from the Greek morphê shape and genesis creation). It is the process of an organism's shape transformation, development, and growth. To study the inter-relations of growth and form and compare the related natural forms, Thompson applied the method of point-to-point evolution of each shape to find the mathematical logic in the biological shapes (Thompson, 1917, and Abzhanov 2017). His work later influenced important computational design works, such as the *Turing Pattern*

[25] Aristotle's the *Parts of Animals* and the *History of Animals*.

(developed from Alan Turing's The Chemical Basis of Morphogenesis), the *Modulor* (the design system by Le Corbusier), and *A Pattern Language* (the design theory by Christopher Alexander). In this research, morphogenesis will refer to form generation, form mutation, and form transformation.

3.5.3 Digital Morphogenesis in Architecture

Architecture, like mathematics, thrives on uncertainties.

- Cecil Balmond (2013)

Digital Morphogenesis (DM) is the study of form generation, transformation, and growth by means of digital technologies. Branko Kolarevic[26] defines digital morphogenesis in the following terms "In contemporary architectural design, digital media is increasingly being used not as a representational tool for visualization but as a generative tool for the derivation of form and its transformation" (Kolarevic, 2003). For Neil Leach,[27] digital morphogenesis operates through a logic of optimization—a logic of form-finding or pattern-making, such as the logic of a bottom-up or stochastic. Leach suggested that morphogenesis places emphasis on "material performance" and "processes over representation" (Leach 2009). The music composer David Rosenboom[28] said, "Form emerges. Form Evolves. Forms emanate from points of singular genesis, defining the space surrounding them, along with sets of dimensions and axes for describing their dynamic processes of change" (Rosenboom, 1997). DM is the method of representation, analysis, prediction, and design of the digital form.

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26 An architecture professor. Dean in Hillier College of Architecture and Design at New Jersey Institute of Technology.

27 A British architect and theorist.

28 An American composer and a pioneer in the use of neurofeedback, cross-cultural collaborations and compositional algorithms.

3.5.4 Material Computation

The future material for design practice is smart, engineered, and responsive materials. In *Smart Materials and New Technologies* (2005), mechanical and nuclear engineer Michelle Addington classified two types of smart material for architecture and design professions. Type I materials change one or more of their properties (chemical, mechanical, electrical, magnetic or thermal) after external stimuli. A Type II material "is comprised of those that transform energy from one form to an output energy in another form" (Addington, 2005). How to integrate a new material in the computational design and fabrication process? For instance, membrane-type acoustic metamaterials demonstrated that low-frequency sound insulation could be achieved across a narrow frequency range and tuned to the desired frequency (Naify et al., 2010).

3.5.5 Lighting Computation

Daylight is an intangible material in architecture. But we can feel it through our skin and see it with our eyes. In architecture practice, lighting has been studied from different perspectives, such as energy, sustainability, visual comfort, and aesthetics. After a decade-long research in daylighting, scientist Marilyne Andersen proposed four types of evaluations based on occupant experience: task illumination, visual comfort, perception, and health and well-being[29] (Andersen, 2017).

[29] Photoreceptor was discovered in the human eye in 1991 by Russell Foster et al.

In the design field, contemporary lighting design gives priority to performance and sustainability. In the arts, the approach is different. Xenakis took light as his musical expression. He composed rhythmic space with lights–both natural light and artificial light. James Turrell demonstrates a new way to experience light, such as his *Skylight*, *Ganzfelds*, and *Shallow Space* artworks.

3.5.6 Acoustic Computation

With computational analysis, modeling, and simulation tools, acoustic design can obtain more sophisticated and reliable outcomes. In the paper *Computational and Optimization Design in Geometric Acoustics* (2014), Bassuet al et. demonstrate how to use 3D modeling programs coupled with new fabrication processes to refine the desired outcomes through iterative design, auralization, optimization algorithms and real-time computer modeling. In the article *Computational Sand Pile Techniques for Diffused Acoustical Ceramics* (2014), Rhett Russo used computer code to demonstrate the replication of self-organizing fractal properties. His demonstration creates an arrangement of rich sand pile configurations with multiple scattering and diffusion coefficients.

3.5.7 Digital Morphogenesis Models

Digital Morphogenesis Models (DDMs) are useful in simulation, analysis, and growth-prediction environments. Three DMMs are particularly useful for my research: diffusion-limited aggregation, differential growth, and tip growth.

3.5.7.1 Diffusion-limited Aggregation

Diffusion Limited Aggregation (DLA) describes a noisy growth process limited by diffusion. We can find DLA processes in nature, such as crystallization, bacteria colonies, snowflakes, coral, and island growth. Introduced by T.A. Witten and L.M. Sander (1981), the DLA model has been studied and simulated in 2D and 3D computer environments. For example, Bourke developed a software[30] to grow objects for 3D printing. The correlation function is described as:

$$c(\vec{r}) = \frac{1}{N} \sum_{\vec{r}'} p(\vec{r} + \vec{r}')p(\vec{r}')$$

where $p(\vec{r})$ is the local density which is equal to 1 or 0 depending on whether the site $\vec{r}$ is occupied or not (Pelcé, 2004).

3.5.7.2 Differential Growth

Differential Growth is the growth of an organ at a rate different from that of other organs in the body (APA dictionary). It is a process that produces winding and undulating forms. Many softwares, computer environments, or even website browsers[31] can run the differential growth simulation. The differential equation can be described as following function:

$$\frac{d}{dt}(c \cdot e^{kt}) \;=\; k \cdot c \cdot e^{kt}$$

3.5.7.3 Tip Growth

Tip growth is a morphogenesis model that describes living cells evolving into an elongated cylindrical cell morphology with rounded tips. In biology, tip growth refers to cells deformed using their membrane and its wall by adding new proteins and their extension (Pelce, 2000). The morphology of coral is an excellent example of tip growth.

30 http://paulbourke.net/fractals/dla/3dprint/

31 https://medium.com/@jason.webb/2d-differential-growth-in-js-1843fd51b0ce

3.6 On the Music Axis

Sound is the vocabulary of nature.

— *Pierre Schaeffer*

3.6.1 Sound Objects

The inventor of *musique concrète*, Pierre Schaeffer, explained the sound object as a critical element of study. In his *Traité des Objets Musicaux* (Treatise on Musical Objects), Schaeffer and his team at the *Groupe de Recherches Musicales* (GRM) worked on the perception of sounds considering their general perceptive properties. He introduced *écoute réduite* (reduced listening), as sounds which are listened to for their intrinsic perceptual qualities. In other words, sounds are independent from their source (the causes) and meaning. The sound object, which has distinctive properties, such as texture, matter, form, etc., is an observed object of our reduced listening (New Media Dictionary, 2001). Above all, the sound object is the result of a particular intention–to be perceived and to be studied.

3.6.2 Sound Morphology

> In reality, concrete music, no sooner than it has been discovered, has been overwhelmed, not only by the proliferation of material but also by the explosion of forms.

– Pierre Schaeffer

The electronic sound object is complex due to its heterogeneity, various hierarchies, and scale and size changes. Varèse noted that “Music, which should pulsate with life, needs new means of expression, and science alone can infuse it with youthful vigor” (Varèse 1966). The desire to understand the endless new possibilities of sound objects led Pierre Schaeffer to attempt to classify them (Roads 2001, p20). Schaeffer’s research into *musique concrète*, involved typo-morphology to examine sounds in the context of reduced listening. Schaeffer proposed to use the term *typology* for the identification and classification of sound objects, and *morphology* for the description of sound objects (New Media Dictionary, 2001). Morphological description involves the comparison of the shape and evolution of sound objects (Roads, 2001).

3.6.3.1 Schaeffer’s Morphological Criteria

Schaeffer analyzed the shape of sound objects in three dimensions as shown in Figure 3.16. The three axises represent *time* as the x-axis, *frequency* as y-axis, and *intensity* as the z-axis. The harmonic (spectrum) plane is the yz-section cutting at a given moment t; the dynamic (amplitude) plane is the xz-section cutting at a given frequencies f; and the melodic (pitch) plane is the xy-section cutting at a given level dB(Schaeffer, 2017). Thus, for each plane, we can gain a profile shape based on a specific criteria. In order to describe the sound object, Schaeffer defined seven morphological criteria related to different perceptual dimensions emerging from reduced listening. They are diagrammed as *mass*, *dynamic*, *harmonic timbre*, *melodic profile*, *mass profile*, *grain*, and *allure*. A summarized table shows in Figure 3.17.

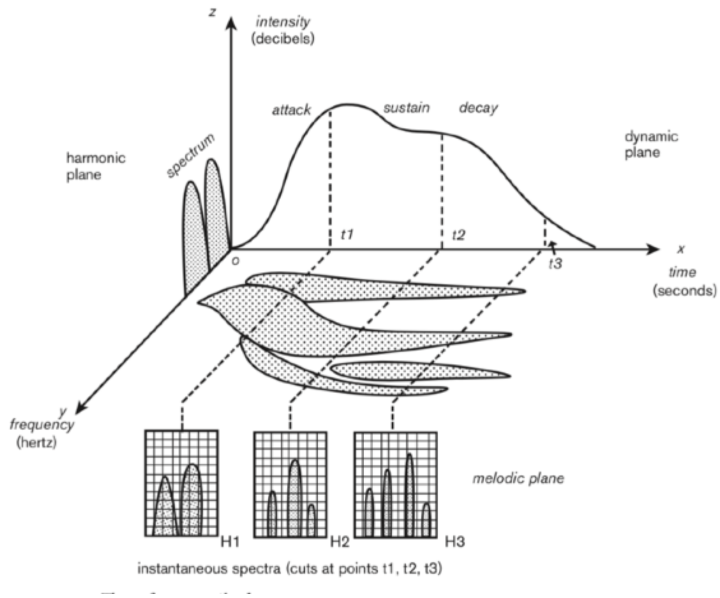

Figure 3.16 The reference trihedron. (Image source: Schaeffer 2017 p331.)

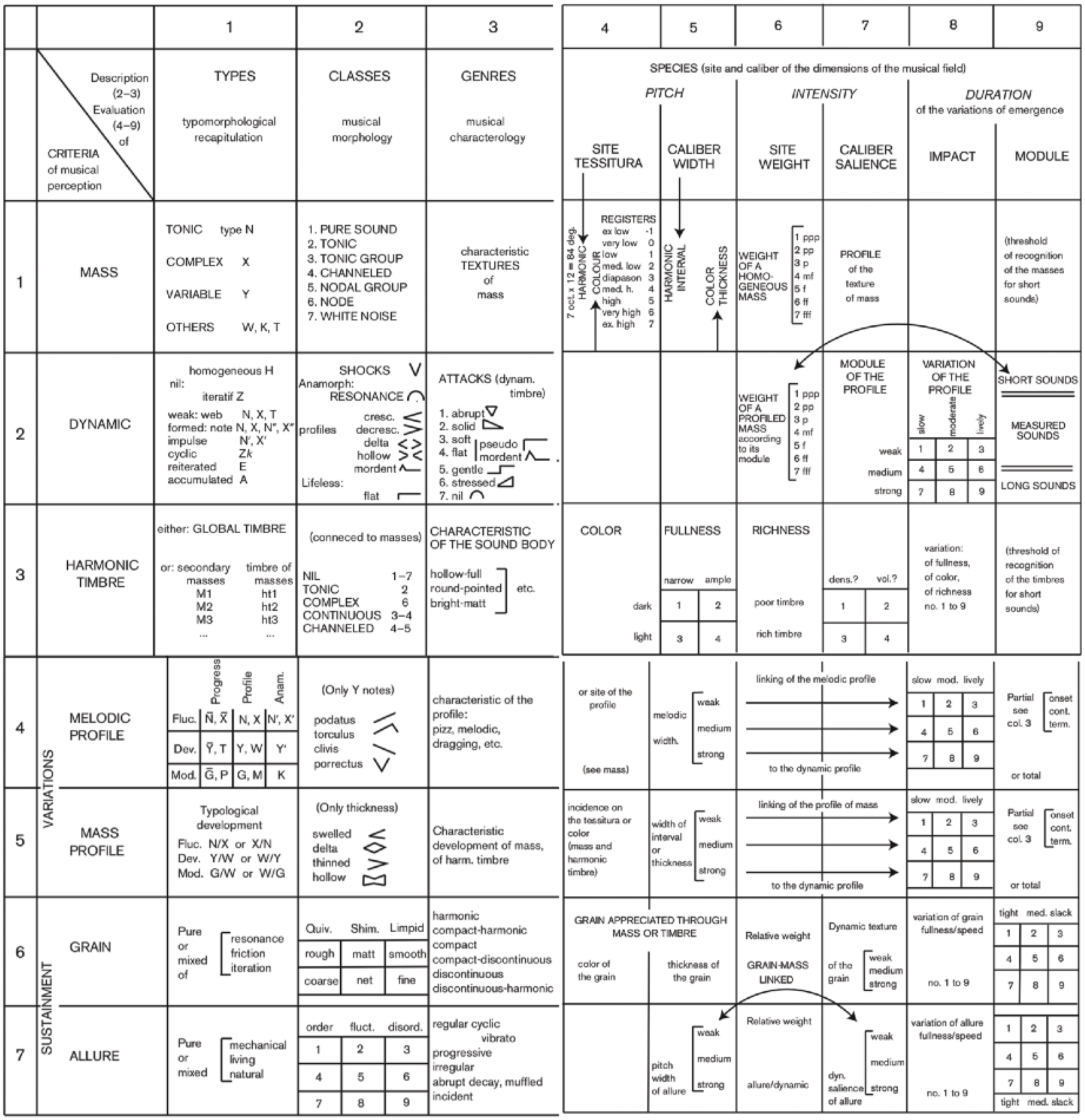

Figure 3.17 Summary diagram of the theory of musical objects. Image source: Schaeffer 2017.

3.6.3.2 Sound Morphological Description

At an early stage, I proposed a morphological description scheme from a perspective of digital morphology. In Table 3.1, I present five basic criteria with classes, subclasses, and evaluations. I intended to use this table to design a music-architecture mapping strategy. However, the music information in this table is based on artistic intrition not scientific research. Thus, MIR techniques come in to facility my original purpose.

Digital Morphologies System of Sound Object Description			
Digital Morphological Criteria	**First Class**	**Subclass**	**Evaluations**
FORM	**Three-dimensional shapes**	Sphere, cube, pyramid, torus, cone, etc.	Round/sharp, deep/shallow, thin/thick, flat/sloped/bumpy, divergence/convergence, shallow/deep, volume, etc.
		Organic forms: tree, cloud, mushroom, etc.	
	Two-dimensional shapes	Dynamic profile	Attacks (smooth, abrupt, release, nip); Ascending, descending, or ascending/descending; Austain, inpulse, stable; Straight/ zigzag, open/close, round/sharp, cyclic, reiterated, diminished/accumulated; area, etc.
		Melodic profile	Crescendo, delta, inverse delta, decrescendo, pitch evolution, consonance/dissonance, etc.
		Harmonic profile	Spectral distribution, pattern, etc.
	Size	Amplitude	Large/small, high/low, etc.
		Duration	Millisecond/second, temporal, etc.
COLOR	**Intensity**		Bright/dull, dark/light, etc.
	Timbre		Primary colors, grey scales, color value, contrast, etc.
	Purity		Full color, hue value, transparency, etc.
	Pattern		Vibrato, Tremolo, Spectral fluctuation, blurred / channeled, rhythmic, organic, noise, etc.
TEXTURE	**Roughness**		Smooth/rough, etc.
	Softness		Metallic / gaseous / solid / soft, etc.
	Grain		Density / porous; consonance/dissonance, etc.
VARIATION	**Synthesis**		Granulation, Mixing, Stochastic synthesis, etc.
	Growth		Proliferation , dilated, condensed, stretch, explord, etc.
	Death		Diminishment, fragmentation, compression, blebbing, explord, etc.
	Stage		Procedures, etc.
	Allue		Speed, rate, pace, scaling, swarm, etc.
	Movement		Rotation, spinning, move path, linear, parabolic, circular, multidirectional, swarming, etc
SPACE	**Location**		Center, edge, corner, top/down, left/right, background/foreground, distance
	Organization		Spatial path (move direction), positive space (light/warm), negative space (dark/cold), order/disorder, parallel, diagonal, cross, etc.
	Hierarchy		Cell size, unit size, etc.

Table 3.1 The first version of Morphological Criteria for Sound Object Description (Yin Yu, 2021)

3.6.3 Music Information Retrieval

When I was a child, I remember being able to recognize which uncle was knocking on the door or walking up the stairs to my grandmother’s place by listening, without seeing them. I could recognize which relative was calling from the other side of the phone when there was no display number function on the phone. As I grew up, my ears were continuously trained with the characteristics of their voices, the sound of their walking, the beat of their knocking on the door, etc. Everyone has their own unique “musical” way of life, and everything has their unique sound.

3.6.3.1 MIR

Music information retrieval (MIR) is the field of science which retrieves relevant information from music (Raguraman et al, 2019). It is an interdisciplinary research area related to various disciplines including signal processing, information retrieval, machine learning, multimedia engineering, library science, musicology, and digital humanity (Müller, 2015). Currently, MIR popular applications are science research and the music industry. In our daily life, we use many commercial services that benefit from MIR research, such as audio streaming platforms' music recommendation by mood or genre, voice recognition and commands on personal mobile devices, or online video-sharing platform’s copyright detection, etc.

3.6.3.2 Music Features

In MIR, music information encompasses a broad range of data. J. Stephen Downie (2003) classified seven facets based on their roles in defining the MIR domain. These facets are the pitch, temporal, harmonic, timbral, editorial, textural, and bibliographic facets (Downie, 2003). Another approach to classify the categories of music information is based on music perception (Schedl et al., 2013). These categories includes *music content* (eg. rhythm, timbre, melody, harmony, loudness), *music context* (eg. tags, lyrics, cover artwork, artis background, music video clips), *user context* (eg. mood, activity, social context, spatio-temporal context), and *user properties* (eg. music preference, experience, musical training, demographics).

In my research, I focus on sound morphology which refers to the manipulation of music audio information. Some existing models currently used to extract music features will be discussed in the following sections.

3.6.3.3 Pitch

In the *New Harvard Dictionary of Music* (1986), pitch is defined as "the perceived quality of a sound that is chiefly a function of its fundamental frequency in – the number of oscillations per second". However, pitch is a sensitive and culturally changed topic among musicians (Roads, 2015). Generally speaking, a high frequency is perceived as a high pitch and a lower frequency as a low pitch. The pitch range for men's voices was 60–180 Hz, and the pitch range of women's voices was 160–300 Hz (Re et al, 2012). When two or more pitches sound simultaneous, harmony occurs (Downie, 2003). In music theory, the difference between two pitches is called an interval, and the pattern of intervals is the melodic contours (Downie, 2003).

The perception of pitch is related to the frequency of the tone. The actual pitch of a sound is affected by other factors, including the sound pressure level and the presence of component frequencies. Pitch perception is a complex process, one that is not yet fully understood. Pitch elicited by some sounds may evoke the same aural response whether or not the fundamental frequency is present. (Raichel, 2006)

3.6.4.4 Chroma

Chroma, in western music, is related to pitch class. The main idea of chroma features is to aggregate all spectral information that is related to a given pitch class into a single coefficient (Müller, 2015). Viewed from the perspective of human perception, we perceive similar "color" if two pitches differ by an octave. Chromagram $C(n,c)$ represent chroma feature as:

$$\mathcal{C}(n,c) := \sum_{\{p\in[0:127]\,:\,p \bmod 12 = c\}} \mathcal{Y}_{\mathrm{LF}}(n,p)$$

3.6.4.5 Timbre

The timbral facet comprises all aspects of tone color (Downie, 2003) The aural distinction between a note played upon a flute and upon a clarinet is caused by the differences in timbre. (Downie, 2003). Timbre information is particularly useful for instrument recognition.

3.6.3.6 Temporal and Beat

Information concerning the duration of musical events falls under the temporal facet. (Downie, 2003) Temporal facet includes tempo indicators, meter, pitch duration, harmonic duration, and accents. (Downie, 2003) Taken together these five elements make up the rhythmic component of a musical work. (Downie, 2003). Zero Crossing Rate (ZCR) and energy are the sample methods to extract temporal descriptors. ZCR measures the number of times the signal crosses the zero axis per second. It is related to noiseiness and high frequency content.

3.6.4.7 Rhythm

As Roads noted, rhythm is the sum product of all parameters, such as time, pitch, space, amplitude, and timbre (Roads, 2015). Music content refers to aspects that are encoded in the audio signal (Schedl et al, 2014). Using existing MIR techniques, rhythm information could be obtained. For example, the temporal structure or pattern (the general concept of rhythm) could use energy-based (Δ_{Energy})or spectral-based($\Delta_{Spectral}$) methods to get the beat estimation. Tempogram ($T^F(n,\tau)$) could be used to represent each time instance the local relevance of a specific tempo (Müller, 2015).

$$\Delta_{\mathrm{Energy}}(n) := |\mathrm{E}_w^x(n+1) - \mathrm{E}_w^x(n)|_{\geq 0} \qquad \Delta_{\mathrm{Spectral}}(n) := \sum_{k=0}^{K} |\mathcal{Y}(n+1,k) - \mathcal{Y}(n,k)|_{\geq 0}$$

$$\mathcal{T}^{\mathrm{F}}(n,\tau) := |\mathcal{F}(n,\tau/60)|.$$

3.6.4.8 Time Domain Analysis

A time-domain (*f*) analysis studies and extracts the parameters from a piece of music in the time domain. Time-domain representations show us the amplitude of a signal at different points of time. The time-domain analysis is useful for basic parameter analysis and applications, such as cutting digital audio fragments or preprocessing the audio signal. It is direct and easy to read, and requires fewer computational steps.

Figure 3.18 is the time-domain representation of three recordings files covered in *AudioSculpt.*[32] Each recording (.wav) file was trimmed into 5 seconds. The top image is the

[32] http://anasynth.ircam.fr/home/english/software/audiosculpt

harmonic sound of *Aeolus*[33] (the sound sculpture from section 2.3.2); the middle image demonstrates the randomness of *Sea Organ* (landscape architecture from section 2.2.3); the bottom image shows the intense sound of *Sonambient*[34] (from section 2.3.4). To compare music in these three architectural projects, we can visually analyze the wave forms. In the wave form of Aeolus, the amplitude is relatively lower and the intervals appear periodically. Whereas, in the sound of the Sea Organ,[35] the wave amplitude shows up and down in varied intervals.

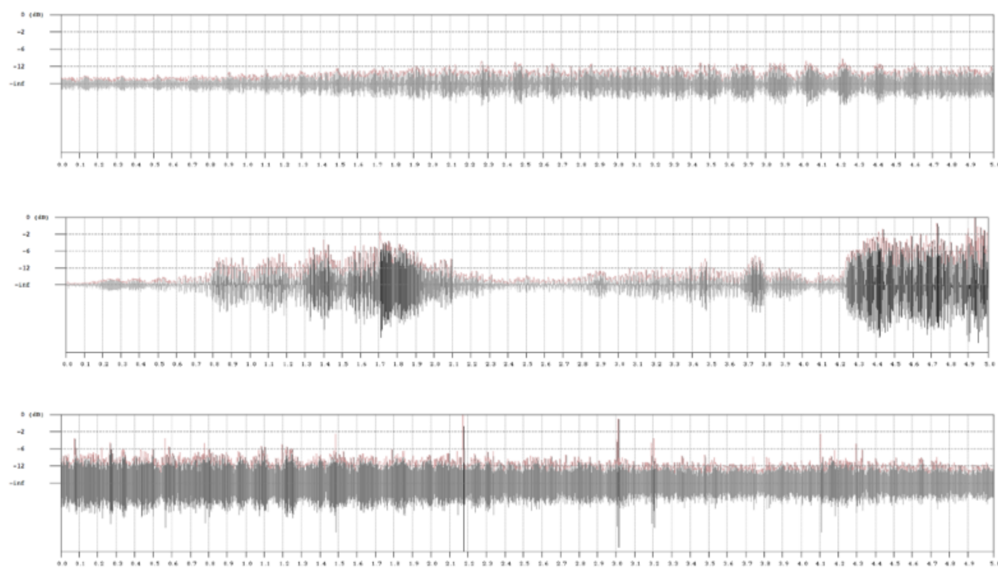

Figure 3.18 Time domain visualizations of the sounds at *Aeolus*, *Sea Organ* of Zadar, and *Sonambient*.

[33] https://www.youtube.com/watch?v=LOPBospfiU0

[34] https://www.youtube.com/watch?v=zS-YQ0-Rmmk

[35] https://www.youtube.com/watch?v=myV3E9uREuI

Other parameters that we can obtain from the time-domain analysis includes *short-time energy* (E_n) , *zero-crossing rate* (Z_n). The audio single in the time domain is $x(l)$, thus, at the frame n, the signal is $X_n(m)$. Then, we can obtain

$$x_n(m) = w(m)x(n+m) \qquad 0 \le m \le N-1$$

$$w(m) = 1, 0 \le m \le N-1;\ 0, m = else$$

Thus, at the frame n, the short-time energy E_n of the signal $X_n(m)$ is:

$$E_n = \sum_{m=0}^{N-1} x^2 n(m)$$

And the zero-crossing rate (Z_n) of the signal $X_n(m)$ is:

$$Z_n = \frac{1}{2} \sum_{m=0}^{N-1} \left| sgn[x_n(m)] - sgn[x_n(m-1)] \right|$$

$$sgn[x] = 1, (x \ge 0);\ -1,(x < 0)$$

3.6.4.9 Frequency Domain Analysis

Frequency domain analysis is the analysis of the audio information on its frequency character, such as *spectrum analysis*, *power spectrum analysis*, *cepstrum analysis*, *spectral envelope*, etc. Common methods include *band-pass filter bank*, *Fourier transform*, *linear prediction*, etc. Some of the common spectral-domain features are fundamental frequency, pitch ratio, spectral moments, spectral flatness, spectral rolloff, spectral centroid, and bandwidth. Figure 3.19 is the frequency-domain representation of the same three sound files.

The y-Axis represents the frequency. Color values represent the energy with red as high volume and blue as low. In the left image, at 20K hertz frequency, a bright blue line indicates the high pitch of Aeolus. In Sonambient (right image), we can see many layers of Tember where the sound is bright (overtone). A series of horizontal red lines mean different pitches of objective vibrate together. Overall, we can say that Aeolus has a darker sound and Sonambient has a brighter sound. Sonogram analysis could be obtained by short-time Fourier transformation.

