Sentience-Towards a responsive and systems driven design process.

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SENTIENCE
Towards a responsive and systems driven design process.
Sentience is a pilot project and call for an alternative to the current design process most widely accepted and practiced in architecture and design. It challenges the current use of technology as simply a means for representation and end production, by suggesting a truly explorative and multi-disciplinary approach to designing through computation. Cutting-edge work such as Neri Oxman’s Material Ecology studies, or the fibrous, robotically-fabricated pavilions by Achim Menges exemplifies the potential for technology’s use in design that is not limited to generating form, but is attuned to the dynamic qualities of living systems. Integrating computation and design in an experimental and nonlinear, systems-driven process, I designed and built custom hardware modules to collect, visualize, and materialize the sound quality of various spaces. While a functioning data collection and design generating system was achieved, I found that in order to maximize the potential of computation for design, in the form of dynamic living systems, a truly interdisciplinary platform of artists, designers, scientists, and engineers is necessary. Sentience serves as a prototype for the future of cross-disciplinary design, experimental processes, and the transformational role computational systems have in contributing to our ever-evolving physical environments.
I WOULD LIKE TO THANK MY COMMITTEE FOR THEIR CONTINUAL SUPPORT AND INSIGHT DURING THIS PROCESS.

SPECIAL THANKS TO THE STAFF AT THE CINC FOR ALLOWING DATA COLLECTION IN YOUR SPACE.

TO MY FRIENDS AND FAMILY, THANK YOU FOR ALWAYS ENCOURAGING MY CREATIVE ENDEAVORS.
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Introduction

The integration of computers into objects and infrastructure is radically transforming the state of our built environment. The most basic definition of computation is the processing of information (Terzidis 2006). However, in the rapidly evolving world of technology, the broadening concept of computing has the potential to manifest itself in architecture and design in a way that more closely resembles the dynamics of living systems, also known as ‘synthetic sentience’. Objects now have the capability to sense, think, and act as a result of embedded technology, and this opens up the potential for the built world to shift from that of a mechanical paradigm to a model based on biology (El-Khoury et al. 2012). The use of organic models for design does not refer to simply imitating naturally occurring patterns or forms, but emulating nature’s governing principles and evolutionary behaviors (Lorenzo-Eiroa and Sprecher et al. 2013).

The integration of experimental computational systems occurs on many scales within design: from the micro scale where new material composites are capable of responding to external stimuli, to extensive mesh networks of data that connect and respond to people, objects, and the surrounding elements.
This migration of computing power from personal computers to the environment is known as ‘Ubiquitous Computing,’ a term coined in the 1980's (El-Khoury et al. 2012). The evolution and continual miniaturization of inexpensive sensors and computational components enables architecture and design to have a proactive role in shaping this new computational reality. However, the broader use of technology in design education, research, and practice does not yet fully harness these capabilities or follow a truly experimental design process.

**Figure 1.**
Silk Pavilion MIT Media Lab, 2013.

"In natural morphogenesis, formation and materialization are always inherently and inseparably related."

-Menges 2015, p.12
TECHNOLOGY AND DESIGN; PAST & PRESENT
Outdated Design Process

The most widely-accepted and practiced design process is based on the notion that if a problem is well-stated, the design solution follows the problem statement, almost automatically (Findeli, 2001). This current structure for designing, as defined by Findeli, a prominent scholar on issues of pedagogical aspects of design research education, is:

1. A need, or problem, is identified: situation A;
2. A final goal, or solution, is imagined and described: situation B; and
3. The act of design is the causal link by which situation A is transformed into situation B.

For the majority of professionals and educational institutions, this design model typically begins with primary iterations carried out by the designer in the form of brainstorms, precedent research, sketching, and modeling. After a series of linear steps, a singular design is selected, and brought into the digital realm by means of 3D modeling software such as AutoCAD or Revit. Renderings, construction drawings, and detailed diagrams are pulled from computer models and used for a variety of applications. In many cases, the 3D modeled design is created using rapid prototyping technologies, or constructed on the site.
Even the most cursory look at recent literature and production in design would be sufficient to reach the conclusion that the general landscape is safe, quiet, and serene. Findelli 2001, p.5

While the use of technology has accelerated the field of design at an unprecedented rate since the Industrial Revolution, the use of advanced computational systems is still limited within design education and practice (Sakamoto and Ferré et al. 2008).