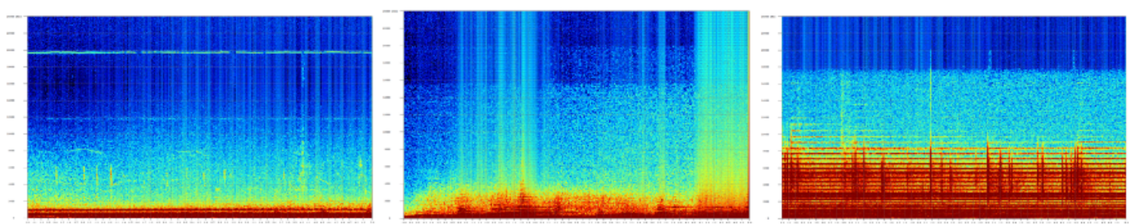

Figure 3.19 Sonograms of Sound of Aeolus, Sea Organ of Zadar, and Sound of Sonambient (from left to right). 2022

The short-time Fourier transform $X_n(e^{jw})$ of the signal $X_n(m)$ is:

$$X_n(e^{jw}) = \sum_{m=0}^{N-1} x_n(m)e^{-jwm}$$

3.7 Summary: Towards a Sound Morphogenesis Design

Digital technology has impacted our current design theory and practice. In my research, I am proposing a new design theory–Sound Morphogenesis Design (SDM)–to expand the current digital morphogenesis theory by integrating sound morphology. Inspired by the Bauhaus Wheel, the ArMeTe is a three-axis diagram representing an intersection of music, architecture, and technology. The SMD diagram represents an overview of my dissertation research. Key concepts and terminology are presented. As a potential design theory, SMD needs to explore, experiment, improve, and evolve. In the next two chapters, I will detail the framework with methodology and analysis.

4. Design by Sound and Music

Continuing the SMD theory, this chapter introduces three strategies of architectural design informed by electronic music. I first introduced the heterogeneity of material in music and architecture. I present three methods: Digital Design through Open Sound Control Protocol, Computational Design through MIDI, and Computational Design through Modular Synthesizer. Then, I demonstrate two design experiments for digital architecture and wearable design. I propose What You Hear Is What You Wear (WYHIWYW) as a new methodology for architecture and design practice informed by sound and music.

4.1 The Heterogeneity of a Material

In music, as in other fields, the organization is conditioned by the material.

Pierre Schaeffer (1977, p.680)

In architecture, a conventional brick has a standard dimension, weight, texture, and color. Building environments that use such materials could result in very similar design patterns and outcomes. For example, one might find resonance when walking in the historical downtown in Portland and The Freedom Trail in Boston. The historical towns were built with a similar material–the red bricks (Figure 4.1). Nature, on the other hand, is highly diverse because of its heterogeneous material. For example, the heterogeneity of fiber structure in woods, plants, and fruits varies in direction, density, and spatial organization. Like the brick of masonry, a note is the basic unit of musical material in traditional European music. The homogeneous note is limited to a fixed pitch, timbre, duration, and dynamic (Roads 2001, p18). Contrarily, in electronic music, the musical material–sound objects–have the natural material behavior. They are highly heterogeneous (Roads 2015, p68).

Figure 4.1 Similar building materials in two cities. Left: Historical Downtown, Portland, Oregon Right: The Bell in Hand concern on the freedom trail, Boston, Massachusetts (Image sources: https://www.portlandmaine.com/events/historic-workouts-4/ https://travelingcanucks.com/2017/03/photos-from-boston/)

4.1.1 The Heterogeneity of Sound Objects

Electronic music opens up endless new possibilities for musical composition. As Edgard Varèse[36] observed:

> And here are the advantages I anticipate from such a machine: liberation from the arbitrary, paralyzing tempered system; the possibility of obtaining any number of cycles or if still desired, subdivisions of the octave, consequently the formation of any desired scale; unsuspected range in low and high registers; new harmonic splendors obtainable from the use of sub-harmonic combinations now impossible; the possibility of obtaining any differentiation of timbre, of sound-combinations; new dynamics far beyond the present human-powered orchestra; a sense of sound-projection in space by means of the emission of sound in any part or in many parts of the hall as may be required by the score; cross rhythms unrelated to

[36] Edgard Varèse (1883-1965), a French-born composer. He coined the term “organized sound”.

> each other, treated simultaneously, or to use the old word, "contrapuntally" (since the machine would be able to beat any number of desired notes, any subdivision of them, omission or fraction of them)–all these in a given unit of measure or time which is humanly impossible to attain.[37]

The heterogeneity of sound objects derives from two categories. The first category is from the diversity of sound sources (Roads 2015, p78). The cause of the sound[38] is not the focus of my dissertation. The second category represents the diversity of morphologies that we can find in sound objects. My research will focus on the transformation, evolution, and growth in heterogeneous materials, such as architectural granular materials and electronic sound objects.

The property variations of a heterogeneous material can be powerful expressive tools for artists. For example, in Curtis Roads' composition *Volt Air III* [39] (2003), the sound material derives from a single click[40] (Figure 4.2.a) granulated into an 80 ms sound object [41] (Figure 4.2.b).

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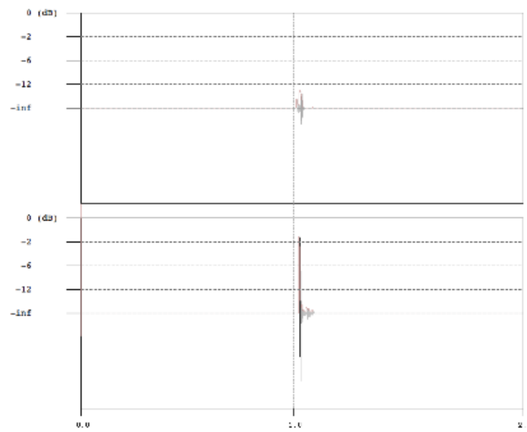
37 From a lecture given at the University of Southern California, 1939. The text was published in *The Liberation of Sound.*

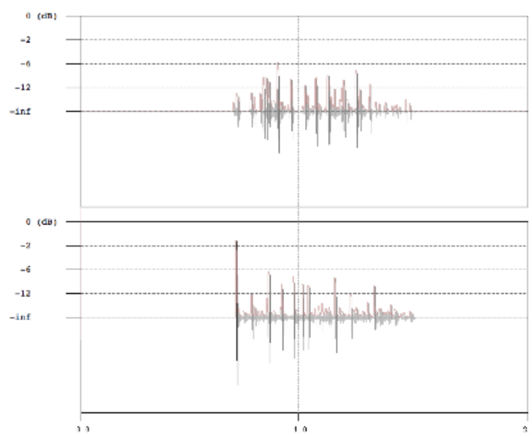
38 Such as a church bell, piano keys, a car engine, a door closing, or a dog barking.

39 Excerpt of Volt air III (2003) by Curtis Roads, https://global.oup.com/us/companion.websites/9780195373240/ch5/audio5.11/

40 An impulse generated by Roads in 1999., https://global.oup.com/us/companion.websites/9780195373240/ch5/audio5.9/

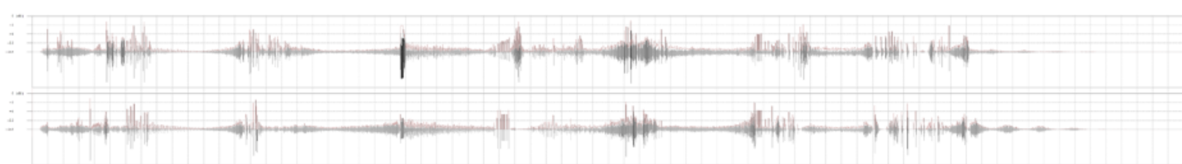
41 An 800 ms sound object, https://global.oup.com/us/companion.websites/9780195373240/ch5/audio5.10/





(a) The waveform of an impulse

(b) The waveform of an 800 ms sound object created by granular synthesis



(c) The waveform of Volt Air III (excerpt)

Figure 4.2 The waveforms of the sound objects. Images rendered in AudioSculpt[42].

42 AudioSculpt is a software developed by IRCAM for viewing, analysis and processing of sounds

Recent technology development has fully empowered artists to have more freedom to manipulate the properties of heterogeneous sound material. For example, pitch can be shifted through algorithms, such as Probabilistic YIN, Wavenet, and NSynth (Mauch 2014, Brazier, 2017). Sound timbre can be liberated as well. For instance, timbre can be transferred with a Differentiable Digital Signal Processing (DDSP) autoencode algorithm trained on a specific sound library (Engel, et al., 2020). Sound space also has been liberated by using spatial synthesis and sound transformation. For instance, ordinary mono sounds can be converted into 3D or 2.5 D sound using AI systems (Gao and Kristen, 2019).

4.2 The Hierarchy of Organization

You: "What do you want, brick?'
Brick: "I like an arch."

– Louis Kahn

The organization of materials is hierarchical at different levels. The hierarchy in material and structure can be found in architectural design, nature, and musical composition. I will discuss the hierarchy in different environments and applications.

The homogeneous architectural material[43] have been organized in complex structures. For example, the base structure of the Eiffel Tower (Figure 4.3) shows a multiple level of hierarchy, from the main structure of the pillar, to the middle level of large diagonal braces,

[43] Such as industry steel and standard glass.

to the detail level of the framing member of braces[44]. Different level hierarchies can also be found in historical buildings. For instance, the extremely complex Gothic style ceiling structure in Henry VII Lady's Chapel at Westminster Abbey, built with homogeneous stone[45]. The vault grows from the vertical piers, to sprandels, and then connects both sides with a transverse. The fan shaped vault and the circular fans not only decorate the ceiling but also hide the structures. In other words, the structures are part of the decorate pattern (Figure 4.4).

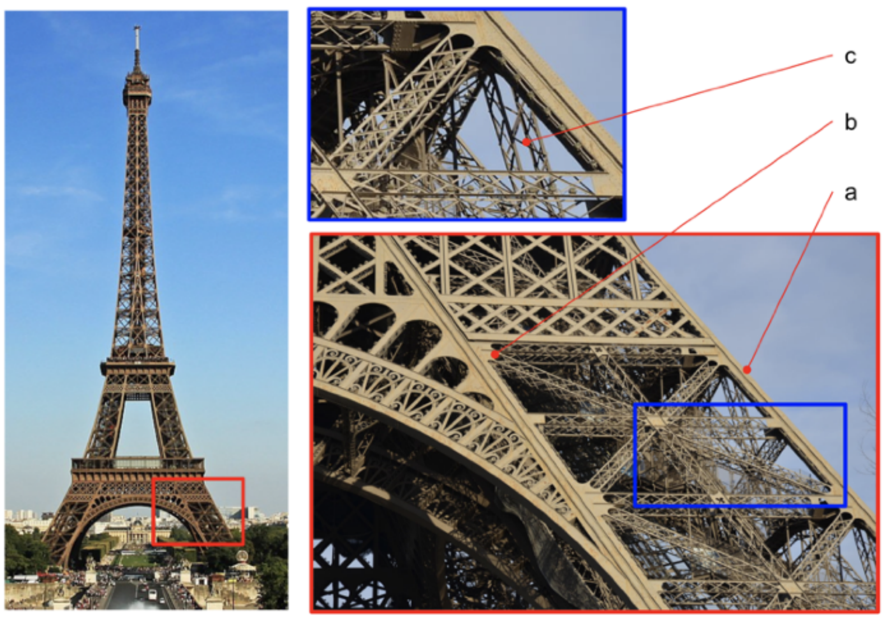


Figure 4.3 Multiple levels of hierarchy structure of the base of Eiffel Tower. a) Main pillar; b) Large diagonal braces; c) Brace (Image annotated by author, image sources: https://commons.wikimedia.org/wiki/File:Eiffel_tower_from_trocadero.jpg https://commons.wikimedia.org/wiki/File:Details_of_Eiffel_Tower_structure,_south_pillar.jpg)

44 Eiffel Tower's technical terms. https://www.toureiffel.paris/en/the-monument/lexicon-technical-terms

45 Henry VII Chapel. https://www.khanacademy.org/humanities/medieval-world/gothic-art/gothic-art-england/v/henry-vii-chapel

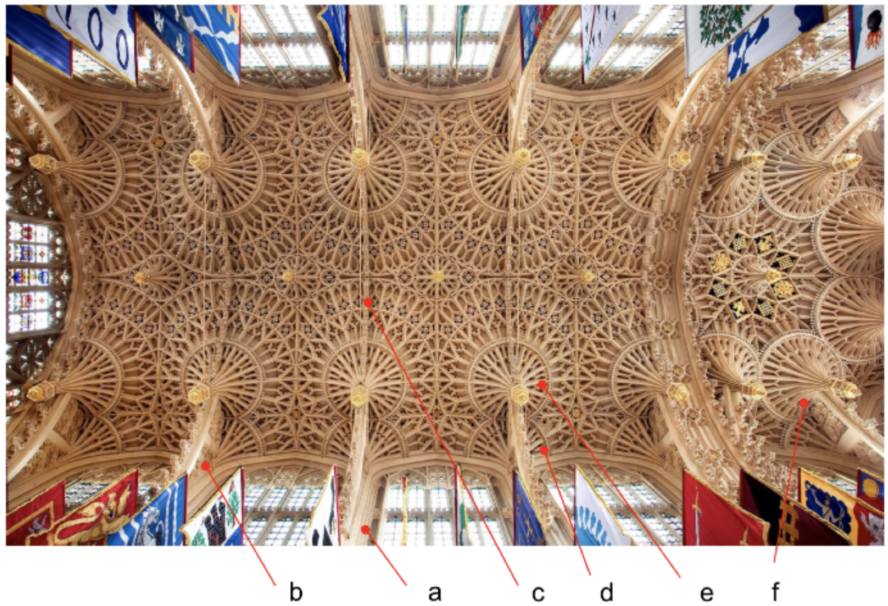


Figure 4.4 The vaulting of Henry VII Lady's Chapel at Westminster Abbey. a) pier; b) spandrel; c) transverse; d) fan; e) circular fan; f) pendant vaults (Image annotated by author, image source: https://www.mallardscollection.com/home/westminster-abbey-vault-of-henry-vii-lady-chapel/

In nature, the level of hierarchy is immensely complex given the heterogeneity of the materials. As material scientists observe, natural structural materials usually comprise hard and soft phases arranged in complex hierarchical architectures, with characteristic dimensions spanning from the nanoscale to the macroscale (Wegst et al., 2015). For instance, bone fragments at microscale have compact bones on their surface and spongy bones in the interior. At the nanoscale, the material structure is organized as a fibril matrix (Figure 4.5).

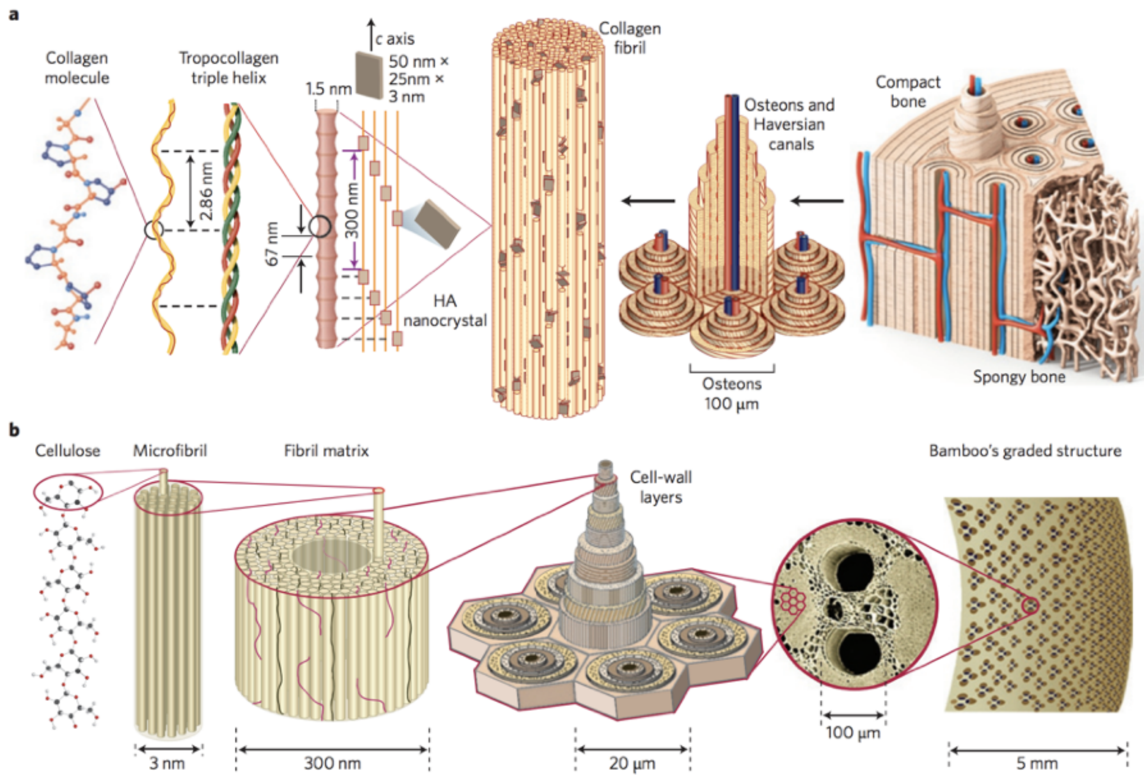


Figure 4.5 Hierarchical structure of bone and bamboo. © 1995 by The Journal of Bone and Joint Surgery, Inc.; rest of panel, ref. 124, Nature Publishing Group. (Image source: https://www-nature-com.proxy.library.ucsb.edu:9443/articles/nmat4089.pdf)

In electronic music, the hierarchy of organizing sound material relies on time. It has often been said (by Stravinsky, Messiaen, and others) that in music time is *everything* (Xenakis 1992, p192). Xenakis summarized five levels of musical structure hierarchy, such as microstructure (= timbre), ministructure (= note), mesostructure (= polyrhythm, melodi scales of intensities), and macrostructure (= global evolution on the order of some tens of minutes) (Xenakis 1972, p266). In *Microsound*, Roads distinguished nine time scales of music, starting from *infinites*–the longest time, to *infinitesimal*–the shortest time. Roads also indicated that hierarchical variations of the same event structure on multiple time scales is one of the compositional processes (Roads 2001, p334).

Xenakis used Poisson's Law[46], a probability theory that arranges events distribution involving both space and time, in his composition *Achorripsis* (1956-57) on multiple hierarchy structures. The top level of the organization is time. Xenakis established the duration of the piece at 7 minutes, then divided the total length into 28 time-blocks. Each time block lasts 15 seconds (Arsenault 2002, Childs 2005). The next level of the organization is timbre. In *Achorripsis*, Xenakis set seven timbral classes, including *flute*, oboe, *string glissando*, *percussion*, *pizzicato*, *brass*, and *string arco*. Xenakis used a 7 rows by 28 columns vector matrix to structure the piece into 196 cells (Figure 4.6). The third level of the organization is the probability (density) of sound events. Xenakis calculated to yield a Poisson distribution of 107 no-sound (silent) events (yellow cell), 65 single events (green cell), 19 double events (blue cell), 4 triple events (red), and 1 quadruple event (dark purple cell). Following this step, Xenakis re-applied Poisson's law on the distribution of sound events in each column and row. *Achorripsis* was the first musical work organized using the stochastic method by Xenakis. It demonstrates various hierarchies of organization of sound cloud. As Xenakis himself said, *Achorripsis* witnessed that stochastic permits a philosophic vision, in which the works of art follow the steps *rules* → *vision* (Xenakis, 1992, p38).

[46] A probability theory that events' distributions involve both space and time.

Roads' *Clang-tint* employed the multiscale composition method in the sound material organization. The four movements were designed as two opposing pairs: *Purity* versus *Filth*, and *Organic* versus *Robotic*. In each movement, Roads deploys the set of sound materials related to the theme and organizes them in a particular way. For example, in *Purity*, pure sinusoidal waveforms, slow glissandi, and slow modulation were the sound material. Roads used melodic structure, harmonic structure, and pulsating rippling methods to organize the material. In the opposite theme, *Filth*, the sound material comprises granular synthesis, controlled distortion, industrial noises, which were organized through the method of mesostructure of dense sound masses and irregular phrases (Roads, 2021). In Figure 4.7, we can see these different approaches result in two contrasting visual sonograms.

Louis Sullivan (1856 - 1924), an American architect, once said, "form follows function". Considering material heterogeneities and the hierarchical structure, we can rephrase this idea as form follows function, structure follows form, and materials follows structure. As Roads observed, a composition is the collection of ideas that a composer uses to organize his or her thoughts, to conceptualize and realize a piece (Roads, 2015). The design of an architectural piece also involves multiple design processes. The material, structure, and design processes are entangled.

$$P_k = \frac{\lambda^k}{K!} e^{-\lambda}$$

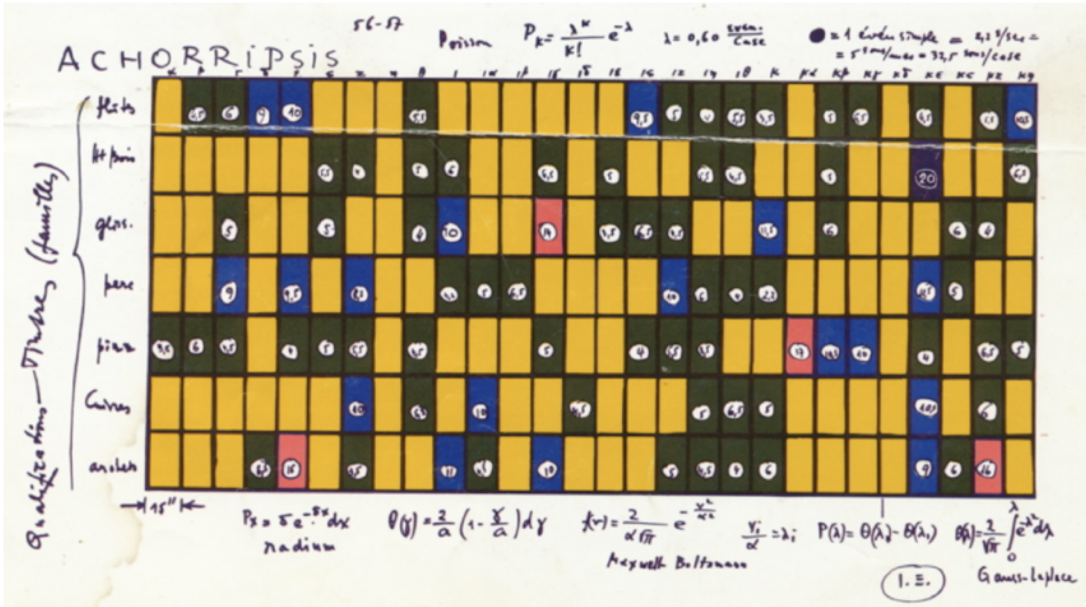


Figure 4.6 Vector Matrix of Achorripsis in Global color diagram. Iannis Xenakis, *Achorripsis*, 1956-1957. © BNF, Musique, Archives Xenakis (Image edited by author, source: Roads, From grains to forms, 2012)

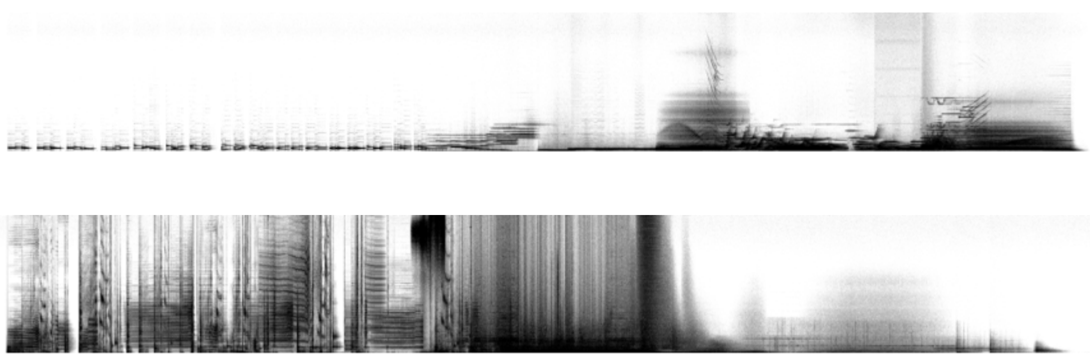


Figure 4.7 The hierarchy of organization represented in sonogram. Above: Purity sonogram Below: Filth sonogram. Images rendered in AudioSculpt sonogram analysis, 2021.

4.3 Scale and Size (Time and Space)

Beneath the level of the note lies the realm of microsound, of sound particles.

– Curtis Roads

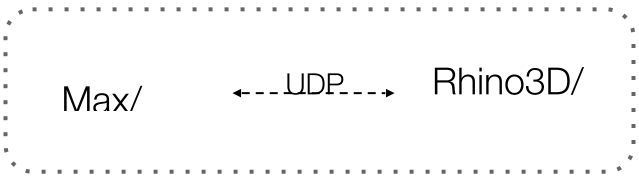
At different levels of structural hierarchies, the material scale varies. Let's take the Eiffel Tower as an example. The material is at 100-meters scale in the high level (the global level) hierarchy and 100-centimeter scale in the low level (the local level) hierarchy. In music, the time scale of a sound object ranges from a fraction of a second to several seconds (Roads 2001). From an architectural perspective, this research will focus on the design and fabrication at a relatively small scale, such as product design, wearable devices, or building elements.

Material size affects design. The material comes in physical forms at various sizes. In nature, the material developed the surface and the shape. One cannot double a surface area without changing its shape (Vogel 2003). The same applies to music, sound material needs space to form its shape, and every sound object has a three-dimensional shape and size. For example, we can use ultrasound waves to levitate and move tiny particles (0.6mm - 2mm in diameter) in three dimensional space (Ochiai et al., 2014).

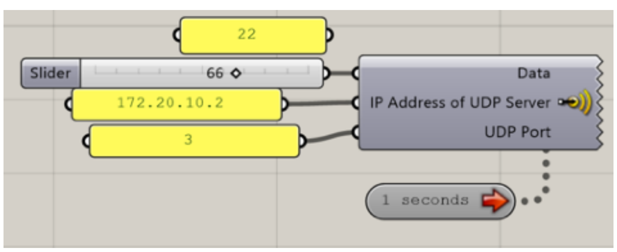
4.4 Digital Design through Open-Sound-Control Protocol

For the first method, we used Max/MSP 7 and Rhino3D 6 on a Windows 10 laptop. In Rhino3D, we have Grasshopper/Firefly installed on the platform. In Max/MSP we use the CNMAT library. To send/receive data between the two software platforms, we can use either

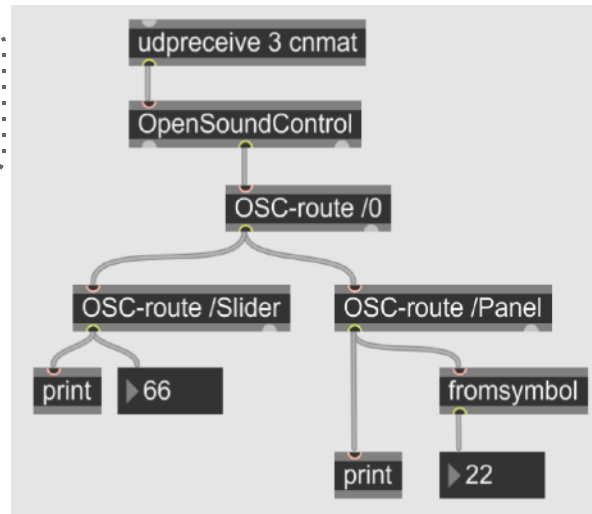
UDP or OSC protocols (Figure 4.8.a). This system can be on the same computer, or on two computers. If the system uses more than one computer, the IP address should be the same for each machine. In Figure (b) shows the example patch in Grasshopper/Firefly that sends data through the UDP protocol. Figure 8 (c) is an example patch in which Max/MSP receives data from OSC protocol.



(a)



(b)

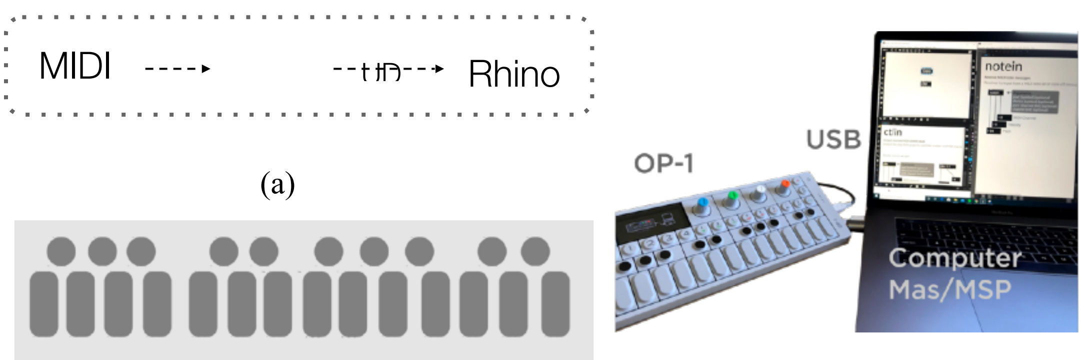


(c)

Figure 4.8 UDP/OSC design system. (a) A diagram of communication between Max/MSP and Rhino3D. (b) Grasshopper patch of receiving/sending data through UDP. (c) Max/MSP patch of receiving/sending data through OSC.

4.5 Computational Design through MIDI

MIDI, or Musical Instrument Digital Interface, is a standard protocol for communications between a variety of electronic musical instruments, computers, and audio devices. MIDI offers an intuitive interaction between humans and computers. In the second method, we used a MIDI device as input in the design system. To set up this system, we used an OP-1 (a digital synthesizer) as the MIDI device to connect the computer through a USB cable (Figure 4.9 a and c). To be able to use the MIDI controller as the input data, we mapped the keys on OP-1 into virtual keys in Max/MSP. To achieve this connection, we used the ctlin object to receive the MIDI key values and the notein object to receive MIDI note messages in Max/MSP. Upon mapping the keys, we can obtain virtual keys in Max/MSP (Figure 4.9 b). With this method, designers could do computational 3D design by pressing keys directly from a music interface.

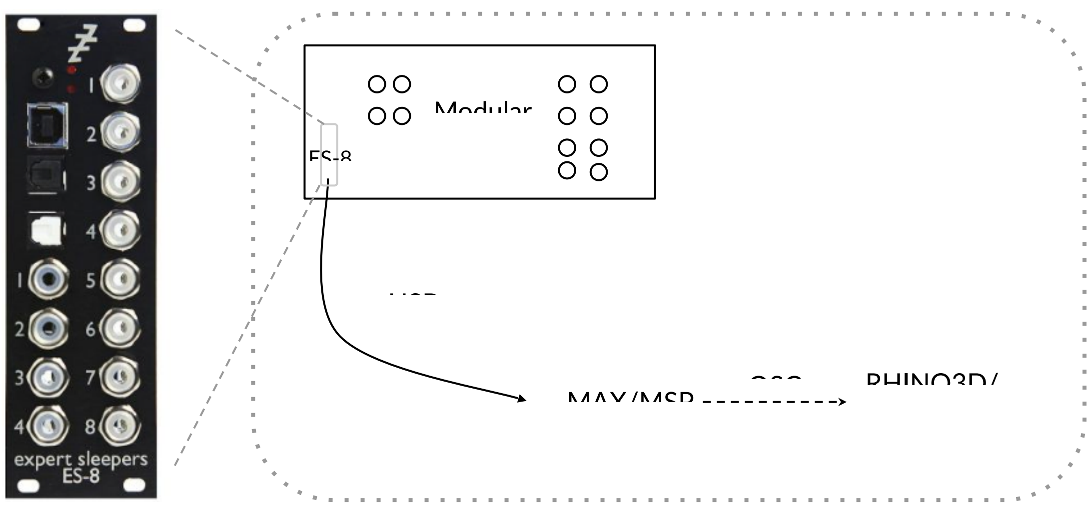


(b) (c)

Figure 4.9 MINI as input for computational design. (a) A diagram of communication between MIDI to Rhino3D. (b) A 24 virtual key pads in Max/MSP. (c) The OP-1 MIDI device connects to the computer through a USB cable.

4.6 Computational Design through Modular Synthesizer

While a traditional synthesizer is prewired with a defined set of components, Modular Synthesizers gives musicians great freedom to design and connect their instruments. In the third method, we used the output from a Modular Synthesizer as the input for the design system. The module that allows us to connect from a Modular Synthesizer patch to Max/MSP is the ES-8 module developed by Expert-Sleepers (Figure 4.10 a). The ES-8 is an audio interface with four analog input channels and eight DC-coupled output channels. Upon connecting the modular synthesizer through a USB cable, we can get the signal by using the adc~ object (analog to digital converter) in Max/MSP. Then, we can use Method I to send data to Rhino3D through OSC protocol. With this approach, designers could design 3D models by patching cables on a modular synthesizer system.



(a) (b)

Figure 4.10 Modular Synthesizer as input for computational design. (a) The ES-8 is a USB 2.0 class-compliant audio interface in a Eurorack module. (b) A diagram of communication between a modular synthesizer system and Rhino3D

4.7 SMD Implementations: What You Hear Is What You Wear

Based on Method I, I developed a SMD mapping strategy (Figure 4.11) for a wearable design–a mask. The raw data is a one minute sound sample; then, I use fzero~ object to get the fundamental frequency of an incoming audio signal and use gain~ to get the energy in Max/MS. With design consideration, we map the data to a certain range in both the size and color. Figure 4.12 is a collection of the design results of nine moments during the real-time demo of the music sample directly controlling the design of the mask.

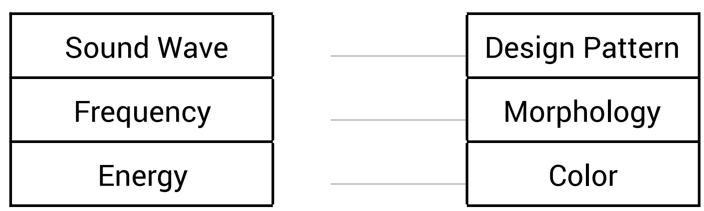


Figure 4.11 Sound MC Mapping Strategy.

The methods discussed in this chapter, I called these approaches *What You Hearing is What You Wear* (WYHIWYW), a design system informed by the real-time sound and music data. WYHIWYW brings an additional sensation–hearing–into the design process. I experiment with this approach in two types of design: wearable and digital architecture. In Figure 4.13, I prototype a wearable design *Between the Points* that is informed by the sound object that was excerpted from Curtis Roads's *Sculptor* (2001). Another experiment is *Modulating Light* (Figure 4.14), an digital architecture window pattern design informed by electronic sound from a modular synthesizer.

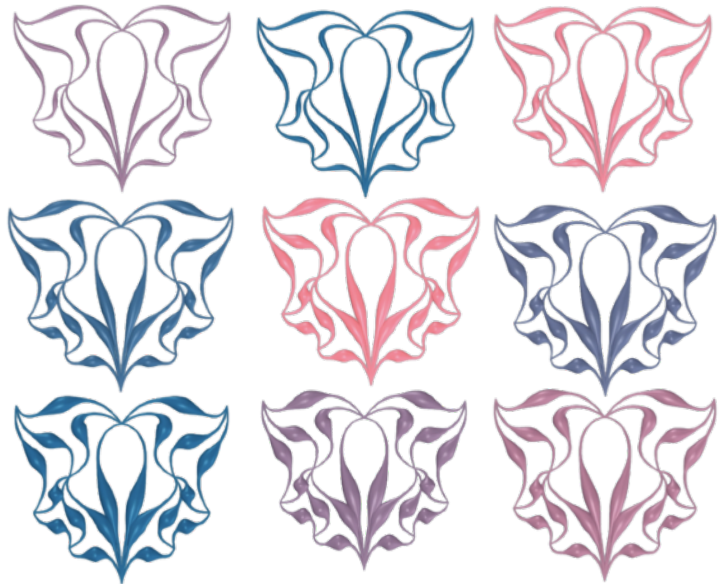


Figure 4.12 Digital prototypes of sound informed 3D design.

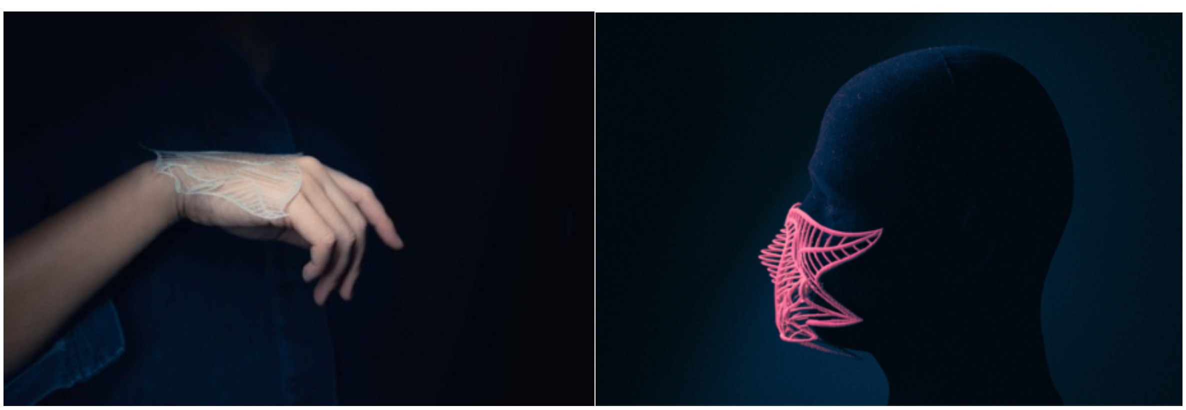


Figure 4.13 Physical prototypes of sound informed 3D design. Left: A 3D printed wearable made of TPU (Shore Hardness = 85A). Right: A 3D printed wearable made of PLA.

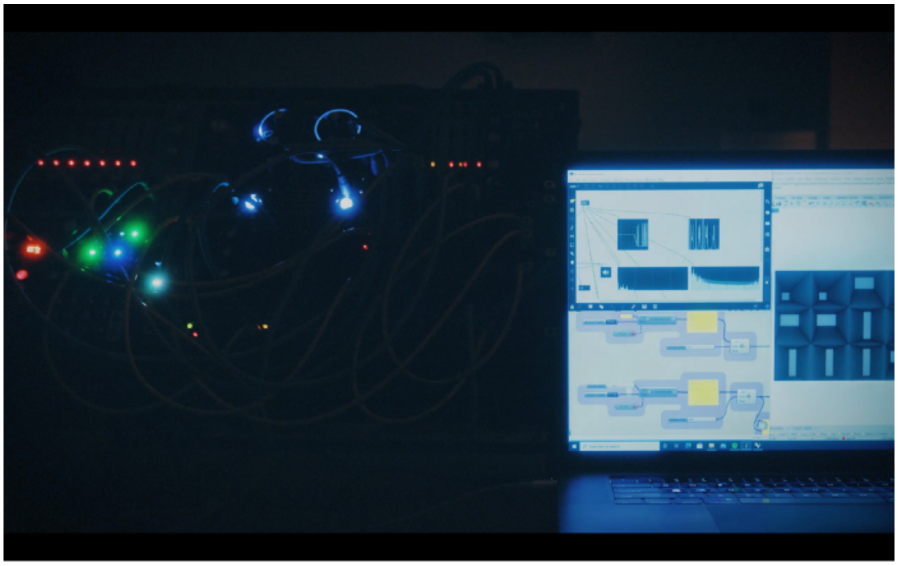


Figure 4.14 Modulating Light system setup. Yin Yu. 2020

4.9 Summary: Towards a design by hearing

Through the SMD methods, I demonstrated the potential of these new design approaches. First, understanding sound information or music information could give designers a powerful knowledge to understand the design outcomes and its relations to the acoustic environment; second, such an approach could take the creative process into a new direction by developing a myriad of unexplored mapping strategies. Finally, the SMC approach could enhance future collaboration research between musicians and designers.

Sound-based Morphological Computation, a new design approach, provides a design strategy by integrating sound into computational design. We described three methods for the system design. We demonstrated a wearable design using one SMD approach. For future work, I would like to explore more SMD approaches for other design applications.

5. A Musicalization of Space Composition

SMD, as a new theory and design philosophy, not only brings novel design solutions but also gives us a different perspective and new opinion on analyzing the historical projects. This chapter used the SMD framework to analyze Iannis Xenakis's work from a morphogenesis perspective. The critical finding is the morphological approach design in Xenakis's work is his light composition, which has not been studied extensively before.

5.1 Light as Morphology

Light, in Xenakis's *oeuvre*, is a material that creates space, generates patterns, changes colors, evolves forms, and composes movement. Light connects his two vocations: architecture and music. For him, *real* architecture is a combination of space and light proportions (Xenakis, 1992), and "everything in light is close to music" (Xenakis, 2008).

From the shape of the Algerian olive oil container for the "light cannons" at *La Tourette* (1954-59) to the "anemone" laser configuration in *Diatope*, Xenakis implemented morphological approaches in light compositions. Unlike static shapes, the light grows, transforms, and evolves. In biology, an organism's shape transformation, development, and growth process are called *morphogenesis*. This paper utilizes morphogenesis models as the analytical tool to offer novel perspectives on the light transformation and growth in Xenakis's compositions.

In this research, I examine Xenakis's light from two categories: *natural light* and *artificial light.* Direct and indirect light from the natural environment are forms of natural light. The interior light of the *Convent of La Tourette* ("light cannons", "machine guns", and "undulating glass panes"), and the "path of light" of *Villa Mâche* (1966-77) belong to this first category. The artificial light category includes artificially generated light sources, such as lasers, electronic flashes, bonfires, torches, and searchlights. I focused on the "streetlight" at the *Unité d'Habitation Marseille*, as well as Xenakis's *Polytopes*, specifically the *Polytope de Montréal* (1967), the *Polytope de Cluny* (1972-74), the *Diatope* (1978), and the *Polytope de Mycènes* (1978).

In this chapter, I used two digital morphogenesis models to analyze the light forms: *tip growth* and *stochastic form growth*. As an emerging computational design method, digital morphogenesis has great potential to investigate these light-based projects thanks to their close relationship with morphology theories, mathematical models, and digital techniques.

Furthermore, I introduce a form-time scale framework to develop an understanding of Xenakis's light compositions. Xenakis's light works have significantly influenced the media arts field. This article surveys a broad range of light design strategies employed by Xenakis spanning more than two decades of his career. Based on the form growth analysis of Xenakis's light works, computational morphogenesis suggests a new system to investigate the design process and to develop future multimedia arts.

5.3 Case Study I: Xenakis's natural light projects

Sunlight, the source of energy for life on earth, travels 8 minutes and 20 seconds from 150 million kilometers away to the earth (Cian, 2013). Xenakis developed a series of approaches to design daylight in architectural space that uses direct light, indirect light, and a combination of both. In the natural light category, we analyze projects at two different geolocations. The first one is Xenakis and Le Corbusier's collaborative project, *The Convent of La Tourette*, near Lyon, France. At this location, the day length is 15.75 hours in summer and 8.6 hours in winter. The second project is *The Villa Mâche* located on the island of Amorgos, Greece, with a day length of 14.65 hours in summer and 9.5 hours in winter.

I focus on five specific light designs: the "light cannons", the "machine guns", the "undulating glass panes", the "path of light" at *La Tourette*, and the "path of light" at the *Villa Mâche*. Xenakis' design approaches can be grouped into three strategies: *protrusion*, *perforation*, and *screen*. In these light projects, he made significant contributions to daylight design using both direct and indirect sources.

5.3.1. Protrusions from an architecture's skin

La Tourette's church features two essential light components, "light cannons" (Figure 5.1) and "machine guns" (Figure 5.2). These elements protrude from the ceiling to the exterior architecture's skin, just like living organisms. One morphogenesis model that describes these forms is *tip growth*. In other words, living cells evolve into an elongated cylindrical cell morphology with rounded tips. In biology, *tip growth* refers to cells deformed using their membrane and its wall by adding new proteins and their extension (Pelcé, 2004). The morphology of coral is an excellent example of *tip growth*. The three "light cannons" grow inconsistently in different dimensions, heights, and directions, whereas the "machine guns" grow steadily in relatively the same size, height, and direction.

The "light cannons", located at the north lower chapel of the church, use indirect light to create a space of contemplation. The north chapel is a grand-piano-shaped crypt apse. Its floor surface is approximately 180 sq meters, and an average ceiling height of 4 meters. This cave-like space is surrounded by an undulating concrete wall that inclines inwards. A partition wall (approx. 2 meters high) visually divides the spaces between the lower chapel and the church nave. Light and sound connect the two spaces.

Xenakis borrowed the shape of Algerian olive oil tins for the “light cannons” form (Xenakis, 2008). The internal surfaces of the “light cannons” are irregularly curved concrete walls painted in white, red, and black, respectively (Figure 5.3). The light contours from the ceiling are three organic circle shapes varying in sizes, with white as the largest circle, red at the middle, and black as the smallest one. Starting from the interior ceiling, the “light cannons” tip grows towards the sky, like fungi, in different directions. The white “light cannon” on the east protrudes from the ceiling and grows towards the northeast. The red “light cannon” in the middle extrudes to the north. And the black one on the west points its tip to the northwest.

Natural light washes the internal surface of the “light cannons” to provide indirect skylight to the crypt and lateral lights of the church (Figure 5.4). The 14-meter-high church adjacent to the lower chapel’s south blocks direct sunlight to the “light cannons”. The only direct light that comes into the lower chapel is the morning light from the east during midsummer (Walker, 2016). With the variety of color, proportion, protrusion direction, and skylight-facing orientation, the white “light cannon” has the brightest luminosity, and the black “light cannon” has the lowest fluorescence.

Unlike the inconsistent *tip growth* of “light cannons”, Xenakis designed seven unified polygons and protruded them from the sacristy’s ceiling towards the south (Figure 5.2 and 5.5). The seven quadrilateral shapes of “machine guns” extrude in two rows. There are four “machine guns” in the front and three in the back. It is worth noting that this arrangement also suggests a natural morphology–the alternate leaf pattern. In addition, similar to the pointed quartz crystal, the “machine guns” have sharp angles, which point to the courtyard of the Monastery. Xenakis oriented these irregular concrete prisms and carefully tilted the top glazing panel. With careful calculation and sun path study, the “machine guns” invite direct sunlight into the church nave during the two yearly equinoxes (Xenakis, 2008).

Xenakis used a protrusion approach on an architecture skin to design daylighting in his collaboration with Le Corbusier. This approach is an excellent example of a poetic relationship between morphology (curved surface, geometry, proportion, arrangement, etc.) and natural light. The “light cannons” and “machine guns” suggest a morphogenesis model of *tip growth* as an approach to develop irregular-shaped lighting devices to create a poetic daylight effect for a space of ritual.

Figure 5.1 A view from north-east of the three “light cannons” protruding from the roof of the piano-shaped lower chapel at La Tourette. The wall of the chapel is an undulating concrete surface that inclines inwards toward the interior space. The church blocks most direct light from the south. (Photo by author in May 2016).

Figure 5.2 A view from south-east of the seven“machine guns” protruding from the roof of the sacristy. Four in the front row, and three behind. (Photo by author in May 2016).

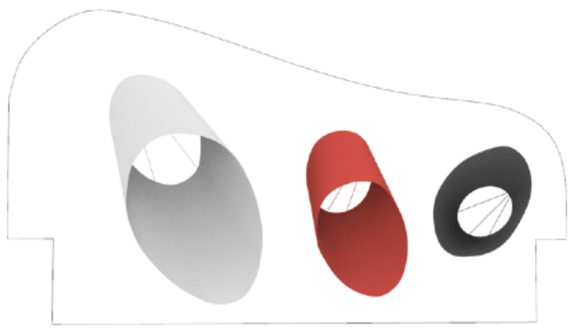


Figure 5.3 A view from the bottom of the “light cannons” with the ceiling contour. The white “light cannon” on the east grows towards the northeast. The red “light cannon” in the middle extrudes to the north. And the black one on the west points its tip to the northwest. (Digital reconstruction by author in March 2022).

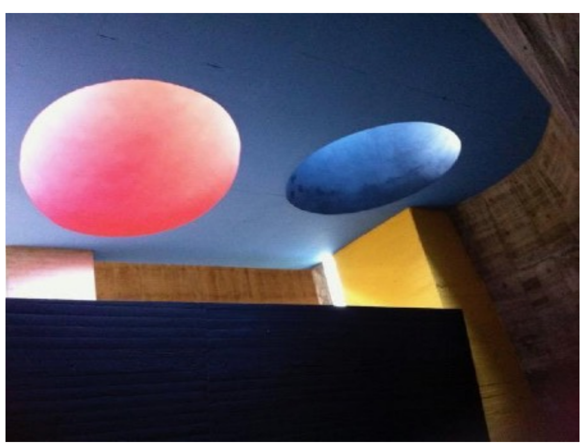


Figure 5.4 A View from the bottom of the red and black “light cannons” with the partition wall underneath (photo credit:51 la tourette CFX © Famille I Xenakis DR).

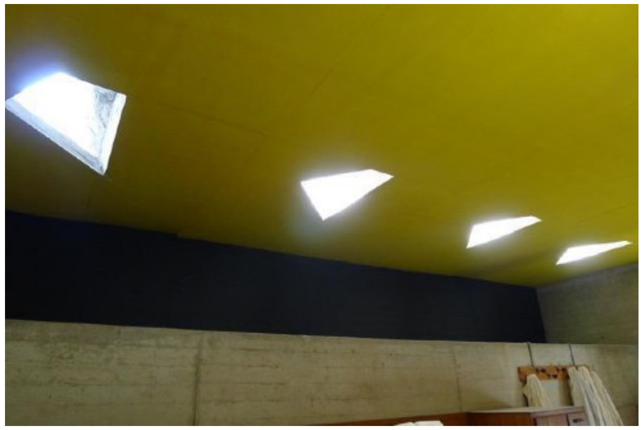


Figure 5.5 A View from the bottom of four polygon shapes from the “machine guns” (photo credit: 30 la tourette CFX © Famille I Xenakis DR).

5.3.2. Perforations on an architecture’s skin

Musical “neumes” and their light paths, a recurrent leitmotif, has become one of Xenakis’s signatures in his architectural projects (Kanach, 2008). Every light path that Xenakis designed is specifically created for a unique site. The light path *perforates* the architecture’s skin by replacing a solid wall with glazed panes. For example, we can find such implementations on the rooftop stairwell bulkhead (Figure 5.6) at *La Tourette* and on the façade of *Villa Mâche*. The light pattern grows stochastically from a relative centre point to a neighboring position. One model describing such a type of stochastic growth is a *random walk*. In mathematics, a *random walk* is a stochastic process that starts from a center point of a lattice and grows on paths based on probability. In nature, crystallization is an example of such a stochastic growth form.

Although it seems to grow randomly, the realization of the light path processes functional, meaningful, and aesthetic goals. The light path at *La Tourette* is the first project where Xenakis applied the perforation approach to a lighting design. If we place the floor plan of the complex next to the "path of light" of the rooftop stairwell bulkhead, one can easily see the visual connection between the circulation plan (Figure 5.6) with the geometry perforated on the wall. The highlighted area represents the walking paths of corridors, the lower church, the sacristy, and the atrium. To be more specific, these are the locations of Xenakis's lighting design: "light cannons", "machine guns", and "undulating glass panes". In other words, Xenakis abstracts his "path of light" to develop a *random walk* that starts from the atrium. It is a symbolic manner for the convent. The walking path of everyday life at the convent is closer to the sky–heaven.

Facing the southwest, daylight at *La Tourette* ends at the "path of light" on the rooftop every day. A perfect location to bid farewell to the daily natural light cycle at the convent. Direct and indirect light comes through the narrowed cuts of the wall into the staircase. Unlike other lights that create space, the slim light beam divides this space. The chiaroscuros and proportion between light and space is an essential design element in Xenakis's architecture projects.

The light paths at the *Villa Mâche* are a combination of random growth paths and stochastic distribution of windows (Figure 5.7). The distribution of such "neume" windows first appeared in the *Unité d'Habitation de Nantes-Rezé* (1950-54), a project also realised in Le Corbusier's studio. Xenakis designed the façade of the roof kindergarten using stochastics. At the *Villa Mâche*, we can find the continuous light paths and the detached windows intertwined together, based on probability theory.

Wall openings are a bridge to nature. Xenakis used the openings to frame the natural landscape from the interior view; meanwhile, the natural light also arranges the interior space by generating visual contrast. The perforations on the façade of the *Villa Mâche* are mainly facing north. In addition, a perforation was also applied to the ceiling in the living room. The narrow cut on the ceiling creates a laser-like light beam that splits the space into two. Although indirect light is the main source, the white surface on the wall and the bright skylight create a strong illuminated spatial composition for the interior space.

The realization of the *Villa Mâche's* façade not only frames the landscape views, but also presents a meaningful abstraction: the composer François-Bernard Mâche's initial. We can identify various abstractions of the letter "F" on the façade. For example, the square window and the light path in the living room compose the letter "F" (Figure 5.8). Xenakis stochastically grew the light form to achieve a new aesthetic of lighting.

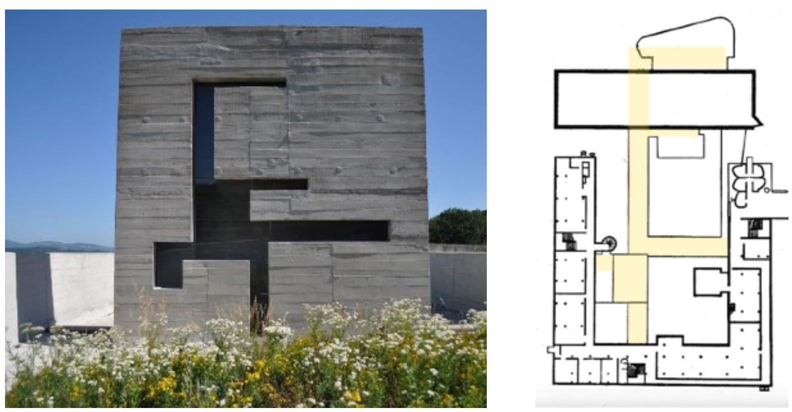


Figure 5.6 Path of light. Left image: The "path of light" on the rooftop stairwell bulkhead on the terrace (Escalier toit-terrasse, vue générale © Famille I Xenakis DR). Right image: Light path abstract diagram on the floor plan of La Tourette (Plan from wikiarquitectura, diagram by author).