**Current Application of Technology in Design**

The present scope of technology application within design is usually restricted to the use of software as a modeling tool for pre-conceived designs, and advanced fabrication systems are predominantly utilized at the final phase of production. In the book “From Control to Design,” the introduction states that the discipline of architecture has lacked the innovation and integration of emergent technologies that other industries such as the automobile and aeronautical industries have employed for years (Sakamoto and Ferré et al. 2008). The author argues that in order to redefine the way architecture is conceived and responds to the fundamental link established between matter and information, we must investigate the capacities of new technologies (Sakamoto and Ferré et al. 2008).
Since the early 1990’s, architects such as Frank Gehry have explored non-traditional uses of technology in architectural design and production processes. Gehry is known for seeking software from the aerospace industry in order to model his highly technical, curved building forms and utilizing non-traditional methods for production (Chang 2015). However, due to the nature of the field and its historically formal construction methods and practices, the integration of innovative technology has mainly been restricted to boutique firms and educational institutions (Sakamoto and Ferré et al. 2008). Even in these special cases, there is a need for further exploration (Rahim 2007). As designers, we must start an interrogation of our methods and processes through the lens of computing. In order to expand our métier’s definition and boundaries, we must first look to truly experimental design processes that provide an open environment for incorporating adaptive technologies (Gerber and Ibañez et al. 2014).

1 After attempting to construct Gehry’s curved designs from 2D drawings, and failing, his studio turned to ‘Catia.’ This was a C++ program used first by an aerospace manufacturer in 1977 that models with vectors and 3D surface algorithms (Chang 2015).
Early Experimenters

While historical precedents for current technologies are non-existent, there is a strong context for experimentation within design practice and pedagogy. Arguments for explorative design processes and non-traditional material studies can be traced back to the teachings of the Bauhaus and the works of Pritzker Prize\textsuperscript{1} winning architect Frei Otto.

Josef Albers, a well-known artist and educator conducted material studies in his foundation course at the Bauhaus in the late 1920s (Menges 2015b). Albers believed that innovation could come from material behavior itself. His material studies were not conceived or scaled as representations of ideas, but as a generative unfolding of material behavior in space and time (Saletnik 2007). Albers, along with many other theorists and designers, continued teaching and writing on the importance of experimentation and material-driven processes even after the end of the Bauhaus (Díaz 2015).

\textsuperscript{1} The Pritzker Prize, often referred to as “architecture’s Nobel,” and is awarded annually to honor “a living architect or whose built work demonstrates a combination of talent, vision, and commitment.”
Buckminster Fuller, a prominent architect, theorist, and inventor, shared a similar emphasis on the “experimental” to those of the Bauhaus. While Fuller was known for denouncing the teaching methods and philosophies of the Bauhaus, his work with experimentation closely echoes that of Albers and others from the Bauhaus (Díaz 2015). In contrast to the material behavior experiments of Albers, Fuller’s experiments concentrated on the technical development of structural systems. Later in his career, Fuller’s writings focused on design pedagogy. He believed that teaching methods ought to involve a freedom to try out responses to problems without regard for success—what he termed “intuitive probing.” His belief was that every experimental failure yielded data, and would therefore speak to the patterns and nature of the test. For Fuller, the ethos of this speculative experimentation, including the risk of failure, emulated the process of personal growth and expansion possible in education.

Figures 4 & 5. Buckminster Fuller with various experiments during his time at Black

/ 15
Frei Otto, a fellow theoretical structural engineer and acquaintance of Fuller’s continued his explorations of structural systems and materiality. Coining the term ‘form-finding’ during his time at the University of Stuttgart in the 1960’s and 1980’s, Otto conducted extensive experiments with various material systems, that focused mainly on engineering (Menges 2015b). Otto worked from a method of experimentation he called a “systematic method of invention.” His explorations ranged from wire and soap bubbles to gridshells and cable netting, and served as starting points for his architectural works (Otto, Trostel, and Schleyer 1973). While he worked closely with the leading engineers of his time, Otto believed that there was a lack of interdisciplinary research within architecture, and called for the collaboration with scholars in fields such as the humanities and natural sciences. Otto declared that “productive research must be brave!” (“Frei Otto and the Importance of Experimentation in Architecture” 2015).