Figure 5.7 Interior view of Villa Mâche (10 Diapo Maison Mâche © Famille I Xenakis DR)

Figure 5.8 An abstraction letter "F" from the interior view of Villa Mâche (7 Diapo Maison Mâche © Famille I Xenakis DR)

5.3.3. Screen: light acting as an architecture's skin

The last approach that Xenakis used in natural light projects is the *screen*, known as "undulating glass panes". The natural light of "undulating glass panes" is not merely a light source. Light becomes part of the architectural body; for him, light is architecture. The first light that comes into interior space is the tip of the growth form. Based on the *tip growth* model, the relationship between the density of the light and the density of the concrete frame is inversely proportional. In other words, when the light's protrusion is high, the density of the concrete frames will be low.

Furthermore, the density and continuity in the “undulating glass panes” became Xenakis’s musical expression in architecture. “Undulating glass panes", first applied on the façade of the Secretariat in Chandigarh, is a modern architectural innovation by Iannis Xenakis and Le Corbusier. It appears in many of Le Corbusier’s projects, as well as Xenakis’s independent architectural works (Kanach, 2008). Perhaps, the most famous one is located on the west façade at the *Convent of La Tourette* due to its scale, proportion, and musical movement. The top two levels on the façade (Figure 5.9) are *Modulor* living cells, and the lower levels are musical glass panes. This façade embodies two architectural ideas: Le Corbusier’s *Machines for Living In*, and Xenakis’s music in architecture.

Facing the northwest, the natural light illuminates the interior space. Selective direct and indirect light grows into the interior space through the glazing. At about 3.66 meters floor-to-ceiling height, light and shade perform a musical gesture inside. While walking at a constant speed, one can perceive dramatic light movements thanks to the continuous change of the concrete frames’ density. The rhythmic experience is a continuity of light transformation. A new lighting aesthetic has emerged through Xenakis’s music composition, intellectual contemplation, and mathematical abstraction.

Figure 5.9 A view of the west façade. Two levels of modulor house unite on the (Photo by author in May 2016).

5.3.4. Analysis of natural light forms and time

Time and duration are important criteria for light composition. On the other hand, growth rate is an important parameter in morphogenesis analysis and design. If we have the duration and the form, we can extrapolate an estimated growing model. Table 5.1 shows a summary of five natural light projects. The time scale is based on hours. For example, the daylight event of the “light cannons” happens once every day; the direct light event of the “machine guns” happens once every six months. For the lights’ surfaces, three design strategies have different calculation methods. In the protrusion group, the light surface is the area that reflects and diffuses natural light. For example, the light surface area for the “light cannons” is the sum area of the three cones. For the perforation group, the light surface is the wall opening area. Lastly, for the screen type, the light surface area is the whole screen size. In section 3.3, we will discuss the analysis of forms and time scales.

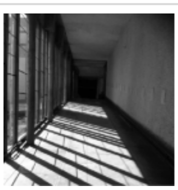
Natural Light Project	Location	Morphogenesis Model	Light Type	Light Surface Area (sq meter)	Light Event Time and duration
 Light Cannons (1954-1959)	Couvent de La Tourette (Lower Chapel)	Tip growth	Indirect light	12	Every 24 hours. Daylight = 15.75 hours in summer, and 8.6 hours in winter.
 Machine guns (1954-1959)	Couvent de La Tourette (Sacristy)	Tip growth	Direct and indirect light	3.5	Every 24 hours. Daylight = 15.75 hours in summer, and 8.6 hours in winter. Direct light every 6 months.
 Path of light (1954-1959)	Couvent de La Tourette (roof stairwell bulkhead)	Stochastic growth	Direct and indirect light	1.5	Every 24 hours. Daylight = 15.75 hours in summer, and 8.6 hours in winter.
 Path of light (1966 – 1977)	Villa Mâche	Stochastic growth	Direct and indirect light	2	Every 24 hours. Daylight = 14.65 hours in summer and 9.5 hours in winter.
 Undulating glass panes (1954-1959)	Couvent de La Tourette (hallways, meeting rooms, refectory, library, etc.)	Tip growth	Direct and indirect light	140	Every 24 hours. Daylight = 15.75 hours in summer, and 8.6 hours in winter.

Table 5.1 Light form and time scales in Xenakis' natural light projects

5.4 Case Study II: Xenakis's artificial light projects

After working with natural light, Xenakis came to see the light – in general – as an architectural gesture. He began to envision light as a material in his compositions in addition to time and duration. As he noticed, "man has access to events made of real light thanks to–for the time being–lasers, electronic flashes, light projectors and computers" (Xenakis, 2008).

Under the artificially light category, I will focus on five projects: the snail-shaped light fixture in the *Unité d'Habitation Marseille* (1951-52), the *Polytope de Montréal*, the *Polytope de Cluny*, the *Diatope*, and the *Polytope de Mycènes*. These projects can be classified as *static* and *dynamic* types. The static type is a light form that does not change over time. In contrast, the dynamic type is a light form that evolves and changes over time. The *Polotypes* belong to the dynamic type. Through artificial light, Xenakis achieved a landmark in light art and paved the road for a new type of art: multimedia.

5.4.1. The Static Light Form

In his first artificial light project[47], Xenakis used fluorescent tubes as a basic light source. The snail-shaped lamp (Figure 5.10) is an organic form lighting fixture for the corridors of the *Unité d'Habitation Marseille*. Designed by Le Corbusier and Xenakis in 1951-52, the lamp can be rotated in several directions. The hidden fluorescent tubes wash the curved sheet-metal surface to achieve an indirect lighting effect. The bent reflecting surface is approximately 0.35 sq metre (0.7m in length and 0.5m in width). The shape is closer to a golden spiral; as the name suggests, it resembles a seashell of a snail. The light glows from

[47] Xenakis once directed a tragedy based on lighting, and lighting changes in his 20s.

the inside to the outside, following a Fibonacci sequence. Once the lamp is turned on during the night, it provides a curvature shape of light. As Sharon Kanach observed, "This organic shaped independent structure creates an interesting contrast with the pronouncedly angular aspect of the main building" (Kanach, 2008).

Figure 5.10 Large snail-shaped lighting fixture (1951-52) along the corridors of the Unité d'Habitation Marseille (photo by author in May 2016)

5.4.2. The Growing Forms of the Polytopes' Light

After the success of "musical glass panes", Xenakis had new thoughts on approaching light: speed and form. In his *Polytopes*, Xenakis used a variety of artificial lights, such as electronic flashes in Montréal, lasers in Cluny, and bonfire and searchlights in Mycenae, among others. Although the sites and scales were varied, there was a unified strategy in his *Polytopes*: using lights to compose movement and evolve forms. In Sharon Kanach's words, a "musicalization of space”.

Both in indoor and outdoor settings, his *Polytopes* inhabit a relatively dark environment, which gives Xenakis an “empty” universe in which to create light. Like the chapel at *La Tourette*, without light, there is nothing. To enact his ideas of light form, Xenakis used lattice structures, such as steel cables or grid systems, on to which the artificial light sources were attached. For example, he designed five curved surfaces that intersected using 200 steel cables at the central void of the France Pavilion in Montréal (Figure 5.11). These cables create hyperbolic geometries for the dynamic and colorful light surfaces during the performance. In Cluny, since it is forbidden to touch the venue’s historical walls, Xenakis used a metallic grid to construct a scaffolding structure next to the vaults and walls (Figure 5.12). Lasers, mirrors, and speakers are positioned at the desired spots; meanwhile, the participants still have a spatial sensation of the original ancient Roman bath. In his *Diatope*, the interior surface of the vinyl PVC fabric was coated in gray to create a dark space for the light performance (Kanach, 2008, Kiourtsoglou, 2018). The most spectacular *Polytope*'s site was Mycenae which took the audience back some 3600 years. After sunset, the ancient land of civilization became the composer’s canvas. If the other Polytopes lights were grown upon a metallic network, the light of the *Polytope de Mycènes* was grown based on the history of human society. We thus become witness of the evolution of civilization through light.

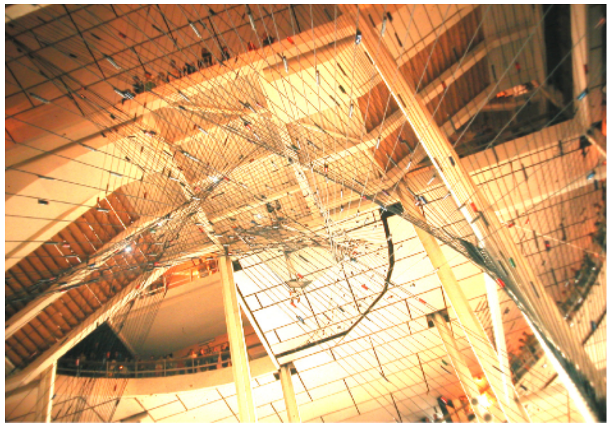


Figure 5.11 Photo of the Polytope de Montréal (Collection of Françoise Xenakis). Music and Architecture, Iannis Xenakis and Sharon Kanach, Hillsdale N.Y: Pendragon Press, 2008. Page 206.

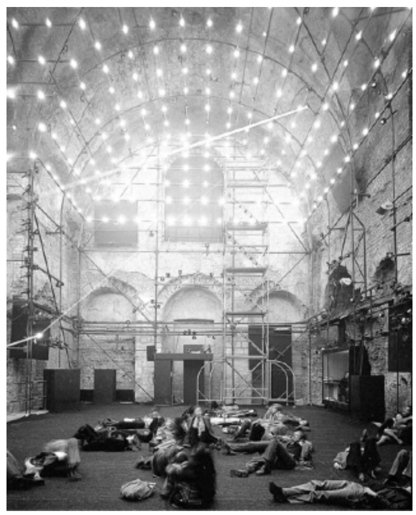


Figure 5.12 Light flashes on metallic grids for Polytope de Cluny in situ (Collection of Françoise Xenakis). Music and Architecture, Iannis Xenakis and Sharon Kanach, Hillsdale N.Y: Pendragon Press, 2008. Page 227.

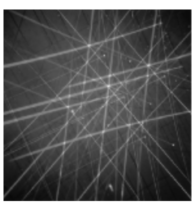
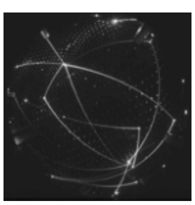
Figure 5.13 An interior view of the Diatope. Rastoin, Bruno (1954-2020). Photographer, "[Diatope 1978-79, Paris, photo couleur : vue de l'intérieur à hauteur du spectateur, lasers 5]," Centre Iannis Xenakis, accessed March 22, 2022, http://www.centre-iannis-xenakis.org/items/show/4006.

Figure 5.14 Polytope de Mycènes (Collection of Françoise Xenakis). Music and Architecture, Iannis Xenakis and Sharon Kanach, Hillsdale N.Y: Pendragon Press, 2008. Page 234.

5.4.3 Analysis of Artificial Light Forms and Time

With digital technologies, such as lasers, flashes, and computers, light becomes a material that creates space, generates patterns, changes colors, evolves forms, and composes movement. More importantly, light can change its speed and design on a smaller scale. For example, the frequency of the fluorescent tube in the snail lamp is 100-120 Hz. Our human eye can barely perceive this frequency range. Once the light is on, the static shape is formed. The illumination of the sensitive range for human vision is 10-25 Hz. In the *Polytopes*, the flashlights' frequency falls in this range. Table 2 summarized four *Polytope* projects' artificial light sources and light event durations. In these four projects, Xenakis's light composition ranges from 6 minutes to 1.5 hours. It is worth underlining again that light became a musical expression for Xenakis and allowed him to explore new forms. That is general morphology.

To develop an understanding of the form-time relationship in Xenakis's *oeuvre,* I identified ten discussed projects in an axis of the form-time scales system (Figure 15). Green star is labeled as a natural light project, and white star as an artificial light project. The X-axis is the time scale from second to year. The Y-axis is the form scale from centimeter to kilometer. As shown in the image, the time duration of the natural light projects is relatively the same. It suggests that the form scale would be more important for a variation and design purpose. On the other hand, Xenakis's artificial light projects varied in both time and form scales based on the site and goals.

Light Project	Location	Light Source	Light Abstract Form and Surface Area	Light Event Time and duration
 Snail-shaped lighting fixture (1951-52)	Corridors at the Unité d'Habitatio n Marseille France	Fluorescent tube	Snail (The curved surface is approx. 0.34 sq.m	100 - 120 times / second (not perceivable by the human eye)
 Polytope de Montréal (1967)	French Pavilion (currently the Casino de Montréal) Canada	1200 Electronic flashes (800 white, 400 colors in yellow, red, green, and blue.)	Rivers, arms, leaps, wisps of fire, etc Surface area estimated 1,300 sq meters	25 times per second. 9000 times during the six minutes of the performance. The show ran once every hour.
 Polytope de Cluny (1972-74)	Thermes de Cluny, Paris, France	Three lasers (green, yellow-green, and blue) Mirrors, and 600 white xenon tubes	Geometrical: circles, parallel, crossing lines, spirals, arcs, etc Natural: rivers, lotus, anemone, etc. 300 sq meter	25 times per second. The performance lasted 24 minutes. Several performances per day.
 Le Diatope (1978)	Place Georges Pompidou, Paris, France	1680 electronic xenon flashes (on cable network, wall of the shell, and under the glass-tile floor) 4 lasers (3 green, 1 red) 400 fixed or pivotal mirrors	Spirals, etc. 400 sq meters	25 times per second. The performance lasts 45’48"

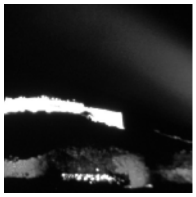
 Polytope de Mycènes (1978)	The acropolis of Mycenae, Greece	Lasers, electronic flashes, bonfires, torches (torch-bearing children), and 12 searchlights, a bonfire, light between goats' horns, and fireworks	30,000 sq. meters	The performance lasted 1.5 hours

Table 5.2 Light form and time scales in Xenakis's artificial light projects

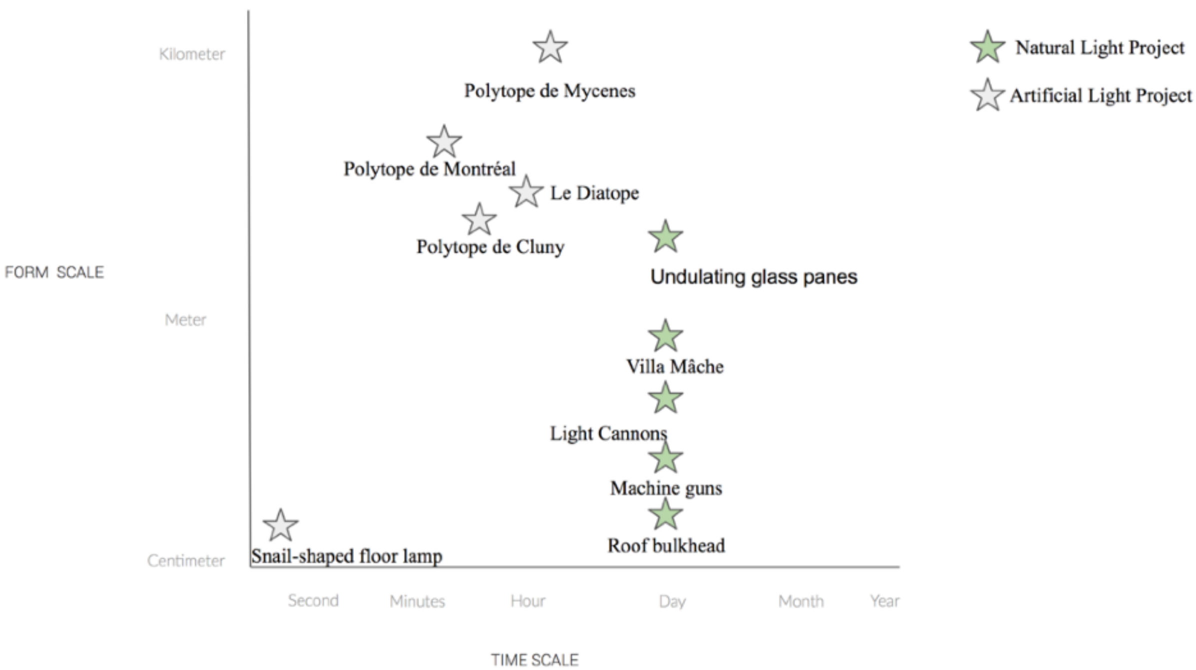


Figure 5.15 A form-time scales framework to analyze Xenakis's light works

5.5 Summary

Light in Xenakis's works has three phrases: light as architecture, light as music, and light as morphology. In Xenakis's early light work, we can find a series of form findings and explorations. From borrowing the shape of an olive oil container to the sharp polygon light guns, Xenakis used both geometric architectural elements and light form to express his ideas. That was light as architecture. A turning point happened during the completion of the undulating glass panes. Xenakis started to compose light with consideration of time and speed. During the period of Polytopes, the light slowly evolved and developed forms and patterns, which led to morphogenesis in multimedia composition. His light is poetic, dramatic, emotional, and powerful. Xenakis not only created a new aesthetic of light art, but also projected a future direction for the role of light.

6. Soft Tectonics

> My black square is a bare and frameless icon for our time. Arise comrades and free yourselves from the tyranny of objects.
>
> *-Kazimir Malevich, 1916*

> Music has several levels of listening. It can be sensual and be only that. Its effect on the body is then capable of being very powerful, even hypnotic.
> It can also express all the facets of sensitivity. But it is probably the only one to sometimes arouse a very particular feeling of expectation and anticipation of the mystery, of astonishment, that absolute creation suggests, without reference to anything, like a cosmic phenomenon. Some music goes even further, sucking you in an intimate and secret way towards a kind of abyss where the soul is engulfed for its happiness.
>
> *-Iannis Xenakis,*[48] *1960s*

6.1 Soft Tectonics: Resonating through Body Architecture

In this chapter, I introduced *Soft Tectonics as* an emerging design methodology under the framework of SMD. It is a novel approach empowered by soft matter, electronic sound, and digital morphogenesis. First, I will show three experiments. Following that, I will explain relevant projects and analyze my approaches. And finally, I will introduce an analysis tool to evaluate my experiments.

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[48] https://www.instagram.com/p/Cdd0Kb8APQb/

6.1.1 Soft Tectonics: three experiments

airMorphologies, an interactive artwork, is a pneumatic wearable device for social interaction in air polluted environments (Figure 6.1 Top let). It is a voice-activated system to control the shape of the body. *DeepOrganism* and *OctoAnemon* are two projects that are part of the *Organism* series. DeepOrganism "interacts" with hand gestures using morphologies of soft bodies. OctoAnemone is an installation demonstrating rhythmic movements by morphing the soft organism bodies. SoftVoss is an multisensor audio haptic wearable art.

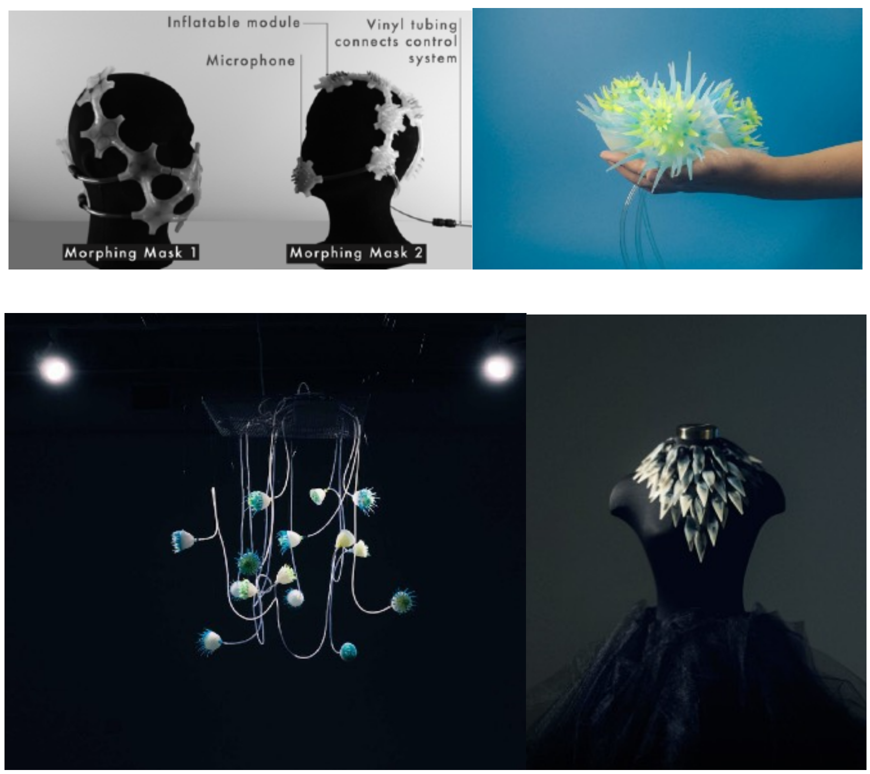

Figure 6.1 Soft Tectonics Experiments. Top left: airMorphologies. Yin Yu. 2019. Top Right: DeepOrganism. Yin Yu. 2021. Bottom left: OctoAnemon. Yin Yu. 2021. Bottom Right: Soft Voss. 2021.

6.2 From Digital Tectonics to Soft Tectonics

Inspired by the Russian Suprematist movement, Zaha Hadid created new possibilities for interior space in her conceptual design *Malevich's Tektonik* (1977). As Ida Kristina Andersson and Poul Henning Kirkegaard noted, the term *tectonics* has two main meanings in the field of architecture: the theory of the inner structure of a work of art, and the shaping and joining of form-elements to a unity (Andersson and Kirkegaard, 2006). In the digital age, computer technology permits architects the design of buildings without the constraints of physics. In the last three decades, the term digital tectonics has appeared in architecture design theory repeatedly. For example, Wassim Jabi, described digital tectonics as "the poetics of digital construction assemblage" (Jabi 2004). Philip Beesley and Seebohm Thomas argued that digital tectonics is "a systematic use of geometric and spatial ordinances, used in combination with details and components directly related to contemporary construction" (Beesley and Seebohm, 2000). Andersson and Kirkegaard suggested that digital tectonics is a combination of interaction between material and construction, clear and logical structure, and performative architecture (Andersson and Kirkegaard, 2006). In the article *Digital Tectonics as a Morphogenetic Process* (2009), Rivka Oxman proposed tectonics as a model of morphogenetic process. Furthermore, she defines tectonics as a concept and the emergence of a theoretical framework reflected in concepts and terms related to morphogenesis (R. Oxman, 2010).

I used *Soft Tectonics* as the title of my first solo exhibition (2021) in the Glass Box Gallery at the University of California, Santa Barbara. The show (Figure 6.2) featured two works exploring soft material and soft structure design. Three interpretations of the *soft* concept unfold in my work. The first one is soft matter, such as liquids, gels. The second is sound material as a soft "intangible" substance. And the third is the "softness" of perceptions.

Figure 6.2 Soft Tectonics at the Glassbox Gallery. Yin Yu. 2021. Santa Barbara.

6.3 Why Soft?

In the book, *Soft Architecture Machines* (1973), Nicholas Negroponte introduced the concept of *responsive architecture*. He proposed that responsive architecture is the natural product of the integration of computing power into built space and structures (Negroponte, 1973). To illustrate his ideas, Negroponte used a couple of *pneumatic architecture* examples. He elaborate further by including concepts of recognition, intelligent systems, response, architectural behavior, materials, and memory in architecture. In the chapter *Intelligent Environment*, the term *responsive* is also referred to as adaptable, or reactive. In this context, the environment takes an active role, initiating to a greater or lesser degree changes as a result and function of complex or simple computations (Negroponte, 1975). The concept of

Soft Architecture Machine brings a cybernetic approach into architecture design. Responsive architecture, such as pneumatic design, provides new design opportunities for architectural experiments. Furthermore, pneumatic architecture demonstrates a great potential for morphological characteristics and morphogenesis performance through the use of soft materials. Due to its lightweight and portability, pneumatic architectural experiments have a strong intimacy potential with the human body.

6.4 Human-Centered Design: Body Architecture

Body architecture could be defined as objects designed for the human body or at the scale of the human body. If we look at objects surrounding us, almost everything was designed at human scale, such as cup holders, food, game controllers, furniture, transportation, and architecture.

While the term, *Body Architecture*, is relatively new; it has been part of architectural history for a long time. Architects have been exploring the relationship between the human body and architecture since antiquity. In Figure 6.3, the image on the left was drawn by the ancient Roman architect, Vitruvius, back to the 1st century BC. In his treatise, *De architectura,* Vitruvius defined perfect proportions in architecture and the human body. We can find the beauty of those proportions in the city of ancient Rome. The ancient Roman architectures that were built based on Vitruvius' works applied mathematics. His drawings inspired the Renaissance design genius Leonardo da Vinci. The middle image is da Vinci's version of "*Vitruvian Man*" (1510). In fact, da Vinci carried out a lot of studies about the human body, such as his sketch of the *Human brain and skull*, *Anatomical study of the arm*, and the *study of a foetus in the wo*mb (Heydenreich, 2022). Moving to the modern time, Le Corbusier materialized his human body studies in the iconic *Modulor Man* (1948) drawing. And more recently, a contemporary photo essay conducted by photographer Paul Gisbrecht (2019) captured a series of trajectories of everyday movements in the space a human is inhabiting.

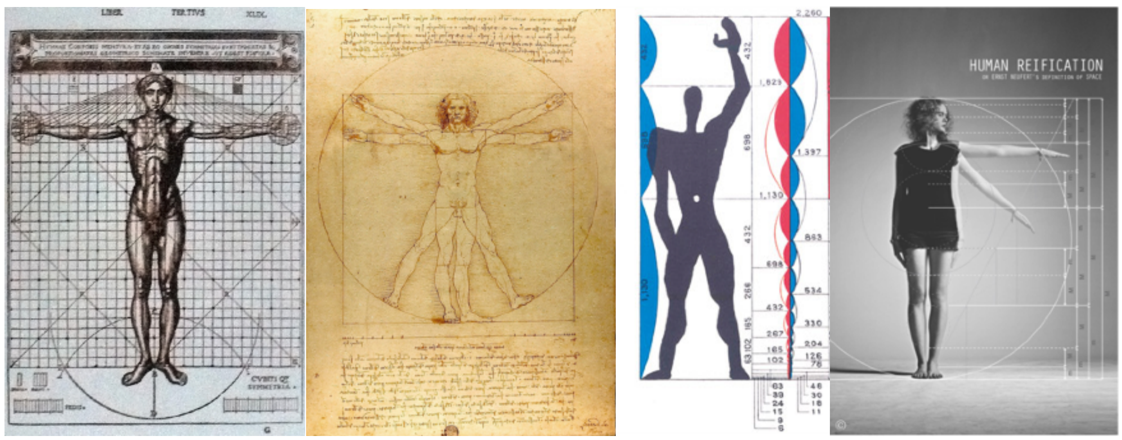

Figure 6.3 Body studies in architecture history. Left: “Vitruvian Man” (15BC), illustration in the edition of De architectura by Vitruvius. Second from Left: Vitruvian Man by Leonardo da Vinci (1490). Second from Right: Le Modulor (1948), Le Corbusier. Right:Arellano, Mónica. "A Photographic Essay on the Reification of Bodies in Neufert's Ergonomics" [Un ensayo fotográfico sobre la cosificación del cuerpo en la ergonomía de Neufert] 09 Jul 2019. ArchDaily. (Trans. Johnson, Maggie) Accessed 5 May 2022. <https://www.archdaily.com/920097/a-photographic-essay-on-the-reification-of-bodies-in-neuferts-ergonomics> ISSN 0719-8884

6.3.1 Body Modification

Body modification is a form of expression. Humans change their bodies for various reasons. One might want to change their identity by dying a different color for their hair; or to tell a story by tattooing a graphic on their skin. Redesigning body architecture is another way of body modification to express an artist's ideas. Oskar Schlemme, a designer and choreographer, transformed the human body into colorful geometries at the Bauhaus theater workshop (Figure 6.4). During the COVID-19 pandemic, body modification was a result of needed social distancing (Figure 6.5).

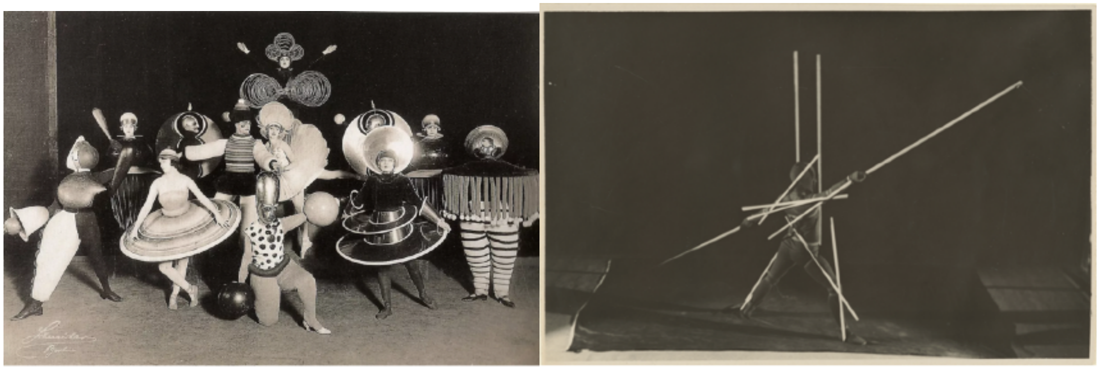

Figure 6.4 Bauhaus body architecture. Left: Oskar Schlemmer. Bauhaus Costumes (1930) (Source: Karl Grill, Courtesy of The Charnel House). Right: Oskar Schlemmer. Stabetanz (Manda v. Kreibig). (1929). (Source: Photograph by T. Lux Feininger. Courtesy of The J. Paul Getty Museum, Los Angeles)

Figure 6.5 Pandemic body architecture. Top left: Wearable rattan cage by Livable's Well-Distance. Top right: Social distancing hats by Veronica Toppino. Middle left: The Beak by Jackson Gaylord. Middle right: A Maryland bar tries out bumper tables. Bottom left: German cafe tells customers to wear pool noodles. Bottom right: Toronto man creates "social distancing machine".

6.3.2 Soft Wearable Machine

Body architecture celebrates the forms, skins, and the dynamic relationships between the body and the space. Wearable machines are wearable devices that integrate with computers, such as smart glasses, smart watches. Artists and designers have also explored body architecture with computers in a fashionable way, such as interactive collar *Iridescence* (2019) by Behnaz Farahi, or as music instruments (Figure 6.6). Soft wearable machines are a type of body architecture that integrates computer power and soft tectonics.

Figure 6.6 Wearable Machines. Left: Instrumented Bodies by Joseph Malloch and Ian Hattwick. Middle: Iridescence (2019), by Behnaz Farahi. Right: Sonifica, designed by MONAD, worn by Viktoria Modesta.
(source: https://www.monadstudio.com/SONIFICA-featuring-Viktoria-Modesta)

6.5 Human-Centered Responsive Architectural Design

6.4.1 Temperature

In a building envelope, human body heat is constantly exchanging energy with the environment (Figure 6.7 Bottom left). In architecture, a temperature responsive building is also called a thermal building. The strategies of designing thermal buildings range from internal system control to outer facade design. The direct impact of the thermal design to the users is the comfortableness of the temperature of the inhabited space.

Negroponte illustrates an integrated environmental control system for the Osaka Kokusai Building, completed in 1973. The hardware is composed of an 8K minicomputer, 131K magnetic drum, and a variety of typewriter and video displays. The system control has sensors and effectors, including temperature sensor, atmospheric pressure, water flow, wind velocity, pumps, fans, heat, fire alarm, hot water supply, electric supply, gas supply, etc. (Negroponte, 1973).

In addition to the HVAC control system, the majority of the heat source of a building gains through the façade. Kinetic façade design has been widely applied in architectural projects. For example, the façade system for Institute du Monde Arabe (Paris, France) in the 1980s by Jean Nouvel (Figure 6.7 Top left), or the responsive façade of Al Bahar Towers (Abu Dhabi, UAE) in 2012 by Aedasl (Figure 6.7 Top middle).

In 2012, I prototyped a window system–Elastic Window–that responds to sunlight during the design process (Figure 6.7 Top right). The design didn't use a kinetic approach, instead, an analysis of the sun's path in the computational model and the use of new building materials were the focus of this project.

With advanced smart materials, designers are able to integrate responsive design into our daily objects. German architect J. Mayer. H. uses thermosensitive dyed textiles to design furniture. The Heat Seat (2001) shows a new way of graphic communication by means of the user's body temperature (Figure 6.7 Bottom right).

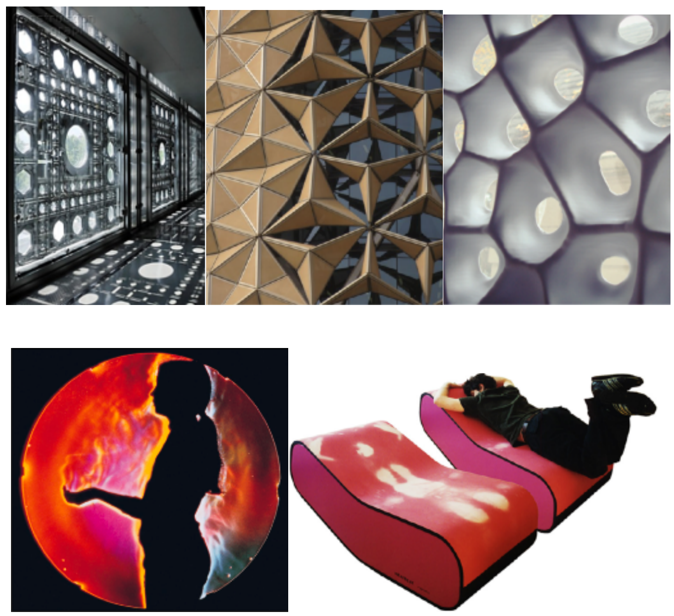

Figure 6.7 Temperature responsive. Top left: Kinetic façade at the Institute du Monde Arabe. (Source: Meagher, 2014). Top middle: The shading devices of Al Bahar Towers, (Source: Photo by Beno Saradzic https://en.wikiarquitectura.com/building/al-bahar-towers/) Top right: Elastic Window (By Author, 2012). Bottom left: Schlieren photograph of the human thermal boundary layer of a teenage girl (Source: Settles, 1997). Bottom right: Heat seat–temperature sensitive object by J. Mayer H, 2001. (Source: http://www.jmayerh.de/47-0-Heat-Seat.html)

6.4.2 Humidity

Like temperature, the humidity of indoor air has been widely recognized as a factor that directly influences the thermal sensation of the human body (Fanger, 1972). For example, we applied cream daily to our skin to preserve moisture. Once the human body temperature exceeds 37 °C, internal heat needs to be released from the body into the environment, via the evaporation of sweat (Scoccimarro et al, 2017). Thanks to nano-technology and micro-scale digital fabrication tools, we can engineer different material properties into a single piece of design work. For example, *HygroScope-Meteorosensitive Morphology*, designed by the IDC lab at the University of Stuttgart, changes its appearance based on the humidity that is measured and controlled in an enclosure glassbox at the *Centre Pompidou* (Figure 6.8 Left). The responsive surface elements close with a decrease of relative humidity, and they open again when the humidity level rises (Menges and Steffen, 2015). Another example, *bioLogic* (2015), developed by the MIT and the Royal College of Art, is a “second skin” that synthetic bio-skin reacts to human body heat and sweat (Figure 6.8 Right). The flaps of the garment prototype open and close enabling sweat to evaporate and cool down the dancer’s body (Yao et al, 2015, Wang et al, 2017).

Figure 6.8 Humidity responsive. Left: HygroScope: Meteorosensitive Morphology, Achim Menges and Steffen Reichert, 2012. (Source:http://www.achimmenges.net/?p=5083). Right: Macroscopic view of the bio- hybrid film that reacts to sweaty skin. (Source: https://tangible.media.mit.edu/project/biologic/).

6.4.3 Visual

The visual effect in responsive architectural design could be the most direct. For example, *One Ocean* (2012) at the Yeosu Harbor in Korea, lets the visitors experience an endless ocean-surface-like kinetic facade, which is made up of 108 fiberglass lamellas that open and close (Figure 6.9 Top left). The actuator of the lamellas is a screw spindle driven by a servo motor controlled by a computer (Sarah, 2012). The Kunsthaus (Figure 6.9 Top middle) mentioned in Chapter 4, executes the visual effect media façade using a computer controlled system with 930 circular fluorescent lamps. The design team realities:united developed a software for users to compose a custom program for the façade (Bullivant, 2005). With the open source software movement, media architectural projects blossomed in the 2000s, such as Moveable Type (Figure 6.9 Bottom) in the lobby of the New York Times Building by Ben Rubin and Mark Hensen, or Roosegaarde studio's interactive landscape Dune (Figure 6.9 Top right).

Figure 6.9 Visual responsive. Top Left: One Ocean, designed by SOMA, Yeosu, South Korea. 2012. (Source: https://www.archdaily.com/236979/one-ocean-thematic-pavilion-expo-2012-soma). Top Middle: Kunsthaus graz's BIX media facade, designed by Colin Fournier, Peter Cook, and realities:united, Graz, Austria, 2003. Top Right: Dune, Daan Roosegaarde, 2007. Bottom: Moveable Type, by Mark Hansen and Ben Rubin, New York City, 2007

6.4.4 Smell

Scent is invisible to human eyes. However, when olfaction occurs, our human sensory input starts to interact with parts of the brain responsible for smell identification, memory, and emotion (Schacter, 2016). Integrating scent is another approach in responsive design for human perceptions. *The Art of Scent* (2012), conceived by Diller Scofidio + Renfro, invites visitors to experience fragrance design. Users lean into the wall alcove and trigger a sensor to release the scented stream of air (Figure 6.10 Left).

Researchers explore the methods of actuating smells through touch. For example, Jyoti Kapur uses impregnation, coating, and printing methods to investigate the application of smell on the textiles. These textiles were designed for interactions such as folding and unfolding, opening and closing, rubbing and pressing in order to activate and release smells (Kapur, 2017). The resulting installations explore olfactive interactions by activating smells through touch and body movement (Figure 6.10 Middle).

Canadian architect Philip Beesley has developed a series of responsive architectural installations in the past few years. *Hylozoism* (Figure 6.10 Right) reacts to the human presence, to the extent that it is capable of "breathing" by filtering chemicals from the environment. The installation consists of tall, plant-like structures made from glass, polymers, and metals that are suspended from the ceiling. Arrays of LED lights flash and ripple with the movements of a viewer, and scent glands emit "musky, ginger-like" odors that, like a flower, lure people in as they draw near.

As Jyoti Kapur observed, smells that are released by body sweat, for example, carry chemosignals; if these chemosignals are incorporated into a design and used as sensors and actuators, adaptive and responsive materials would add to the spatial qualities and experience of such spaces (Kapur, 2017). With the digital scent technology development, the future architectural design will embrace a multi-sensory environment design

Figure 6.10 Olfactory experience. Left: The Art of Scent, Diller Scofidio+Renfro, 2012. Middle: Sight of smell, Jyoti Kapur, 2017. Right: Hylozoic Series: Vesica, Philip Beesley, 2012

6.4.5 Haptics

Haptics actuation might be the most straightforward method for user interaction with architecture. We press a numbered button to choose our destination level in the elevator; we push and pull the handle to open the door. With digital technology, architecture becomes more dynamic and interactive. For example, the *Water Pavilion* (1997), designed by Lars Spuybroek and Kas Oosterhuis, integrates music, visual art, and technology in the space (Figure 6.11 Left). Photocells were used as sensors to detect the presence and motion of the audience in a certain area. Touch sensors are meant to be pushed by the hands; pressure sensors are meant to be stepped on by the feet of the audience. As Spuybroek said, "these sensors would influence the computer generated projections of virtual worlds and surfaces, sound spatialisation and light movements."

In the early 2000, Mark Goulthorpe of dECOi led a project called *Aegis* which features a programmable wall 10 meters wide and 3 meters high (Figure 6.11 Middle). A central computer analyzes the acoustical changes in the environment, and responds to these stimuli by sending signals to each individual piston to produce complex patterns on the wall surface. The wall interacts spatially with people in the environment. Aegis marks the transition from determinate architecture to interactive (indeterminate) architecture (Goulthorpe, 2004).

Ten years later, Random International, a UK studio, used water, injection molded titles, solenoid valves, pressure regulators, software, and 3D tracking cameras to build a room called *Rain Room* (Figure 6.11 Right). This project is not a wall system but a ceiling system. Upon entering the room, visitors are simultaneously exposed to and protected from the water falling all around. Although the sound and smell of the rain are intense, its touch remains absent leaving visitors dry within a continual downpour as they navigate the space (random-internationa.com, 2012). It is worth noting how haptic design could be controlled by switching between a positive (active) and a negative (passive) effect.

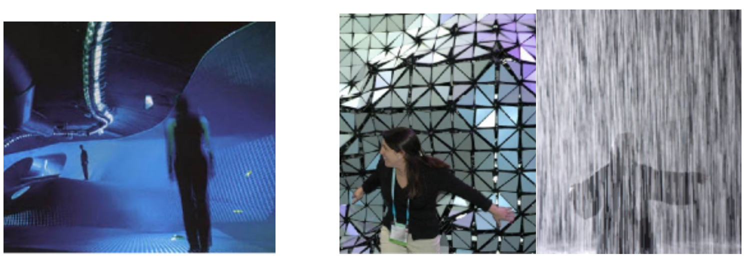

Figure 6.11. Haptics response. Left: Lars Spuybroek of NOX, Water Pavilion (Netherlands) 1997. Middle: Mark Goulthorpe, Aegis, 2003. Right: Rain Room, Random International, 2012

6.4.6 Sound

Lastly, I want to discuss hearing related to responsive architecture. Sound art will not be included here because I prefer to focus on the architecture building environment. *Sound box* (Figure 6.12), designed by Peter Zumthor, is the Swiss Pavilion for the World EXPO Hanover, Germany in 2000. In his book Thinking Architecture (2010), Zumthor said:

> “There is disharmony and broken rhythm, fragments, and clusters of sound, and there is also the purely functional sound that we call noise. Contemporary music works with these elements. Contemporary architecture should be just as radical as contemporary music.”

No high-tech element was used in the pavilion. Not even a single screw, nail, or glue was used in this project. The beams that form the walls are separated and stacked with wood. The walls are connected with tension rods and steel springs. The whole structure only works by compression and friction of the beams each caused by stacking them. Zumthor wants to use this simple architecture to evoke the visitor's senses. “It is a sentiment of feeling.” he said. Visitors can enter the pavilion from any different path they might take. The *Sound Box* is a performance space that is constantly changing by visitors, nature (wind or rain), and the curated music program. The gaps of the wood structure wall allowed the music to resonate throughout the pavilion. Zumthor found a harmonious resonance between building, inhabitant, and the natural world. The architecture responds to the sound harmonically.

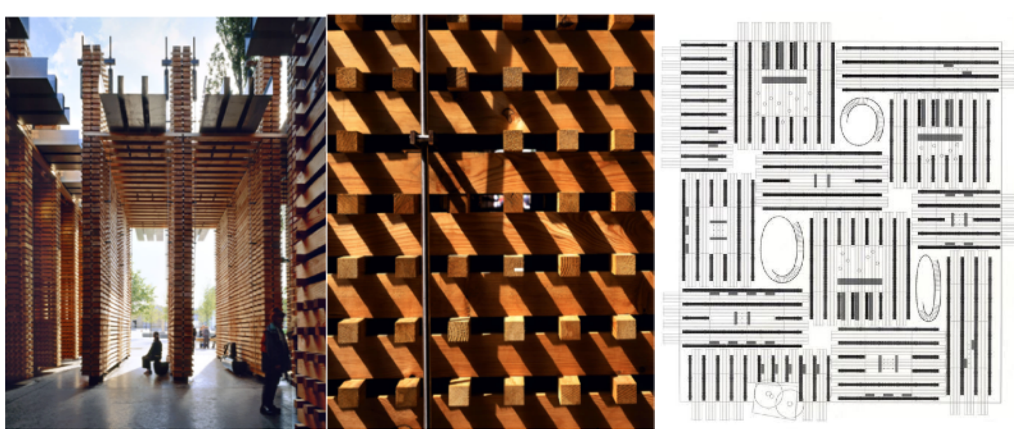

Figure 6.12. Swiss sound box. Peter Zumthor, 2000 (Source: https://en.wikiarquitectura.com/building/swiss-sound-pavilion/)

6.4.7 Emotion

Negroponte once asked “How do we recognize mood?” Designers have been exploring emotion, memory, and psychology factors in responsive architecture with new digital technologies and the internet of things. For example, the *D-tower* (1998), a permanent public art in the city of Doetinchem, Netherlands, shows local residents’ emotions through colors. Designed by artist Q.S. Serafijn and architect Lars Spuybroek/NOX-Architekten, *D-tower* measures the local residents' emotions using online questions on their website.[49] Based on the statistics result, the *D-tower* will turn blue for happiness, red for love, green for hate, or yellow for fear (Figure 6.13 Left). Does D-tower really tell the mood of the inhabitants of the city? Everyone has their own color mood. Only locals could tell.

Los Angeles based artist Behnaz Farahi created a gaze activated 3D printed body architecture called *Caress of the Gaze* (Farahi, 2016). Using vision-based eye-gaze tracking technologies, Farahi explored the interactive system by investigating how our clothing could interact with others. According to her, if one “feels” the gaze of other people, “we develop goose bumps on our skin as a natural involuntary response to the cold or even to emotions such as fear, nostalgia, sexual arousal, and admiration.” With an embedded image sensing camera, the body architecture responds to the onlooker’s gaze by actuating and controlling the shape of the garment. The actuating system is based on facial tracking algorithms that are capable of detecting gender, age, and orientation (Figure 6.13 Middle).

Jenny Sabin, research artist in residence at Microsoft, created a two-story installation in the Microsoft Building 99 called *Ada* (Figure 6.13 Right). It is made of 3D printed nodes,

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[49] www.d-toren.nl

fiberglass rods, and fabric digitally knit with photoluminescent yarn. One of the responsive fibers includes photoluminescent thread, which absorbs energy from UV lights, then later emits the light as knitted light. Microsoft 's AI team translates captured anonymized data of facial expressions into color and light. Ada is a representation of the inhabitants 'emotions at the atrium of Building 99.

Figure 6.13 Emotion related projects. Left: D-tower, designed by Lars Spuybroek/NOX, 1998. Middle: Caress of the Gaze, Behnaz Farahi, 2015. Right: Ada, Jenny Sabin, 2019

Responsive architectural design has a strong interdisciplinary character. Often, the same technology could be used in different contexts and variety scales.

6.6 Soft Tectonics: Soft Actuators Morphological Design

In this research, I explored three actuation methods using silicone, including tip-grow, feather-flip, and pneumatic-cavity.

6.6.1 Tip-grow

Tip-grow is a sandwich-layer fabrication method that is commonly used in soft robotics. The top and bottom layers are silicone. A piece of film or fabric placed in the middle creates a separated space between the two layers of silicone. To ensure the growing direction, one can attach additional strength on the opposite side by using a slightly harder silicone or other supporting materials. For example, the top layer uses Hardness[50] Shore 00 10, and the bottom layer uses Shore 00 30. Figure 6.14 shows the tip-grow actuation.

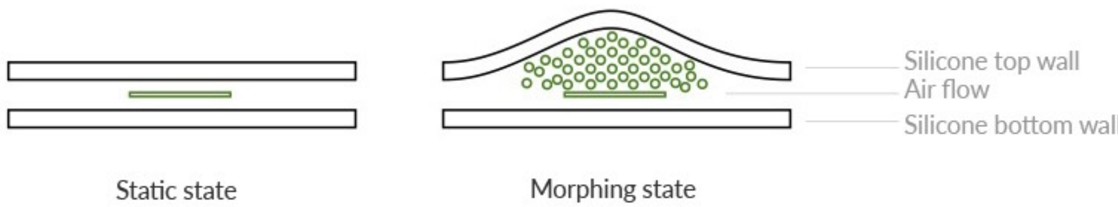

Figure 6.14 Tip-grow actuation. Yin Yu. May 2020.

6.6.2 Feather-flip

Feather-flip applied a similar sandwich-layered fabrication approach (Figure 6.15). The difference is that the actuation combines air pressure and gravity. By folding the actuator, the shape of the "feather" arranges its pattern towards downwards due to gravity. When the air inflates the space, the bottom layer of the silicone layer pushes the central feather body life upwards to flip over the feather.

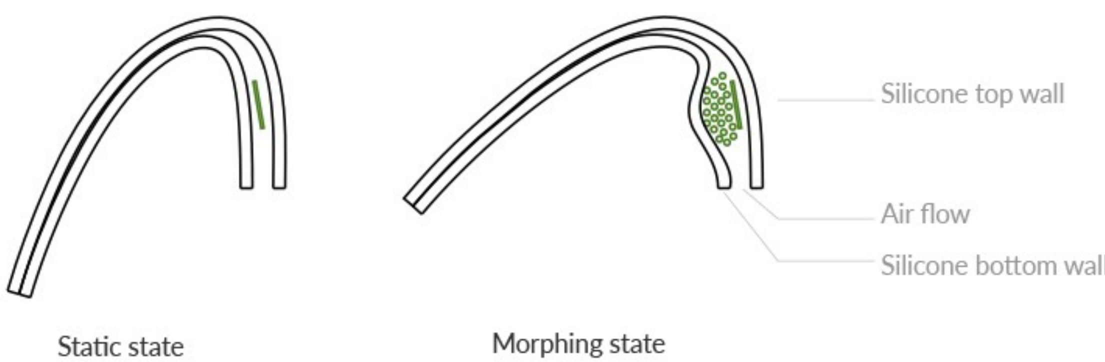

Figure 6.15 Feather-flip actuation. Yin Yu. May 2022

50 https://www.smooth-on.com/page/durometer-shore-hardness-scale/

6.6.3 Pneumatic-cavity

Pneumatic-cavity uses a 3D printed molding fabrication technique. Cnidarians' body forms inspire the mechanism. It contains three parts: exterior wall, internal structure, and interior wall. All of them are made of a single material: silicone. The exterior wall, like a bell, envelops the whole organism. When it is not actuated, the interior wall half hides inside. However, whenever air comes into the main body, the interior wall is pushed out by the air pressure and becomes visible. The internal structure is a key component to keeping the organism back to its original shape. As shown in Figure 6.16, When air pressure is reduced, the internal structure drags the interior wall back to the inside.

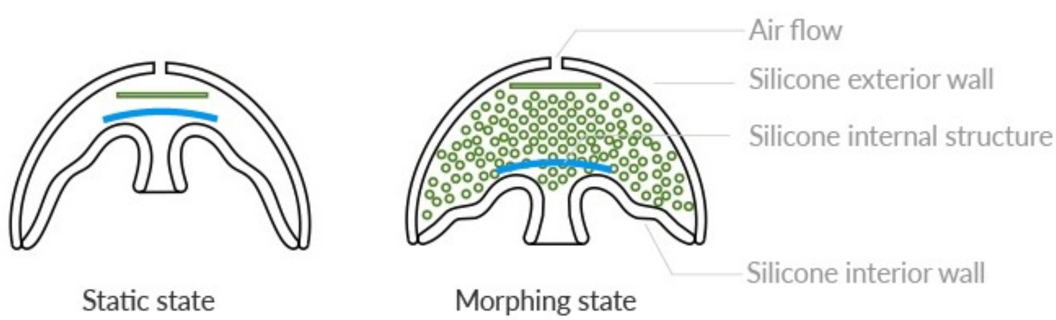

Figure 6.16 Pneumatic-cavity actuation. Yin Yu. May 2022.

6.7 Performances of Soft Tectonics

6.7.1 Tip-grow performance

Inspired by nature, the design of the inflatable module is a biomimicry of pufferfish's skins. A high density of fins attached on the top of each inflatable module. When it is inflating, the silicone layer stretches and the density of the fins is reduced. The fins are blue and the silicone layer is white. During the inflating process, the module transformed visually from a darker blue to a lighter blue. Figure 6.17 shows a single inflatable modular's appearance changing over time from 0° to 83°. The fins are clustered together when the module is at 0° and separated when it is at 83°. When observing it from a distance, we perceive a color and shape change of the module. Figure 6.18 shows the mask in two states: inflate and deflate.