These early experimenters led the innovations of their time, and many of their projects resulted in successful built works¹. While they spanned a wide range on the spectrum of pedagogy, practice, and time; they serve as conceptual roots for movements towards design experimentation, multidisciplinary research, and the fusion of computation and architectural form.

¹ Buckminster Fuller is known for the invention of the Geodesic Dome (Kim et al. 2015). Frei Otto explored the possibilities of tensegrity, and lightweight tensile structures (Otto, Trostel, and Schleyer 1973).
Figure 6.
Frei Otto’s
Deutscher Pavillon
Montreal 1967.

Figure 7.
Frei Otto
early soap and wire experiment.
The non-traditional approach to design and the experimental processes of early thinkers such as Albers, Otto, and Fuller parallel contemporary explorations in the era of continual technological advancement. In addition to innovations in material science and structure, current works exemplify the limitless potential computation has when applied to design experimentation. The following projects range from oscillating networks of breathing vessels to robotically fabricated fibrous pavilions, and showcase only a small portion of a vast and provocative movement of research and design thinking.

Figure 8. Phillip Beesley’s Hylozoic installation.
Design as Breathing System

Building from ideas of form language based on diffusion and dissipation, the world-renowned Canadian architect and designer Philip Beesley explores computation in design through responsive, living art and architectural systems. This form language of material interactivity and evolution drives Beesley’s works which seek to interact with the environment through “subtle phenomena, and expanded physiologies” (Gerber and Ibañez et al. 2014, p.25).

Hylozoic Ground, one of his most prolific and continually exhibited works was first unveiled at The Venice Architecture Biennale, a biennial exhibition of provocative architectural works, in 2010 (Etherington 2010). Hylozoic Ground is an immersive environment composed of thousands of digitally fabricated lightweight components that house custom microcontrollers and sensors. The use of protocells in the installation allows for a “primitive, metabolic system to emerge within the sculpture” (Lorenzo-Eiroa and Sprecher et al. 2013, p.268). The intricate, hovering environment is designed for interaction, with a sensitivity to surrounding gestures, and is arranged laterally to support collective experience (Gerber and Ibañez 2014).

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1 Diffusion and Dissipation: Ilya Prigogine, a 20th Century physicist defined as key terms for understanding how materials can dynamically interact and evolve (Gerber and Ibañez et al.2014).
Mechanical fronds of laser-cut meshwork oscillate as humans move through the space, and touch sensors create reactions of diffuse breathing motions within the material. This living, breathing sculpture captures the essence of sensitivity found in human touch, and references ‘hylozoism,’ the ancient belief that all matter has life (Etherington 2010).

The oscillating network environments of Philip Beesley contribute to a renewed architecture, informed by dynamic form-languages and living systems. He argues that his works, “do not achieve high, efficient functions, but instead they offer a sketch of possibility”(Gerber and Ibañez et al.2014, p.25).
Material Ecology

Existing at the intersection of Biology, Materials Science and Engineering, and Computer Science, with a focus on environmentally informed computational design and fabrication, is Material Ecology an emerging field in design. Defined by Neri Oxman, an architect, inventor, and instructor within MIT’s Media Lab, Material Ecology focuses on material-based design computation that relates units of matter to units of performance, resulting in products that are biologically informed and digitally manufactured “by, with, and for Nature” (Oxman 2012).

Oxman and her team, Mediated Matter Group, perform research across varying scales that include elements of synthetic biology and which are produced using custom-engineered fabrication technologies. Water-based Digital Fabrication Platform, the group’s recent work, was inspired by aqueous material formation and combines a crustacean-derived composite with robotic fabrication to construct forms that decompose upon contact with water (Oxman 2014).
The custom fabrication system is a multi-chamber extruder armature attached to a robotic arm that is programmed to place biodegradable composites in varying gradients of function across differing length scales. An advanced computational workflow is used for the direct fabrication of this multi-material structural meshwork. Applications for this work range in scale from fully biodegradable household products, to tent-like shelters that could be implemented efficiently and material composition controlled based on the surrounding environment (Oxman 2014).