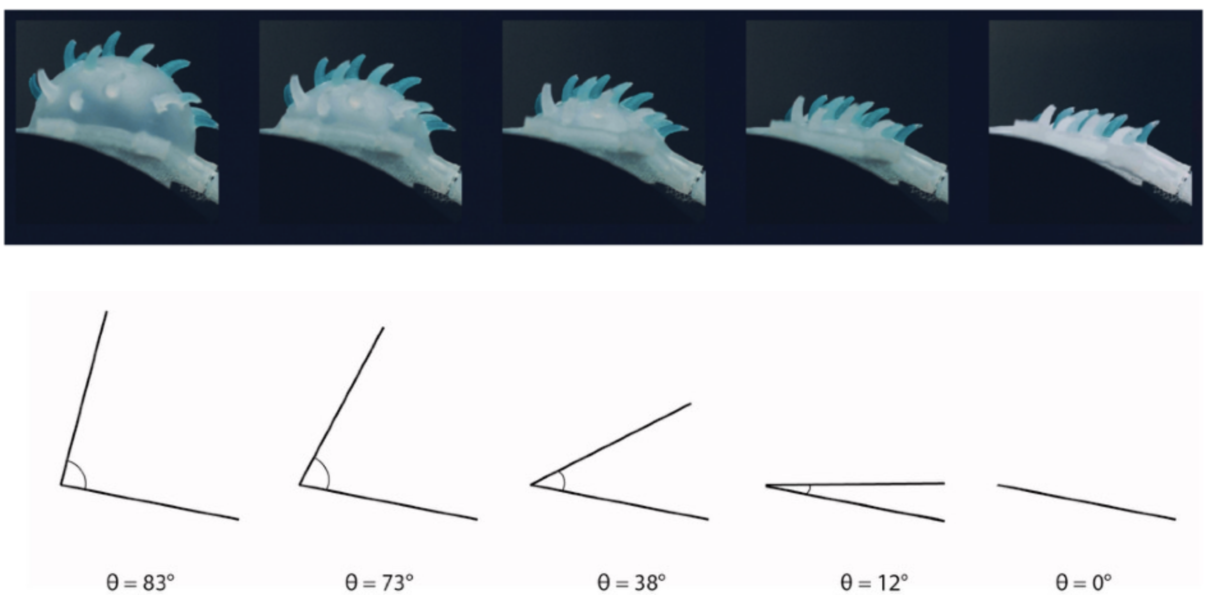

Figure 6.17 Feather-flip demonstration. Yin Yu. May 2022

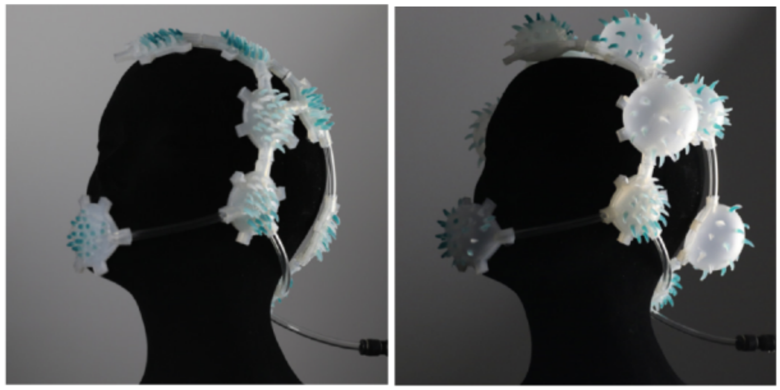

Figure 6.18 airMorphologies. Yin Yu, 2019

6.7.2 Feather-flip performance

The design of feather-flip is a combination of material experiments and bird feather studies. Birds inspired the shape, movement, and color of feather-flip (Figure 6.19). To be more specific, magnificent frigatebird and birds-of-paradise were the two primary references. Fascinated by the red pouches of magnificent frigatebirds, the red color design highlights the inflating area. The red spot is designed as invisible during the static state. When the module is inflated, the size of the red pouch increases. Like the stamen of flowers, the red pouch becomes visible when the wing is open. The wing opens and closes based on the state of the red pouch. During the static state, the red pouch is deflated and the wing is closed due to the gravity. While the red pouch is inflating, the air pressure stresses material at the neck area. The muscle, or the silicone, moves the wing upward to open its arm. Figure 6.20 shows the changes and relationships between the size of the red pouch and the angle of the wing.

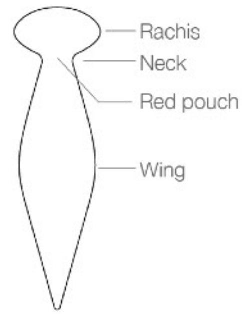

Figure 6.19 Illustration of feather-flip design. Yin Yu. May 2022

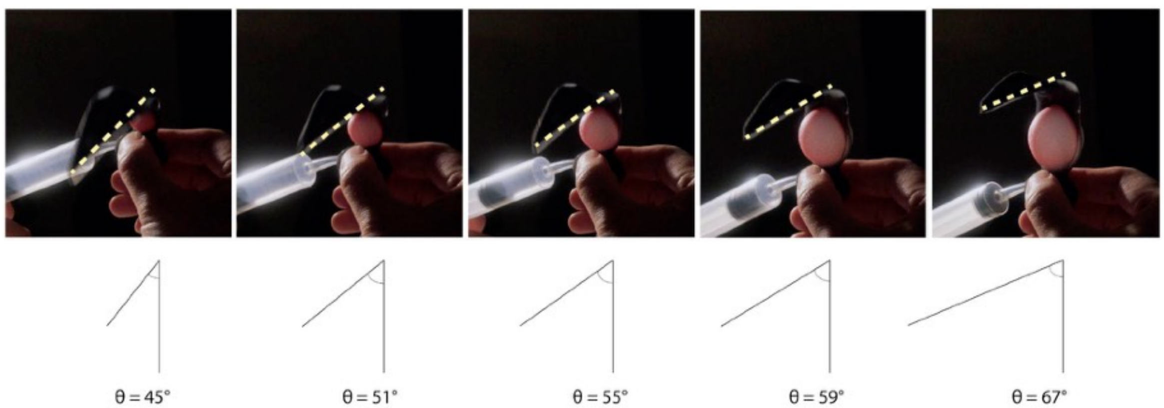

Figure 6.20 Feather-flip demonstration. Yin Yu. May 2022

6.7.3 Pneumatic-cavity performance

The performance of the pneumatic-cavity mimics the movement of deep-sea creatures. Inspired by sea anemone, the soft body of the deep organism moves like capturing prey and feeding itself. The overall performance of the deep organism transforms radically from a smooth blue ball to a pointed yellow-blue sphere (Figure 6.21). A high density of tentacles is attached along the interior wall. The interior wall pushes out when inflating, and the tentacles stretch towards the outside. The longer tentacles slowly unveil the colorful and various patterns of inner tentacles, which enhance the visual effects (Figure 6.22).

Figure 6.21 The overall pneumatic-cavity demonstration. Yin Yu. May 2022

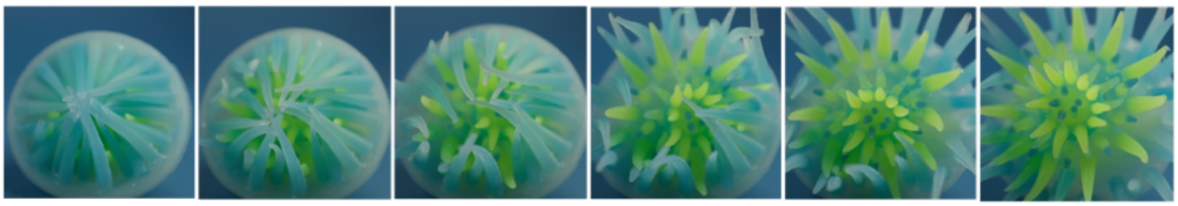

Figure 6.22 The centered-detail pneumatic-cavity demonstration. Yin Yu. May 2022

6.8 SMD System Design

6.8.1 Human Voice to Morphogenesis

In the experiment, *airMorphoglies*, the system uses a voice-activated pneumatic control of the morphologies (Figure 6.23). Two microphones were embodied into the wearable devices to receive the sounds from users. The sounds, captured by the microphones, are input data for the control system. A microcomputer transformed the sound signals into digital signals. In this experiment, the amplitude of the sound triggers the valves' signals to inflate each wearable device. In Figure 6.24, it shows the hardware of the control system on the top left concern. Most of the parts were commercial hobby hardwares, such as an arduino microcomputer, air pump (12v), and solenoid valve (12v). The control system is heavy and noisy.

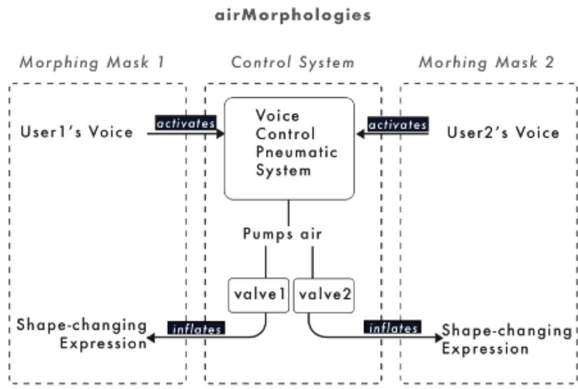

Figure 6.23 The diagram of the control system for airMorphologies. Yin Yu. 2019

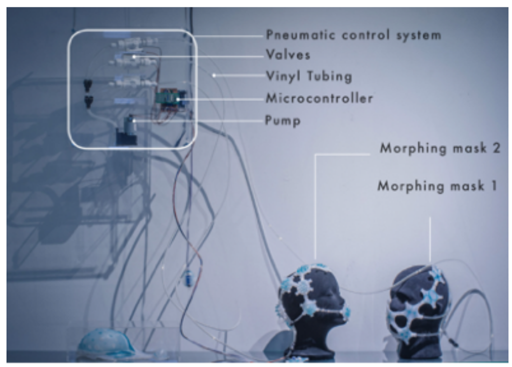

Figure 6.24 Installation of airMorphologies at the Elings Hall. Yin Yu. 2019

6.8.2 Hand Gestures to Morphogenesis

Taking the lessons from *airMorphologies*, smaller pumps (5v) and valves (5v) were used in the next prototypes. *Deep Organism*, as the first prototype of the *Organisms* series (Figure 6.25), has three soft bodies. The system used a machine learning model on the Teachable Machine[51] and a data set of hand gestures. Then, four classes of hand gestures were created. The data input is from a webcam of a computer. Once the input data is classified as one type of hand gesture, the microcomputer will send the signal to inflate one soft organism. If the model is keeping training, a language would slowly develop between human gestures and the

[51] https://teachablemachine.withgoogle.com/

deep organism. Figure 6.26 shows the Deep Organism control system structure. The second prototype of the Organism series is OctoAnemone (Figure 6.26). The project is intended to create a stand alone sculpture rather than interactive through a camera. The data was pre-encoded into the control system. During the exhibition, 15 organisms open and close at a varied speed and time to compose random rhymics.

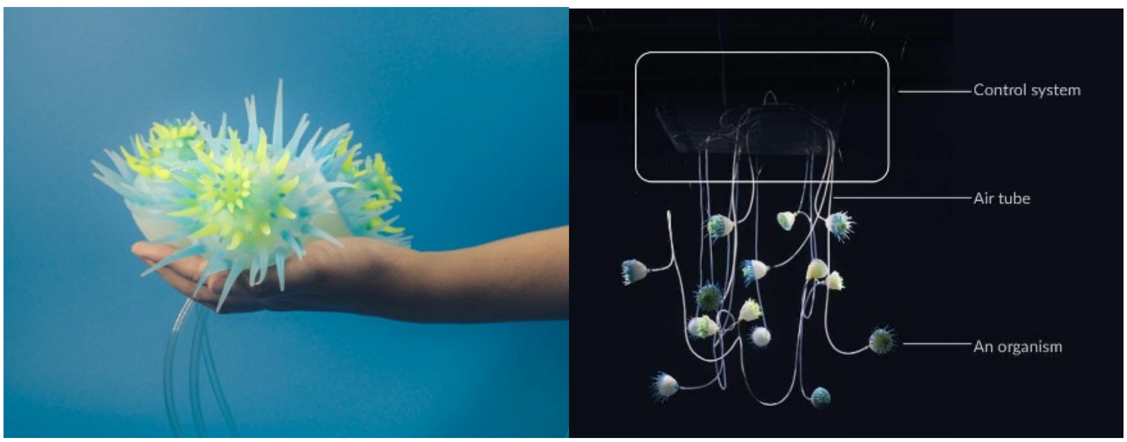

Figure 6.25 Deep Organism. Left: First prototype. Right: Installation of OctoAnemone at the Glass Box Gallery. Yin Yu. 2021

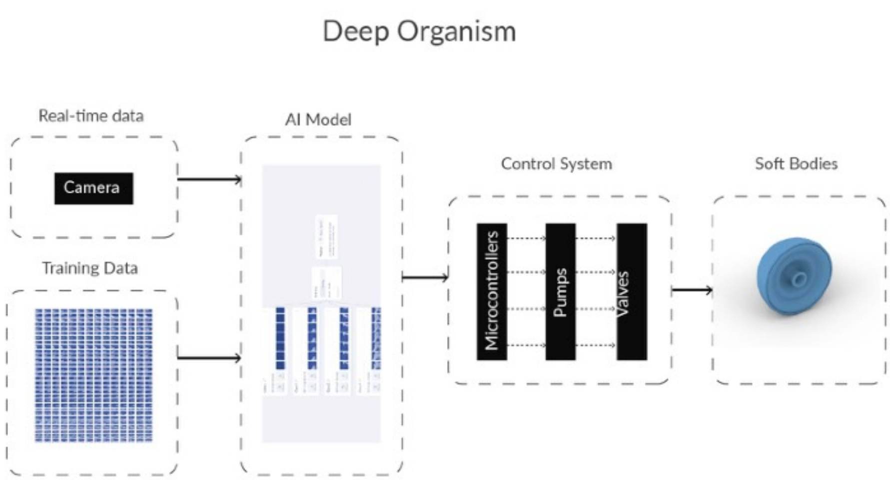

Figure 6.26 The diagram of the control system for Deep Organism. Yin Yu. May 2022

6.8.3 Morphagene to morphogenesis

Figure 6.27 illustrates the system structure of SoftVoss. Due to the COVID-19 pandemic, the research facility is a home-based lab. The sound was recorded in a bread dough-rising bucket of water at the kitchen. I used a hydrophone to record sound materials of water. Four sound materials were selected from 0.3 second to 6 seconds. Then, the sounds transformed by the Morphagene[52] module. I recorded eight samples and selected four (between 1 to 7 minutes). These sound materials later were mixed and arranged in the SoftVoss video documentation. The four water sound materials can be used as the input signal to control the four layers of feathers (blue, green, orange, and red). The first prototype used data randomly.

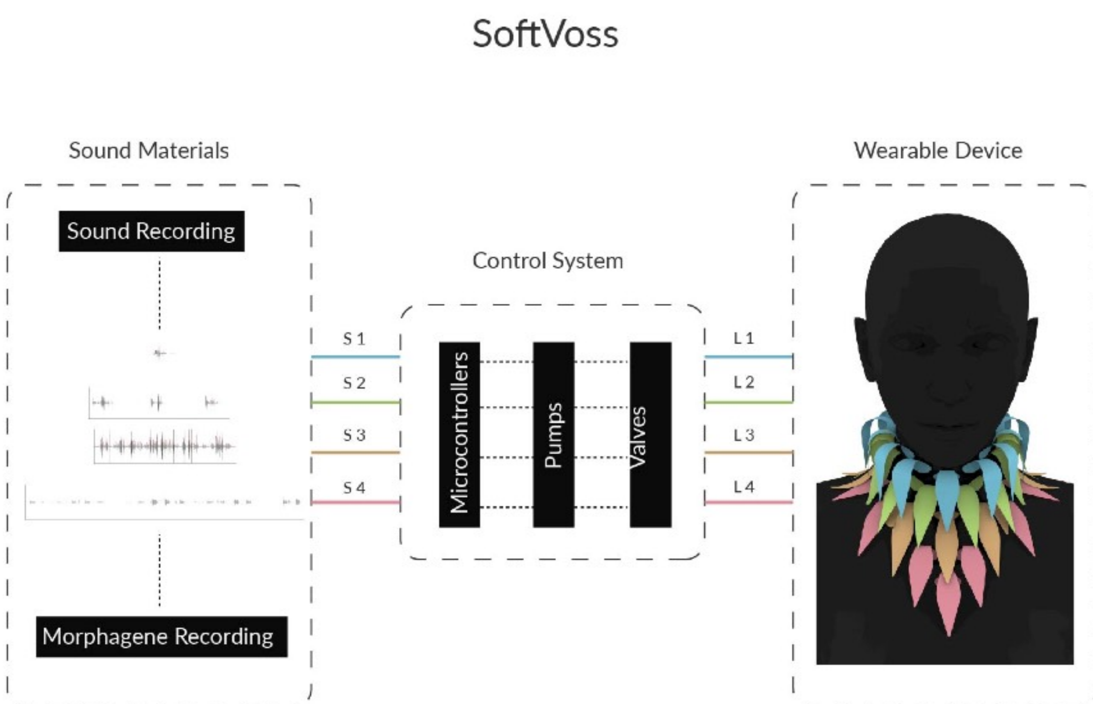

Figure 6.27 System diagram of SoftVoss. Yin Yu. May 2022

52 https://www.makenoisemusic.com/content/manuals/morphagene-manual.pdf

6.9 Summary

Soft Tectonics is an noval design approach that integrates soft material, electronic music, digital technology, and morphogenesis. The chapter presents case studies of human-centered design that utilize digital technology. Then, it demonstrated three design experiments that use soft tectonics for a human-centered design. It introduced three innovative fabrication techniques and control system design. airMorphologies has an expressive visual design and human interaction elements (as shown in the exhibition). It demonstrates the softness of interaction between humans and computers. OctoAnemon shows novel fabrication techniques of soft matter in 3 dimensional. It demonstrates a biomimicry morphogenesis performance. SoftVoss has a unique visual and aural experience (as the video demo), which could enhance the human body as a media of “listening”. Soft Tectonics demonstrates a creative and interdisciplinary approach of sound-based digital computation for architecture practice.

7. The ArMuTe Pedagogical Implementations

My research outcomes have directly informed my teaching. Based on the ArMuTe diagram, new courses were developed for multidisciplinary design research. Over the past four years, I have taught in various departments and initiatives at the University of California, Santa Barbara (UCSB), including the Art Department, the History of Art and Architecture Department, the Media Arts and Technology graduate program, the Creative Computing Initiative, the Summer Research Academies program, and the School for Scientific Thought program. The following are the courses that I taught as an instructor, organized by departments:

Art Department

Art185AI–Machine Learning and the Arts

Art102MM–Mobile Media Art

The Creative Computing Initiative

Art122CD–Computational Design through Responsive Architecture

Summer Research Academies

INT93LS–Morphological Computation–Exploring Wearable Robots for the Post-pandemic Era

INT93LS–Sensing the World–Exploring Wearable Technology through Soft Robotics

INT93LS–Digital Age: Experiencing Architecture and Music Through STEM

School for Scientific Thought (5-weeks short course)

The Art of Quantum Science

Morphology Synthesis: Exploring sensory wearable design computation

Experiencing Digital Architecture and Computer Music through Virtual Reality

7.1 Interdisciplinary College Education

Interdisciplinary subjects start from the course title. I design the course title to reach out to students from diverse disciplines. For example, *Digital Age: Experiencing Architecture and Music Through STEM* (Summer, 2019) attracts students interested in music, architecture, or both. Another course in the Art Department, *Machine Learning and the Arts* (2021), opens to any major. The roster has students from backgrounds in art, film and media studies, physics, philosophy, and social sciences. Lastly, in collaborating with a graduate student instructor from the Department of Electrical & Computer Engineering, we developed a STEM course called: *The Art of Quantum Science.* This course is an excellent example of art and science outreach. By integrating art in both the title and the course content, we built a new pedagogical method of teaching quantum mechanics to a broader student body.

7.2 Creativity

Creativity can be taught. I believe the role of teachers in the 21st century should not be limited to only conveying knowledge and skills. As a mentor, I ensure my students know that everyone possesses the creative potential, and I encourage them to think out of the box. For example, in one of the Machine Learning class group activities, I ask my students to redesign the human body with AI technologies. Each group chooses a different body part. I gave them a checklist, such as new functions, AI technologies, and the design sketches. After 20 minutes, every group comes back with their innovative designs. Students got so excited about this exercise because they are familiar with the human body but never thought about redesigning it. Such exercises help students vision a potential future application. With a design exercise or assignment, we can draw out our student's unique creativity and potential. In Appendix C, I include examples of assignments that reflect my teaching philosophy.

7.3 Research Driven Design Courses

I believe hands-on is an effective approach in teaching. I explore practiced-based teaching methods from three areas: in-class activities, reading assignments, and student projects. To create an engaging lesson, I balance the lecture time with class activity, so that students can apply the knowledge directly to a small exercise during the class time. For example, during the Biomimicry lecture, students use the website asknature.org to search for keywords that are relevant to their projects. After the group breakout time, each group shares their findings and sketch biomimicry design ideas for their project. For the course readings, I selected both theory and practice articles that could give students a solid foundation of the topic and real-life applications. I also prepared some open questions to help students to digest the concepts and share their thoughts during the class discussion. To facilitate student final projects, I designed a couple of individual projects for students to explore their ideas and gain the pursued skill set. I continuously record studio tutorials to explain technical parts in detail. Before the final project, my students have more confidence when working on their projects. For instance, in the Machines Learning and the Arts course, I prepared four labs on the topics of classification, image, sound, and 3D. By the end of four studios, students are comfortable to work on their final art projects using machine learning techniques.

7.2.1 Developing Interdisciplinary Research Questions

For leading students to do research, one key component is to ask a beautiful question. I encourage my students to create their work based on their interests and passions. For example, in my Wearable Robotics class, I prepared a general questionnaire to help students find their research directions. I met with each team and discussed their potential research topics. After the first group meeting, I brought in new examples, current research, and relevant applications to the whole class to discuss and inspire. By the end, we have diverse research topics, spanning from marine exploration to piano playing physical therapy, from hearing protection to a wearable translator.

7.2.2 Developing Research Skills for Undergraduate and Pre-college Education

I have developed a digital version of an inflating mechanism using a parametric design method in my soft robotics class. My students were able to use this method to integrate it into their customized soft robot designs and analyze their performance. Similar pedagogical resources have helped my students learn and expand their interdisciplinary research and design skills. For instance, one method I used in my research is a combination of biomimicry design with wearable technology–this method has impacted my students' interdisciplinary research. In my recent course, Morphological Computation, one group published a research report titled *EarBloom: A Bio-Inspired Intersection of High-Fidelity Hearing Protection and Fashion Technology* in the peer-reviewed Journal of Student Research. The course outcomes have a long-term influence on the student's career. The methods developed during the research process pave the road for future design projects and pedagogical tools. I am revisiting a set of previous teaching materials based on the theory of SMD. With these teaching materials, students can develop their original research projects and turn them into future applications based on the framework and pipeline I structured.

7.4 Summary: Towards a New Pedagogical Framework ArMuTe

My teaching philosophy is a reflection of my interdisciplinary design research framework: ArMuTe. Based on the framework of intersection of Architecture/Music/Technology, I designed college level research courses for students in arts and STEM fields. In the Appendix D, I include three examples of course syllabus schedules. These three courses ranged from a four-weeks research camp, a six-week summer course, to a 11-week quarter system course. Students developed their art works or research projects in a short period of time. As part of the course outcome, some students published their work to the peer-reviewed Journal of Student Research. For example, in my 2021 summer course, *Morphological Computation*, two groups published articles titled: *The Piano Press: A Cable-Actuated Glove for Assistive Piano Playing* and *EarBloom: A BioInspired Intersection of High-Fidelity Hearing Protection and Fashion Technology*. Based on the ArMuTe framework, the student publication increased from one article in the 2020 course to two articles in 2021.

8. Conclusion

This chapter presents a summary of the dissertation contributions and future directions.

8.1 Musicality in Architecture Practice

The distinction between this research with architectural acoustics is the way to treat sound. Architectural acoustics, as a science field, has the function of controlling sound through absorption, cancelation, and diffusion. The science of architectural acoustic is based on the understanding of music before the 20th century. Although technology has developed significantly, the way we see sound is still as a pollutant. This dissertation asks designers and architects to rethink the role of sound in architecture design by introducing the concept of sound morphology from electronic music into the new theoretical framework.

After surveying 26 contemporary projects, we can find musicality in architecture that goes beyond general acoustics and architectural practice. I conducted a music-oriented systematic classification of these projects from two perspectives: design approach and design outcome. For design approaches, I classified ten important music design methods. For design outcomes, I category seven criteria to evaluate musical features in architecture. This analysis provides a thorough understanding of musicality in architecture and will guide the future practice in art, architecture, and design.

In the classification of music as a design approach, there are ten categories: *Architectural Acoustics, Musical Instrument, Pitch, Chromesthesia, Notation, Music Form, Rhythmic, Music Information, Spatialization, and Sociomusicology*. In each class, I provide one or more examples to explain the music approach. Designers could reference this classification to carry out case studies and design projects. This classification benefits designers who do not have a music background but want to integrate music into their design. This classification, as a foundation, establishes music design approaches in our field.

I categorize seven important characteristics to evaluate the musical features in design projects. They are *Visual Musicality, Musical Movement, Aural Experience, Musical Interactivity, Sociomusicology Representation, Energy Perception, and Time*. These criteria provide a foundation of musical aesthetics in architecture. Practitioners could use these criteria to access others' projects or their own designs.

Overall, the classifications of design approaches and outcomes build a framework for a musicality design philosophy for architecture and design practice.

8.2 Theory Contributions: Sound Morphogenesis Design

The field of music in architectural design has been previously studied and practiced by scholars and designers (Holl 2015, Libeskind 2000, Kanach and Xenakis 2008, Zumthor 1996). As a contribution to the field of music in architecture, a new design theory–Sound Morphogenesis Design–is outlined in my dissertation. One of the key findings is the notion of technology as a common language between music and architecture. To be more specific, it is based on information theory, the fundamental communication theory in the digital age. The SMD theory consists of a framework, key concepts, and terminology for the 21st century music related architecture and design practice. It provides a mathematical foundation to understand the theory of SMD with explanations from architecture and music perspectives. New design outcomes would emerge if one design under the umbrella of SMD.

I used the SMD framework to develop three methods of design by music. These methods show the potential applications of such a framework. Two main findings are: (1) mapping strategy is a critical step for a design project; (2) the design process enriched by adding another dimension of design experience—listening. These methods only explored the early stage of the SMD framework.

I also used the SMD approach to carry case studies of Iannis Xenakis's architectural projects. My paper titled *Towards a Morphogenesis: Light in Xenakis's Work* has been accepted by the Xenakis 22: Centenary International Symposium. It proves that SMD could offer researchers new perspectives and novel discovery on music in architectural projects.

8.3 Novel Design Practice

8.3.1 Design Implementations

I used the SMD approach for three types of implementations: digital architecture, wearable designs, and art installations. *Modulating Light* and *Between the points* are digital projects that expand traditional design approaches by inviting designers to listen. As a first hand experience, both projects present to me a new dimension–music–during the 3D design process.