Oxman’s work, and the field of Material Ecology, is an example of design that manifests not only as a result of emergent systems in computation, but also material compositions that are biologically engineered to embody natural elements and inform design.
Adaptive Structural Fabrication

Based on the study of the biological construction processes of underwater nest creation, the ICD/ITKE Research Pavilion 2014-15 demonstrates an architectural application for adaptive robotically fabricated fiber composite structures (Vasey 2016). The research project acts as a case study for generative behavioral design modeling and online fabrication, building off of previous research on these structures from the University of Stuttgart, where Achim Menges is an instructor (Menges 2015a).

Generated by computational form finding technology, the initial geometry for the structure is installed in the form of a flexible membrane shell. Using a custom applicator attached to a robotic arm, carbon fiber strands begin to reinforce the inside of the membrane. A method for online programming of the robotic arm during the construction process was developed based on live sensor feedback. The additive construction process allowed for adjustments to be made in real time during implementation in order to reduce deformation of the outer form membrane.

Figure 14.
Diagram depicting the inflation and weaving fabrication process of the pavilion.
This method of fabrication reduced the amount of formwork necessary for construction, produced minimal material waste, and explores the capabilities of integrating logic into the material, structural, and fabrication elements of architectural design. The fabrication process discovered allows feedback between the live production of the shelter and the code running the fabrication tool. This enables constant analysis and reveals new insight into adaptive technological fabrication processes (Vasey 2016).
While these projects do not represent common archetypes or architectural icons, the collection of these boundary crossing projects speak to a fertile architecture to come. The continual, and rapid advancement of technologies and fabrication capabilities will only further the scale, application, and possibilities of embedded design. The work and writings of these pioneers serve as the catalysts for a paradigm shift that is far from reaching synthesized conclusions, but enables a truer manifestation of the imagined world (Gerber and Ibañez 2014).
“Combined with the designer’s capacity to analyze structural and environmental forces, the enabled mediation between matter and the environment through fabrication appears to be as powerful as the ethos of craft itself.”

NERI OXMAN, 2014
Re-Defining the Role of the Designer

Cutting-edge work that incorporates computational and emergent systems research is re-imagining the design process and bringing new meaning to the role of the designer. In response to these new technologies, Findelli suggests that “the designer’s task is to understand the dynamic morphology of the system, its ‘intelligence,’” a role that one could argue is more attune to the complexities of natural systems (Findeli 2001, p.10). This new definition aligns with the thinking presented by Moholy-Nagy who said, "the key to our age [is to be able] to see everything in relationship" (Findeli 2001, p.11).

Architectural computing does not remove the designer, and is not mere utility, but a manner of design ‘thinking.’ The old archetype of the linear design process can now be re-imagined, to incorporate multi-disciplinary thinking, experimentation, and as Findelli suggests,

a new logical structure of the design process is:
1 Instead of a problem, we have: state A of a system;
2 Instead of a solution, we have: state B of the system; and
3 The designer and the user are part of the system (stakeholders) (Findeli 2001, p.10).
This new design process model suggested by Findelli and others, refreshes the original model of linear processes driven by concrete end-products, and allows for an inventive exploration of what it means to shape designs through computational systems. Incorporating technical advances from the sciences and juxtaposing them against clear goals that maintain the iteration, expedience, and exploration in the design process will aid in "collectively charting a unique disciplinary path in applied science and art" (Gerber and Ibañez et al. 2014, p.39).

Embracing the Modern Designer

In regards to a new educational framework as well as the future progression of the field, Sakamoto states that we must look to a "less stable, more intimate" relationship when designing with technology (Sakamoto and Ferré et al. 2008, p.3). In response to this call, the goal of this project is to push the boundaries of my existing design education environment by incorporating experimental technologies and a non-linear design process into my personal design research. This project utilizes ideas and technology from disciplines outside my field of study, and serves as a call for the integration of computational technologies, and design environments that enable and provide a foundation for advanced experimentation within the context of the Program in Environmental Design.
Fueled by the works of Beesley, Oxman, Menges, and dozens more, that incorporate technological systems in their design, I developed a data collection system for generating designs that serves as a foundation for further design development and architectural application. My process for experimentation was broken down into several components including hardware development, module implementation, data collection, and the designing of a visual algorithm using the scripting plug-in ‘Grasshopper’ to process the live data. The final product is a series of graphical visualizations and physical, 3D printed, objects that embody the data collected by the custom designed and built hardware modules.