Soft Tectonics is a series of SMD projects that used soft material as a media to explore the morphogenesis of physical prototypes. Three projects have developed and exhibited in local and international venues. They are *airMorphologies, SoftVoss,* and *OctoAnemone*. *airMorphologies* has been published at ACM in 2020, and has been cited by the ACM community in 2021 and 2022, respectively. *SoftVoss* and *OctoAnemone* were shown as a solo exhibition in the Glassbox Gallery at UCSB in Fall 2021. The exhibition was well received. It reached audiences from outside of my own department. For example, an unacquainted student from the art department wrote to me in an email, “The show looks fantastic. I spent a lot of time with the OctoAnemone, congratulations!” A STEM field colleague from the UCSB summer program texted me, “This looks amazing!!!! I can’t believe this moves! Wow!!!! I’m incredibly impressed!!!” The show featured at the UCSB Humanities and Fine Arts’s news website on March 9 2022.[53]

8.3.2 CIMT Analysis

In addition to design theory and methodology, I introduce the CIMT evaluation method (Creative/Impact/Musicality/Technology) for design projects under the SMD umbrella. As an awarding practiced designer, my aesthetics is developed over the years of refinement and self-critics. As I propose the new potential design theory and developed the experiments, I am the best person to access them. I illustrate how to use CIMT to evaluate significant architectural works as well as my experiments. CIMT proved to be a valuable tool for the future SMD design research paradigm.

SWOT (Strengths, Weaknesses, Opportunities, and Threats) is an analysis tool for strategic planning and management in business school. Inspired by SWOT analysis, I assessed four critical components to examine design works under the framework of SMD. They are: Creativity, Impact, Musicality, and Technology (CIMT). The CIMT diagram (Figure 8.1) is an evaluation and principles of SMD. Each component has two criteria and a

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[53] https://www.hfa.ucsb.edu/news-entries/2022/3/8/soft-tectonics-brings-graduate-research-projects-together

total of eight criteria to assess a design. A project will be evaluated from *Size 1* to *Size 3* in each criterion.

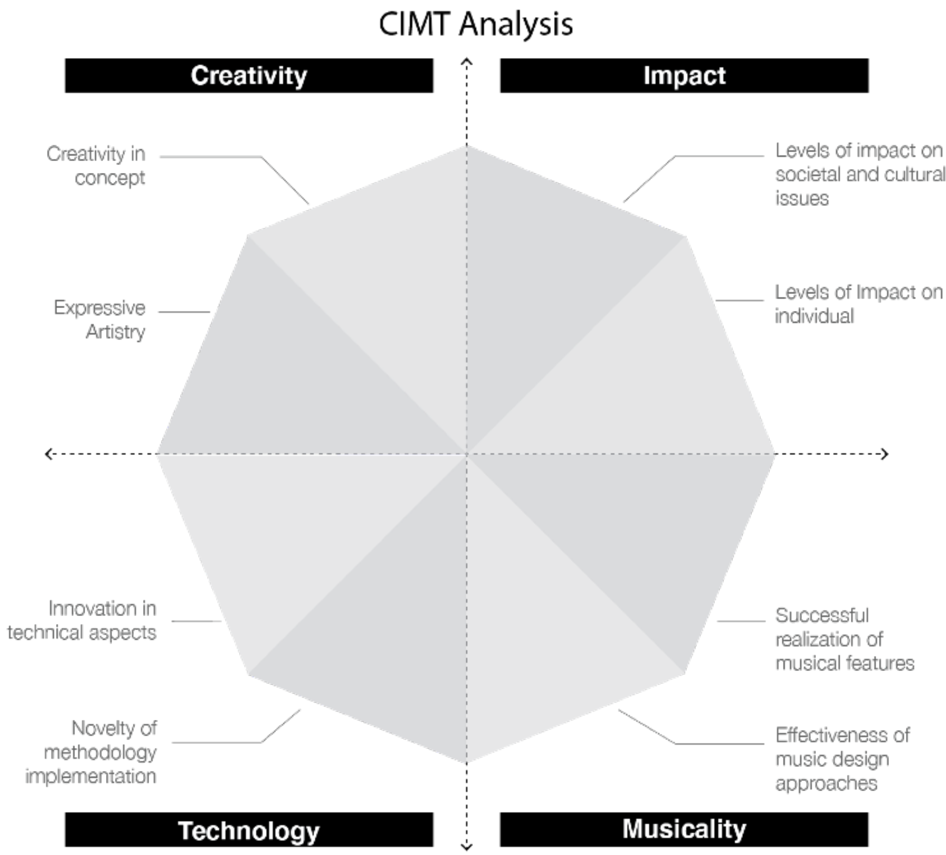

Figure 8.1 CIMT Analysis: An Evaluation and Principles of SMD. Yin Yu. May 2022.

Figure 8.2 demonstrates an example of using CIMT to evaluate the significant SMD project-the Philips Pavilion. For the creativity in the concept, Philip Pavilion has size three because it is a unique idea of translating a sound morphology as the architectural *parti*. The creativity of the expressive artistry also has size three because the architectural form of the Philips Pavilion is an iconic piece of architecture. From a social and cultural perspective, Philips Pavilion has size three due to its importance in the history of multimedia work, and it continues to impact architecture and the music community. Visitors experienced a pioneer visual and aural experience for the impact on individuals. However, it is hard to know how much impact it had on each individual. I put it as size three based on such a historical event. For the musicality, the architectural form of the Philips Pavilion successfully represents three dimensions of the glissando movement. It has size three for its musical feature. However, for the effectiveness of music design approaches, since computers were not used in this project, there is no way to translate sound and music information directly to the architectural design. The project was mainly based on drawing and structure calculations, which is less effective. And finally, for the technology, Philip Pavilion has a novel construction method: use concrete to build the hyperbolic paraboloid shell structure. It has size three in the novelty of its technical implementation. For the innovation in technical aspects, the primary approach was based on a traditional physical model, a small-scale prototype, and drawing and structure calculation. The innovation of lightweight concrete panels can make the project size two for the innovation in the technical aspects.

Based on CIMT analysis, I evaluated three Soft Tectonics experiments. In *airMorphologies* (Figure 8.3), the musicality has size 1 because the sound and music feature is based on the user's voice as sound information. There is no musical feature yet. In technology, the novelty of the implementation has size two because the fabrication method expands the existing soft robotic fabrication technique. It integrated a layer of fins and used a modular approach for air control and assembling. Thus, the impact on individuals has size three. During the EoYS, I demo airMorphologies to visitors. Once the system is activated, the audience immediately touches their skin. The reaction is because I explain the project's motivation and tell them the device could be our human second skin.

OctoAnemone (Figure 8.4), as an ongoing project, is evaluated based on the version shown in the Glassbox gallery. In this project, the individual impact has size three because of its unique morphological movements, which have a strong visual expression.The gallery version did not include the sound system, and the installation was limited to three microcontrollers. I assign a different frequency for each microcontroller. The result was surprising. Because each organism opens and closes at a different speed and time, the rhythm of the work evolved. For this silence composition, the musicality has size two in this project.

In *SoftVoss* (Figure 8.5), the creativity in ideas has size two because of the translation of electronic water sounds to an artificial skin. In addition, the concept is not merely skin. It is bird-feather-like skin. For the impact, the video's unique visual and aural experience could influence artists and designers. This project's musicality has size three because of the resonation between architecture and music. For the technology, I integrated gravity with the actuator. Michelle Addington, the author of *Smart Materials and Technologies*, comments on this actuation approach as a novel implementation.

With the three project assessments (Figure 8.6), I identify that innovation in technical aspects could be a breakthrough in the future SMD paradigm. Perhaps a new fabrication tool integrating sound morphology and material morphogenesis would embrace a new era of digital design.

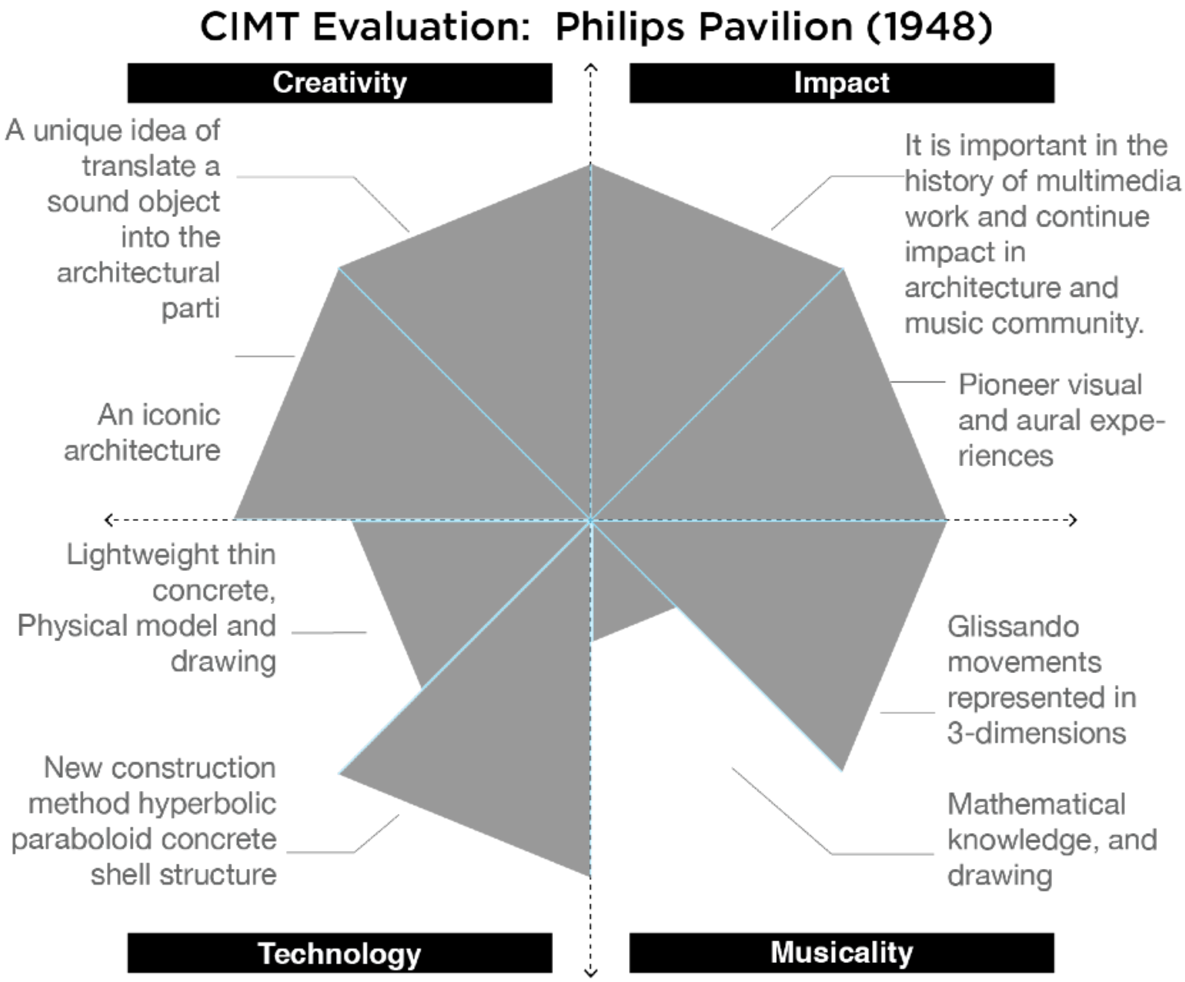

Figure 8.2 CIMT Analysis: An Evaluation of the Philips Pavilion. Yin Yu. May 2022

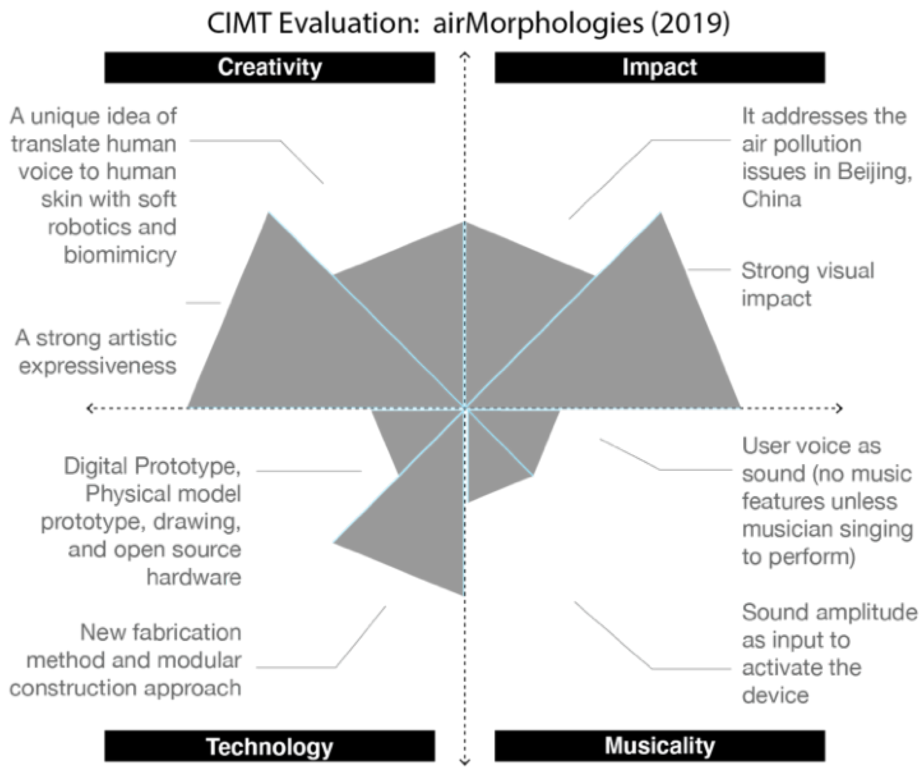

Figure 8.3 CIMT Analysis: An Evaluation of airMorphologies. Yin Yu. May 2022

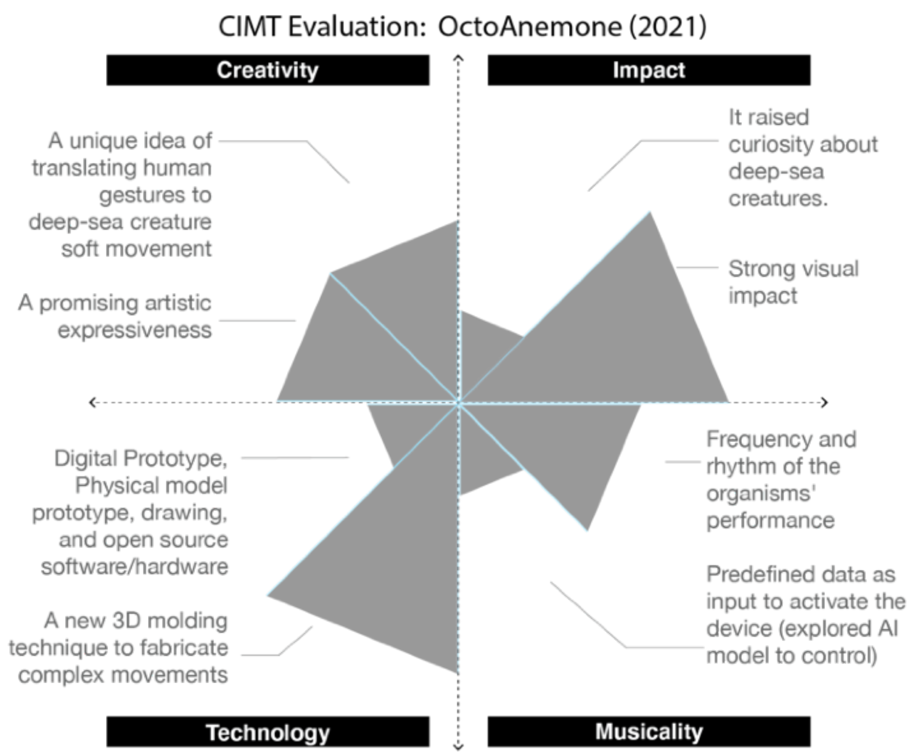

Figure 8.4 CIMT Analysis: An Evaluation of OctoAnemone. Yin Yu. May 2022

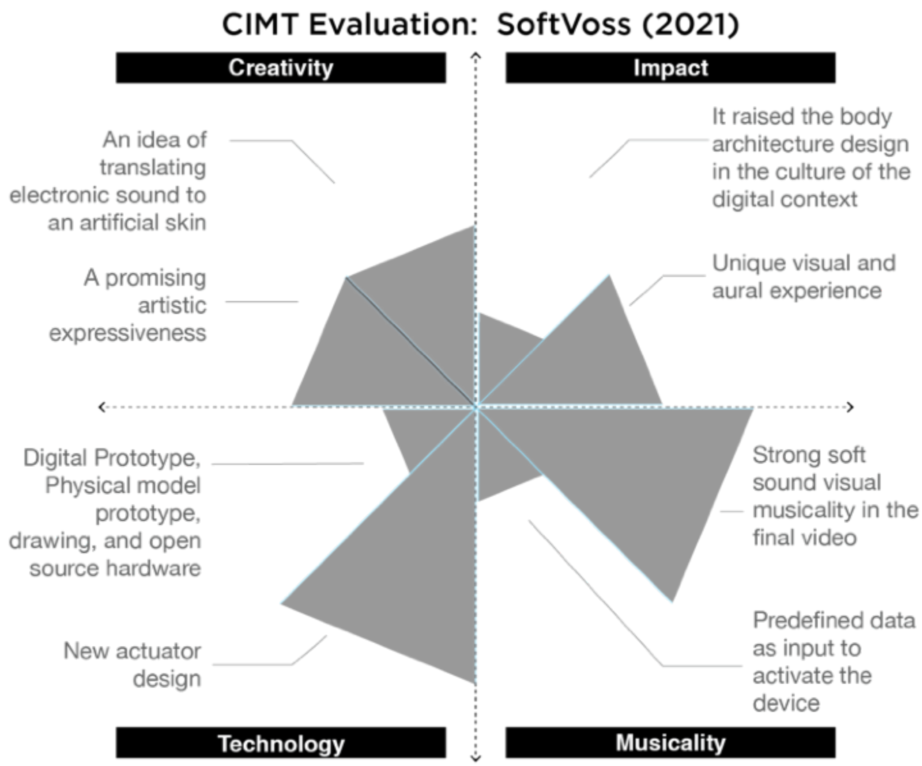

Figure 8.5 CIMT Analysis: An Evaluation of SoftVoss. Yin Yu. May 2022

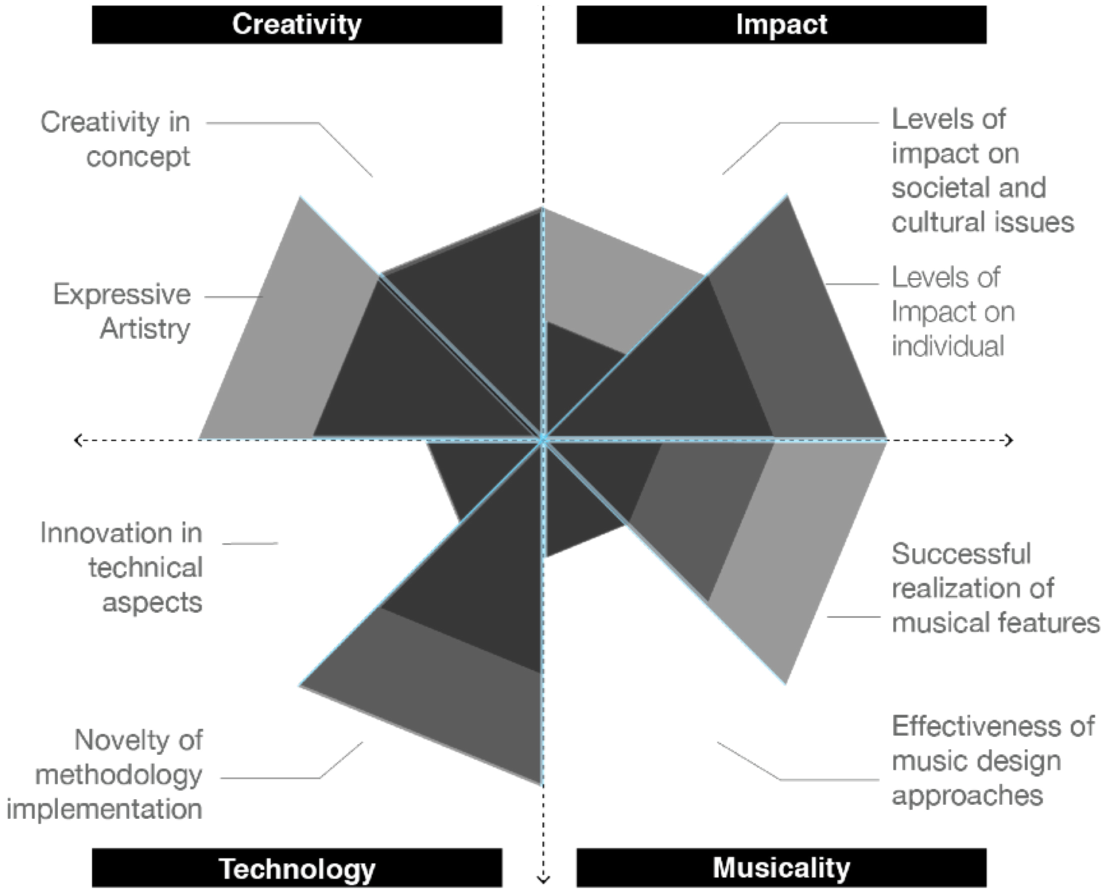

Figure 8.6 CIMT Analysis: Overlapping three evaluations. Yin Yu. May 2022

8.5 Pedagogical Implementations

The ArMuTe diagram in Chapter 7 proposed an interdisciplinary college education framework, focusing on design research pedagogical approaches. I designed and taught five courses using the ArMuTe framework by providing students with hands-on activities opportunities, various research methodologies, and guidance on student-initiated projects. The course outcomes include artworks, architecture designs, product designs, and research papers. These courses helped students to continue their design and research careers. For example, one of my undergraduate students from UCSB was recently admitted to the graduate program in *Integrated Innovation for Products and Services* at Carnegie Mellon

University. Some of my students' research papers were published in the peer-reviewed Journal of Student Research. For example, *The Piano Press: A Cable-Actuated Glove for Assistive Piano Playing* and *EarBloom: A Bio-Inspired Intersection of High-Fidelity Hearing Protection and Fashion Technology.* The paper acceptance rate increased 100% from one paper in 2020 to two papers in 2021. The ArMuTe pedagogy empowers future generations of interdisciplinary designers and researchers.

8.6 The Current Limitation

In this research, one of the main challenges was using technology and soft liquid materials simultaneously. Thanks to the ECL[54] lab at MAT, I had access to a hobby desktop 3D printer to continue my experiments during the pandemic, where many activities switched to a remote modality. However, to fabricate a soft material, such as silicone, would require a 3D printer to have functions that allows two-part platinum to cure. A few institutions have prototyped such additive manufacturing technology, for example, the Oregon State University (Yirmibesoglu et al., 2018). To develop a smooth digital fabrication of soft material would enhance the design process and create more possibilities.

From an architectural perspective, the experiments in this research were fabricated at relatively small scales. New design challenges will emerge when we enlarge the scale of the experiments. When I showed my *OctoAnemone* at the Glassbox Gallery, Roads asked me how large each organism could be? My answer was it can be bigger, but are currently limited by the tools at our disposal and must find new design solutions for larger scales.

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[54] Expressive Computation Lab https://ecl.mat.ucsb.edu/

Software issues also challenged the design process, such as the limitation of cross-platform communication. Systems compatibility also discouraged some ideas during the research. Currently, SMD has only been implemented on my personal computer. Future software and digital platform development would allow designers and users to test and examine the framework on multiple operating systems and platforms.

8.7 Future Directions

8.7.1 Questions on SMD

SMD as a new design theory requires time to explore and experiment. The design outcomes in this dissertation demonstrated the early stage SMD implementations. Silicone as a soft material shows a great potential of soft machine designs. What would be the priority morphogenesis we are looking for? What music information would be more meaningful to extract in the design process? How to integrate sound information in real-time or different time scales into the fabrication process? And what soft tectonics applications can extend to other research fields?

8.7.2 Questions on Architectural Acoustics

Much work remains in rethinking existing architectural acoustics paradigms when bringing the electronic music domain and MIR applications. How to design a dynamic acoustic interior environment? What would be the best practice MIR model for site specific acoustic installation? How can we bring architectural acoustics back to our creative practice?

8.7.2 Questions on Human-Centered Design

In interior architecture, our practice on human-centered design is mainly based on tasks. How can we better integrate the SMD approach into our exciting practice? What are the music features that we overlook previously or miss treated in human-centered design?

8.8 Summary

Figure 8.7 is the time and frequency domain representations of the ancient universe sound that was "heard" by the Planck space telescope (Jet Propulsion Laboratory, 2013). Music and architecture, the art form of time and space, are bounded. The present dissertation attempts to pavel a path to cross these two fields for future discovery, design, and human perceptions.

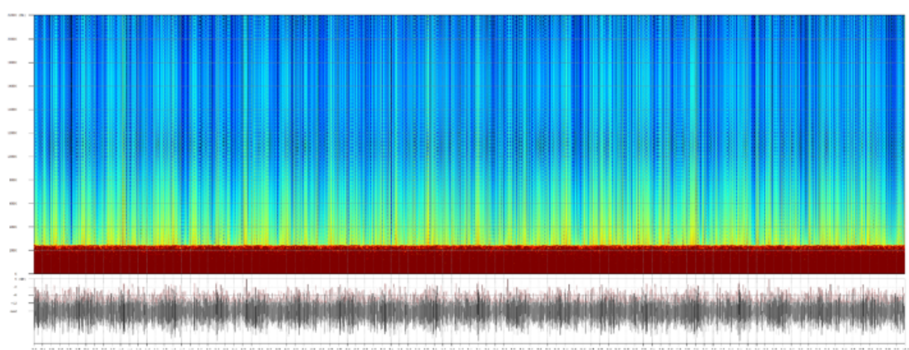

Figure 8.7. The wave and the spectrogram of sounds of ancient universe (Image by Yin Yu April 2022, sound source: https://www.jpl.nasa.gov/images/pia16881-sounds-of-the-ancient-universe)

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Appendix

A. Sound Examples

The sound files of the dissertation are organized on this address:

https://yinyudesign.com/sounds-sample-smd

B. Ph.D. Timeline

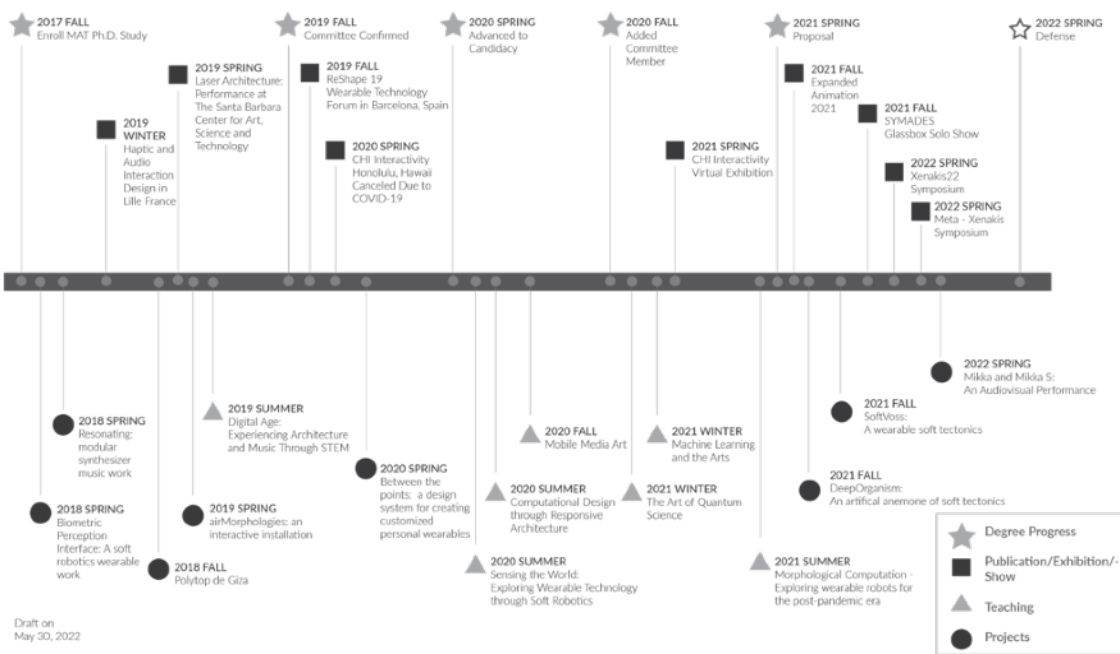

Figure B.1 Ph.D. timeline Yin Yu. May 2022.

C. Course Assignments

Art185AI Assignment 1: Classification

Due Tuesday, January 19th at 11 am on the Gauchospace

In machine learning, classification refers to a predictive modeling problem where a class label is predicted for a given example of input data. For example, given a handwritten character, the machine classifies it as one of the known characters.

From a modeling perspective, classification requires a training dataset with many examples of inputs and outputs from which to learn. A model will use the training dataset and will calculate how to best map examples of input data to specific class labels. As such, the training dataset must be sufficiently representative of the problem and have many examples of each class label.

Using Studio 1 as a starting point, create an artwork or a creative application with p5.js. Your model needs to have at least 5 classes.

Requirements

A Work title;

Have a concept/theme/topic;

Code running without errors;

Demonstrated research and effort;

Sources properly credited.

Be creative.

Format

-Submit a 1-3 minute video file of your work demo.

Name the file “yourname_worktitle.mp4”.

-Submit a .zip file of your p5.js sketch, including the xx.ttml, xx.css, xx.js, and other assets files. Name the file “yourname_worktitle.zip”.

-Prepare 2~3 minutes to talk about your process, inspiration, concept, challenge, and the result.

Grading Criteria

1. Follow instructions - 10 points;

2. Concept - 10 points;

2. Research - 10 points;

3. The effort of the work - 40 points;

4. Creativity - 30 points.

Art185AI Assignment 2: styleGAN Experiment

Due Tuesday, January 26th at 11 am on Gauchospace

GAN learns to generate entirely new images that mimic the appearance of real photos. However, they offer very limited control over the generated output. In December 2018, researchers at NVIDIA introduced a novel generative adversarial network called StyleGAN.

Using Studio 2 as a starting point, create your own dataset. Your dataset should have a theme. Train your model with Runway, write a report about your process, and discuss the result.

Report Requirements

Work title;

Write a short paragraph about your work (50 ~200 words);

Include two screenshots of your dataset;

Quote your sources and references.

Format

-Submit the video file of your trained model. Name the file “yourname_worktitle.mp4”.

-Submit the report. Name the file “yourname_worktitle.pdf”.

-Prepare 1~2 minutes to talk about your process, inspiration, concept, challenge, the result, and further plan (if any).

Grading Criteria

1. Meet the requirements - 10 points;

2. Concept/idea - 10 points;

3. The quality of the data collection- 50 points;

4. Written report - 30 points.

Art185AI Assignment 3 WaveNet Experiment: AI Philosophers

Due Tuesday, February 2nd at 11 am on Gauchospace

Imagine you meet your favorite philosopher in person today, and you ask them: “What would be (your choice of the philosopher)‘s opinion on AI and the future of humanity?” For example, What would be Simone de Beauvoir’s opinion on AI and the future of humanity?

Write down their answer. The answer should be about 50 - 200 words (around 30 seconds to 2 minutes). You might use their original quotes or generate the content yourself.

Create a 30 seconds to 2 minutes short film on what philosophers say about AI and humanity? Referencing studio 3, create the input mp4 file from your choice of philosopher’s photo or video, and transfer your answer to a wav file. Write a short report about your art work.

Requirements

Work title;

A short paragraph about your art work;

The script of the answer;

Quote your image sources and references.

Format

-Submit the video file. Name the file "yourname_worktitle.mp4".

-Submit the report. Name the file "yourname_worktitle.pdf".

-Next session, be prepared to talk about your process (1~2 minutes), inspiration, concept, challenge, the result, and further plan (if any).

Grading Criteria

1. Meeting requirements - 10 points;

2. Concept/idea - 10 points;

3. Research - 10 points;

4. Video quality 30 points;

5. Written report - 20 points.

6. Creativity - 20 points

Art185AI Assignment 4: ML x 3D Experiment: Embodied AI Sculpture

Due Tuesday, February 9th at 11 am on Gauchospace

An AI research organization commissions you to do a public sculpture! There is no budget limit. It can be indoor or outdoor at any scale with any material you propose. Your sculpture could be a temporal art installation or a permanent art piece. The commissioner has two requirements. One, the artist needs to use AI and machine learning technologies in their works; and two, the artist should provide a digital 3D file so a team of local builders could construct the sculpture.

You, as the artist, will need to come up with a theme. For example, the work can be a memorial for Dr. Li Wenliang, who was one of the whistle-blowers dedicating his young life in the front lines during the early COVID-19 period in Wuhan. It can be a temporary installation for Valentine's Day at NYC Times Square. It also could be a sculpture at your favorite museum, for instance, the sculpture park at the Louisiana Museum of Modern Art in Humlebaek, Denmark. Or, it might be a celebration of AI technology and art at the MIT Museum, and so on. You are welcome to choose a site that you are familiar with or meaningful to you, such as the UCSB campus, or your hometown. Your site can be in the city, in nature, or even on the moon (robots will construct it).

Present your work in a digital format. You might export the sculpture as an image to place it (using photoshop or another image editing tool) into the context; you might also make a short video to illustrate the idea.

Format

-Submit a digital representation of the sculpture as either an image or a video file. Name the file “yourname_worktitle.mp4”, or “yourname_worktitle.jpg”.

-Submit the report. Name the file “yourname_worktitle.pdf”.

-Submit the .obj file of your art piece. Name the file “yourname_worktitle.obj”. (You might also turn in your Rhino (.3dm) and Grasshopper (.gh) files)

- In the next session, be prepared to talk about your process (1~2 minutes), inspiration, concept, challenge, the result, and further plans (if any).

Report Requirements

Work title;

A concept statement (the theme of the work);

Artwork information, such as the location, the size, the training data, technologies, and so on;

Quote your image sources and references.

Grading Criteria

1. Meeting requirements - 10 points;
2. Concept/idea - 20 points;
3. The quality of the digital representation - 30 points;
4. Written report - 20 points;
5. Creativity - 20 points.

ART185AI Final Project: 2071

Total Points (30%)

Part I: Proposal and Prototype (5%)

Part II: Final Project (15%)

Part III: Presentation and Online Exhibition (10%)

Timeline

February 11th: Final Project assigned

February 23rd: First Proposal and Prototype

March 11th: Final Presentation and Online Exhibition

Description

Today is March 11th, 2071, the 50th anniversary of a vast wave of machine learning artworks. In 2021, a group of students at UCSB used AI technologies to explore their creative endeavors. They asked themselves, what were the emerging possibilities of AI in art? What was the function of AI? What was the current form of the new media arts?

The year 2020 was an unprecedented period of time in human history. Our species faced a myriad of universal issues, such as a global pandemic, social unrest, economic impacts, political tensions, and climate change. It was the right moment to ask questions. And more importantly, it was a critical moment for young individuals, to start THINKING about the future of AI Arts and the overall role of technology as it shaped our society.

Part I: Proposal and Prototype (5%)

Due Tuesday, February 23rd, on Gauchopsace at 11:00 am

Sometimes, questions are more important than answers. In the first half of the quarter, we explored the potentials of current AI technologies and their creative applications in web browsers, images, sounds, and objects. Before we dive into the final project, we need to THINK about THINKING. Now, it is time to ask ourselves the question about AI and the future of humanity.

Start your proposal with a question you want to ask now. You might come up with your own question or use a sample question to construct a more specific one. Below, please find some sample general questions. Your artwork will be the answer to your question or an interpretation of the question. The prototype is a work in progress that reflects your initial idea and research.

Use readings, the essay assignment, artworks, articles, and library research to draft your question and concept statement.

Use our previous studios as a technical resource. You might want to dig deeper into one method or combine two or three methods together. You could also research, develop, or use technologies we did not cover in our studios.

Sample Questions

Can machines think creatively?

What is the future of AI arts?

What are the new possibilities for the arts?

What is the function of AI arts?

What is the form of AI arts?

What is the nature of AI arts?

What kind of art would be impossible to accomplish without AI?

How to archive an AI artwork? Is there a way to secure access and digital preservation?

How to make AI Arts unique? Rather than an endless repetition of a certain style or 'look'.

Format

-Submit a proposal. Name the file "yourname_proposetitle.pdf".

-Be prepared to talk about your proposal, inspiration, concept, work in progress, current challenge, and timeline (plan for the next two weeks).

Requirements

Work title;

Your question;

Concept statement;

Prototypes (it can be images, links to videos, screenshots of 3D models, links to audio files, website demos, or a mixed-media format).

Researches (resources/references/inspiraitons/code/tools/technologies)

Grading Criteria

1. Concept/idea - 10 points;

2. The question - 20 points;

3. Research depth - 20 points;

4. Prototype quality - 50 points;

Part II: Final Project (15%)

Due Thursday March 11th ~ March 16th, on Gauchospace at 11:00 am

Format

-Submit the digital file of your artwork. Name the file "yourname_worktitle.zip"

Requirements

Revised work title;

Revised description of the work;

Updated resources;

The final version of your art piece(s).

Optional: An architectural diagram of the project's data flow

Grading Criteria

1. Artistic impression - 20 points;

2. Idea implementation and execution - 20 points;

3. Written text (title, artist statement, work description) - 20 points;

4. Technical complexity - 20 points;

5. Creativity / innovation - 20 points.

Part III: Final Presentation and Online Exhibition (10%)

Due Thursday, March 11th, on the Course website at 11:00 am

Location

Zoom + Online Gallery (https://class.arts.ucsb.edu/art185/Sites/w21/)

Presentation Format

We will review final projects through presentations over zoom. Each student will have 7~8 minutes to present with 2~3 minutes for questions/ discussion per person. Presentations should cover the concept, idea, your approach, challenges you encountered along the way, final result, and plans (if any) for a future extension. Each person will have the opportunity to present their final work in a format of their choosing. Any presentation format you select is acceptable as long as you constrain your presentation within the required time and cover these elements. You may choose to simply present your work via screen sharing. If your internet connection is unreliable, a pre-recorded presentation is acceptable (please email the instructor in advance). We will conduct the reviews in 2 sets of 6 and 7 presentations with a 10-minute break in between. The goal of these reviews is to share your work with one another and celebrate powering through the winter quarter.

Online Exhibition Format

Work title;

Artist name;

Digital documentation of the artwork;

Artwork text;

If it is an interactive art piece, please include a link to the live demo.

Grading Criteria

1. On zoom, the presentation was clearly articulated and well structured- 20 points;

2. On zoom, questions were answered thoughtfully during the Q&A- 10 points;

3. On zoom, the presentation did not go beyond the allotted time - 10 points;

4. On the class server, all files and folders were well organized 10 points;

5. On the class website, the artwork was well presented - 50 points.

INT93LS Assignment 1 Precedent Study and Digital Reconstruction

Due Tuesday, July 6th at 9:30 am on Gauchospace

Introduction

In the first week, we learned the basic concepts of soft robotics. During the lab and discussion, we also learned hands-on skills related to wearable design and 3D modeling techniques. This assignment will bridge the skills and knowledge that we have learned, and ask you to create digital work.

Objective

To be able to use the skills developed in the first week to carry out a research case study and build a digital wearable device.

Assignment

Choose a case study from Appendix (page 3-11) and Sign up here. If you want to work on a research project that is not on the list, please confirm with the instructor. Do a case study to understand the project. Reconstruct the work in 3D software.

Format

1. Submit a PDF file of your research. Name the file "yourname_assignment_1.pdf". See below the checklist.
2. Submit the 3D model file. Name the file "yourname_projectname.3dm" and/or "yourname_projectname.gh" if you use Rhino.
3. Submit one rendering image of the 3D model. Name the file "yourname_projectname.jpeg (png)".
4. Prepare 3 minutes presentation slides to show your research and the reconstruction digital work you made. Name the file "yourname_Assignment1_presentation.pdf". Submit a pdf file of the presentation file on Gauchospace. The presentation should mainly focus on the case study (70~80%). Your reconstruction work is not required perfectly like the case study project. You should include the challenges you encountered.

Case Study Checklist

- Researchers, designers, or research lab
- Project name
- Project Feature (The features could be the innovative design process, the material they created particularly for this project, the special function, or the creative concept, etc.)
- Function
- Research method
- Material
- Structure
- Technology
- Innovation
- If you are redesigning this project, how could this work be improved?

- Reference

Grading Criteria

1. The depth of the research, the effort of digital reconstruction, and the oral presentation - 50 points
2. The quality of the documentation (research report, digital images of the reconstruction, and presentation slides)- 50 points

INT93LS Assignment 2 Case Study and Control System Design

Due Monday, July 12th at 9:30 am on Gauchospace

Introduction

In the past week, we have learned about wearable sensors, morphological design, and AI. During the lab and discussion, we learned hands-on skills related to computational design and simulations. This assignment will bridge the skills and knowledge that we have learned, and ask you to design a wearable soft robot control system.

Objective

To be able to use the skills and knowledge to carry out a research case study on a soft robotic control system and design a wearable control system.

Assignment

Choose a research project from Appendix I (if you want to work with a project that is not on the list, please confirm with the instructor), and sign up here.

Step I: Do a case study to understand the control system design.

Step II: Design a wearable control system.

Report checklist

- Write a 1 page summary of your case study.
- Project name
- Researchers, designers, or research lab
- Project Feature (what is this robot about, its function, what is the sensor/actuator, mechanism, etc.)
- Material (what is the material of the robot body)
- Input/output (What is the control system's input, and what they do)
- Techniques (model/mathematical function/hardware/algorithm)
- Describe the control system, and how it works
- Block diagrams
- Reference

Design checklist

- Write a 1 page summary of your design.
- A name of your design
- Design features /functions
- Sensors
- Actuators
- Data flow
- Communication
- Human-robot interaction
- AI technologies
- Input/output
- Draw a block diagram of the control system design
- Reference

Format

1. Submit a PDF file of the case study report on Gauchospace. Name the file "yourname_assignment_2.pdf".
2. Submit a PDF file of your design on Gauchospace. Name the file "yourname_projectname.pdf".
3. Prepare 3 minutes presentation slides to show your research and the wearable control system. Name the file "yourname_Assignment2_presentation.pdf". Submit a pdf file of

the presentation file on Gauchospace. The presentation should be 50% about the case study and 50% about your design.

Grading Criteria

1. The depth of the research, the effort of the new control system design, and the oral presentation - 50 points
2. The quality of the documentation (research reports and presentation slides)- 50 points

D. Syllabi Schedule

Week 1	Lecture	Studio	Assignment/Due
Tuesday Aug 4	Introduction	Studio 1: Introduce Rhino3D–From Drawing to Digital Modeling	Studio 1 Assign Reading: Claypool. The Digital in Architecture: Then, Now and in the Future Suggest Reading: Peter Zumthor. Thinking architecture.
Thursday Aug 6	A Short History of Responsive Architecture	Studio 2: Introduce Grasshopper–A Visual Programming Language Group Discussion on Claypool	Studio 2 Assignment 1: Precedent Study and Digital Reconstruction Assign Reading: Simitch and Warke. The Language of Architecture. Suggest Tutorial: Danil Nagy, Computational design in Grasshopper.
Week 2	**Lecture**	**Studio**	**Assignment/Due**
Tuesday Aug 11	Computational Design	Present Assignment 1 Studio 3: Pattern Design Group Discussion on Simitch & Warke	Studio 3 Assign Reading: Mark Garcia and Theodore Spyropoulos Suggest Reading: Reichardt, et al. Cybernetic Serendipity. 1969.
Thursday Aug 13	Generative Design	Studio 4: Parametric Pattern Design Group Discussion on Garcia and Spyropoulos	Studio 4 Assignment 2: 2D/3D Pattern Mapping Assign Reading: Lars Spuybroek, The Digital Nature of Gothic Suggest Reading: Zubin Khabazi, Generative Algorithms.
Week 3	**Lecture**	**Studio**	**Assignment/Due**
Tuesday Aug 18	Morphological Design	Present Assignment 2 Studio 5: Form Finding Group Discussion on Spuybroek	Studio 5 Assign Reading: Hensel, Menges. Versatility and Vicissitude. Membrane Spaces
Thursday Aug 20	Interactive Design	Studio 6: Data Tree Group Discussion on Hensel, Menges	Studio 6 Assign Reading: Beesley, Hirosue and Ruxton. Toward Responsive Architectures
Week 4	**Lecture**	**Studio**	**Assignment/Due**
Tuesday Aug 25	Materializing Design	Present Final Part I Studio 7: Scripting Sculpture-ghPython Group Discussion on Beesley	Studio 7 Assign Reading: Oxman, Structuring Materiality.
Thursday Aug 27	Control System Design	Studio 8: Digital Fabrication / Physical computing with Firefly Group Discussion on Oxman	Studio 8 Assign Reading: Gillipie and Calderona. A framework towards designing responsive public information systems.
Week 5	**Lecture**	**Studio**	**Assignment/Due**
Tuesday Sept 1	Digital Fabrication	Present Final Part II 1-to-1 meetings	Assign Reading: La Magna, etc al. From Nature to Fabrication: Biomimetic Design Principles for the Production of Complex Spatial Structures
Thursday Sept 3	Course Review	1-to-1 meetings	
Week 6	Final Presentation		
Thursday Sept 10			

Figure D.1 Art122 Computational Design course schedule. Yin Yu. August 2020.

Week 1	Introduction	Assignment / Due
Tuesday Jan 5	Introduction of Machine Learning and the Arts	Assign Short Essay
Thursday Jan 7	Studio 1	Reading: Cizek, etc.,al. Media co-creation with non-human systems. 2018 To watch: AlphaGo Documentary Assignment 1
Week 2	**AI History**	
Tuesday Jan 12	A short history of Artificial Intelligence	Reading: Arthur I. Miller. The Birth of Artificial Intelligence. in The Artist in the Machine. 2019. Reading: Joler and Pasquinelli. The Nooscope Manifested AI as Instrument of Knowledge Extractivism. 2020
Thursday Jan 14	Neural Networks	Reading: Goodfellow, Ian. "NIPS 2016 tutorial: Generative adversarial networks." (2016).
Week 3	**AI Art History**	
Tuesday Jan 19	History of Computer Art	Due Assignment 1 Reading: Fabian Offert. The Past, Present, and Future of AI Art. 2019 Watch Seminar: Claudia Schmuckli. Uncanny Valley. 2020
Thursday Jan 21	Studio 2	Reading: Kyle Mcdonald. A Return to Machine Learning. 2016 Assignment 2
Week 4	**Visual**	
Tuesday Jan 26	Computer Vision	Due Assignment 2 Watch: Frieder Nake - Do calculating machines like drawing? And if so, why? (2018)
Thursday Jan 28	Studio 3	Reading: Olah, etc.al. Feature Visualization. 2017 Optional Reading: Christopher Olah. Visualizing MNIST. 2014. Assignment 3
Week 5	**Sound**	
Tuesday February 2	Computer Music	Due Assignment 3 Watch: Project Magenta: Music and Art with Machine Learning.
Thursday February 4	Studio 4	Reading: Roads. Research in music and artificial intelligence, 1985. Optional Reading: Fiebrink and Caramiaux. The Machine Learning Algorithm as Creative Musical Tool. 2018 Assignment 4
Week 6	**3D / Architecture**	
Tuesday February 9	Guest Lecture: Sihwa Park @ 12pm	Due Assignment 4
Thursday February 11	Digital Architecture and ML in Architecture Design	Reading: Bidgoli, etc. DeepCloud, The application of a data-driven, generative model in design, 2018. Optional Reading: Wang, etc.,al. Shape Inpainting using 3D Generative Adversarial Network and Recurrent Convolutional Networks. 2017. Optional Reading: Artificial intelligence in architecture-Generating conceptual design via deep learning Assignment Final Project

Figure D.2 Art185 ML and the Arts course schedule. Part 1 of 2. Yin Yu. January 2021.

Week 7	AI in Design	
Tuesday February 16	Guest Lecture: Weidi Zhang @ 1pm	**Due Draft Essay** Reading: Brown and Mueller. Designing With Data: Moving Beyond The Design Space Catalog. 2017.
Thursday February 18	Design Intelligence	Reading: Umetani. Exploring Generative 3D Shapes Using Autoencoder Networks. 2017. Reading: David Newton. Generative Deep Learning in Architectural Design. 2019.
Week 8	**Robotics/Human machine**	
Tuesday February 23	AI in Robotics	**Due Final Prototype** Reading: Chin, etc. al. Machine Learning for Soft Robotic Sensing and Control. 2019.
Thursday February 25	Living machine	Reaching: Tamke, etc. al. Machine learning for architectural design: Practices and infrastructure. 2018
Week 9	**Design Aesthetic**	
Tuesday March 2	Gallery Mockup	**WIP Update**
Thursday March 4	The Aesthetic of Design Intelligence	Reading: Manovich_Lev_AI_Aesthetics_2018 Reading: Collective intelligence in design
Week 10	**AI Art Exhibition**	
Tuesday March 9	No lecture: Prepare final project presentation	
Thursday March 11	Final Presentation and Online Exhibition	**Final Presentation**
Week 11	**Final week**	
Tuesday March 16	Work submission	**Final Essay + Final Project**

Figure D.3 Art185 ML and the Arts course schedule. Part 2 of 2. Yin Yu. January 2021.

Week 1	Lecture 9:30 - 10:30 AM	Discussion/Lab 11:30 - 2:20 PM	Assignment Due
Monday June 28	Lecture 1: Introduction to soft robotics and wearable technologies	Introduction	
	Live Lecture 1: Course overview		Assign Reading: Rus,DesignFabricationControlSoftRobots,2015
Tuesday June 29	Lecture 2: Body Architecture	Writing 1	Due: Lab 1
	Live Lecture: Design A Body Architecture	Lab 1: Measuring and 3D Modeling	Assign Reading: Gannon, Digital Design for Wearables, 2016 Gannon, Tactum- A Skin-Centric Approach to Digital Design and Fabrication, 2015
Wednesday June 30	Lecture 3: Soft Material	Lab 2: Computational Design I	Due: Lab 2 Due: Writing 1
	Live Lecture: Design an inflatable structure		Assign Reading: Ou, aeroMorph,2016 Schmitt, Soft Robots Manufacturing, 2018
Thursday July 1	Lecture 4: Biomimicry	Writing 2	Due Lab 3
	Live Lecture: Biomimicry study	Lab 3: Computational Design II	Assign Reading: Duro-Royoa, Metamesh, 2014 Smith, Hybrid Living Materials, 2020 Assignment 1
Friday July 2	Group research		Due: Writing 2

Week 2	Lecture 9:30 - 10:30 AM	Discussion/Lab 11:30 - 2:20 PM	Assignment Due
Monday July 5	No Class. Happy Holidays!		
Tuesday July 6	Lecture 5: Wearable Sensory	Writing 3	Due: Assignment 1
	Live Lecture: Sensory application	Present Assignment 1	Assign Reading: Heikenfeld, Wearable sensors, 2018
Wednesday July 7	Lecture 6: Digital Morphogenesis	Lab 4: Simulation	Due: Lab 4 Due: Writing 3
	Live Lecture: Computational Morphology		Assign Reading: Vergara, Soft Modular Robotic Cubes, 2017
Thursday July 8	Lecture 7: AI in Robotics	Lab 5: Analysis	Due: Lab 5 Due: Writing Abstract
	Live Lecture: Design a control system	* Group Research Week 2 presentation	Assign Reading: Tolley, Electronic skins and machine learning for intelligent soft robots, 2020 Assignment 2
Friday July 9	Group research		

Figure D.4 INT93LS course schedule. Part 1 of 2. Yin Yu. June 2021.

Week 3	Lecture 9:30 - 10:30 AM	Discussion/Lab 11:30 - 2:20 PM	Assignment Due
Monday July 12	Lecture 8: Soft Actuators	Present Assignment 2	Due: Assignment 2
	Live Lecture: Design A Soft Actuator	Prototype I Studio: critique on Final Project	Assign Reading: Yao, bioPrint: A Liquid Deposition Printing System for Natural Actuators
Tuesday July 13	Lecture 9: Soft Interaction	Writing 4	Assign Reading: Kim, Thermal display glove for interacting with virtual reality, 2020
	Live Lecture: Design A Soft Haptic Interaction	Studio: work on Final Projects	
Wednesday July 14	Lecture 10: Wearable Design and Fabrication	Studio: work on Final Projects	
	Live Lecture: Design for human transformation		
Thursday July 15	Lecture 11: Creativity in Robotics	*Group Research Week 3 presentation	Due: Writing 4
	Live Lecture: The Art of Soft Robot	Prototype II Studio: work on Final Projects	
Friday July 16	Group research		

Week 4	Lecture 9:30 - 10:30 AM	Discussion/Lab 11:30 - 2:20 PM	Assignment Due
Monday July 19	Guest Lecture: Diarmid Flateley	Prototype III Studio: work on Final Projects	
Tuesday July 20	Lecture 12: Review	*Presentation Rehearsal	
Wednesday July 21	No Lecture	Presentation preparation and practice Paper Editing and Polishing	
Thursday July 22	Capstone Seminar		

Figure D.5 INT93LS course schedule. Part 2 of 2. Yin Yu. June 2021.