My work incorporates computation within an explorative design process to sense, think, and act with the help of microcontroller technology. This synthetic sentience prototype is rooted in the theoretical writings and precedents, and aims to contribute to the larger movement of emergent technologies and systems embedded in our built environments. My intention with this project is not only to contribute to this larger discussion of computational design pedagogy, theory, and practice, but to act as a foundation for future research to build upon.
OFF THE BREADBOARD
In order for this project to explore designing with a computational system, it was crucial that I incorporate a component with the capability to collect data, be responsive to surrounding conditions, and have an element of interactivity. My pre-existing skillset from my education in Environmental Design did not include the knowledge or tools to achieve this, but I was excited to explore and utilize technologies from other disciplines to accomplish my objective. Without any prior experience building interactive systems, and with only an elementary understanding of physical computing, I looked to the Technology, Arts, and Media Program as a resource for integrating interactive technology into my work. This is where I learned about Arduino.
Microcontrollers and Open-Source Culture

The Arduino project was founded on the idea of creating an open-source microcontroller community, which makes prototyping interactive physical systems more approachable for beginners. Open-source is a movement that began in software where developers openly share their source code which allows others to freely utilize and build on this work, it also refers to the broader philosophy of open collaboration. The Arduino platform is composed of two elements, hardware and software, both of which are open source. The Arduino hardware is a microcontroller which is a very simple computer on a single integrated circuit that takes inputs from the physical world and controls outputs.

Many of the electronics that surround us, including our cellphones, incorporate some form microcontroller in them. Because Arduino is open-source, there is a dynamic community that openly shares thousands of tutorials, example projects, and sample code to encourage novice to expert users to experiment with and improve the technology.
For someone like myself, with limited knowledge of physical computing and zero experience with coding or hardware prototyping, Arduino seemed to be an obvious starting point. The Arduino hardware and various breakout components are fairly affordable, and accessible from the locally based company Sparkfun. The Arduino software is free to download, and the open-source nature of it makes getting started quick and somewhat intuitive. The idea behind prototyping is a trial and error process that allows real time revising and adapting, so I purchased an Arduino microcontroller and began tinkering.
Figure 20. Kit of parts for initial prototyping.

1/ Jumper Wires
2/ Electret Microphone
3/ Resistor (330ohm)
4/ LED
5/ Arduino Uno
6/ Breadboard
Initial Hardware Development

Starting from square one, I worked closely with my committee member, Arielle Hein, to develop an understanding of the Arduino hardware and software prototyping environment. For the first round of hardware testing, I prototyped a simple circuit for audio collection using a breadboard. Breadboards are a prototyping tool used in electronics to quickly test and adapt a project before soldering it permanently. I worked with the ‘Electret Mic Breakout Board’ from Sparkfun, which captures sound waves and translates them into electrical waves; this breakout board allowed me to measure amplitude, or volume of the sounds wave. The board has three pins, VCC, GND, and AUD; I soldered wire to each pin and connected it to the Arduino for an initial test. The connection consisted of VCC to 5v (power), GND to GND (ground), and AUD to A0 (analog 0). After several trials, I found the microphone to be faulty, but learned this is common and part of the electronics prototyping process. Though the circuit did not function, this initial experiment was a crucial first step in learning how to set up a functioning circuit and work with the various Arduino hardware elements.
This first experiment was also an introduction to the Arduino programming environment. Programming provides the logic that allows the chip in the microcontroller to process inputs and outputs. My most basic understanding of coding was enough to get started communicating with the microcontroller. The Arduino code structure is based on “Processing”, a popular software sketchbook for coding, and is written with C++, a general-purpose programming language. The software allows users to upload code directly to the microcontroller board. The "void setup()" area runs the code written once, and initializes serial communication. The "void loop()" runs continuously and the code written tells A0 (analog pin 0) to read the values from the microphone. The "//" before text denotes a message that is viewed by the person writing the code, but not processed by the microcontroller. To test the code, it must first be compiled, then uploaded to the board through a USB port. The serial monitor function allows the activity to be monitored in a pop-up window.
Adapting the Hardware

After reconsidering the sound collection component, I moved into the second round of experimenting with a new microphone breakout. I opted for Sparkfun’s ‘Sound Detector’ because it is more customizable than the initial mic. The Sound Detector is an audio sensing board with three different outputs. The envelope reads amplitude of sounds by measuring analog voltage which is exactly what I was interested in measuring. The circuit I prototyped with the Arduino and Sound Detector reads and logs the levels of sound collected. The code uploaded to the board reads from the A0 pin, when that input reaches a level above (volts >= 1.0), it lights the LED. The success of the second circuit was encouraging, but still needed to be improved in order to successfully collect data.

Figure 23. Sound detector
The final phase of hardware development expanded on the trials of the previous circuits. After the second round of experimentation, I found that the ‘Sound Detector’ functioned well for sound collection. It sensed clapping, medium to loud conversation, and substantial movements within range of the component. In order to collect data on location and record the sound quality of the space over time, it was necessary to integrate a data logging component to the circuit. After testing a few different SD options, I chose the Sparkfun 'microSD shield' which stores the written data, and has a large prototyping area. The shield provides space for the mic breakout, LED, and resistor to be soldered directly in place, and using headers it is attached directly to the pins of the Arduino board. The shield enabled the development of a compact audio collection module that reads, writes, and stores data to a microSD. Once I tested this final module, I replicated my process and created four additional modules for data collection.
1/ Resistors (330ohm)
2/ Jumper Wires
3/ Arduino Uno
4/ Sound Detector
5/ Male & Femal Headers
6/ MicroSD Shiel
7/ LEDs
8/ MicroSD card
Figure 26. Final data collection component
Figure 27.
Schematic drawing for final circuit
Online resources, access to hardware from Sparkfun, and the multidisciplinary community of makers I found in the BTU Lab encouraged my process of experimentation and were crucial to the successful integration of custom hardware and software in my project. Without this community, and the open, creative, learning environment that fosters it on campus, it would have been difficult for me to design and build the key component of my project.

The learning from this process was not limited to acquiring a new skill that I can integrate into my design work, but the opportunity to experience and contribute to a collective of people from varying backgrounds who are joined by the open-source culture. The most value came from experiencing an environment where the power of sharing knowledge and collaboration is crucial, as Massimo Banzi, founder of Arduino, states “a piece of culture you share” (Banzi 2012).
DATA COLLECTION
Hardware Implementation

The next phase of the design process was implementing the hardware modules and collecting data. The sound modules were installed at ‘The Center for Innovation and Creativity’ (CINC) on East Campus which houses the Programs’ creative labs, woodshop, computer lab, classrooms, and upper level studio spaces. This location was chosen for data collection because it houses various programmatic elements, it is a space I am familiar working in, and is easy to access and monitor. In order to get an understanding of the varying conditions within each space, modules were placed in the classroom, computer lab, woodshop, and two studio pods. The module is secured by a custom acrylic enclosure and is mounted near the ceiling to avoid being tampered with. Each module is powered by a wall adapter power supply cord, this also played a role in the placement. When connected to a power source, the module reads data every second, and writes to a .txt file stored on the microSD card.
Figure 28.
Site plan of the CINC

Center for Innovation & Creativity (CINC)
1777 Exposition Dr, Boulder, CO 80301
Data Collection

The initial round of testing revealed values on average ranged from 5-7 volts, and denoted a fairly quiet, almost silent space. When excessive activity occurred, the sensor located in the woodshop picked up levels as high as 50 volts, when heavy machinery such as the table saw was being used. In some of the data there were unexplainable outlier values as high as 250 volts; this may have been due to a quick blip in the microphone or excessive tampering with the device. This test made it clear that there is a visible difference in the sound levels across the spaces of the CINC facility, and that the microphone was able to pick up these varying levels. One of the shortcomings of the module, discovered during testing, was the lack of a time-logging device. In initial phases of hardware development, a timer or clock component was not implemented, thus making it very difficult to log the time and date of the data collections. Time tracking was done manually, but future development of the module, it would be beneficial to include an element that keeps time accurately.
Visual Scripting with Grasshopper

I worked in Grasshopper, a visual programming plug-in for Rhinoceros 3D, to make sense of the data collected from the CINC. Most commonly utilized in architectural and design settings, Grasshopper is used to create generative algorithms that have corresponding 3D geometry. The grasshopper environment is an intuitive way to generate designs, and doesn't require learning how to script. With Grasshopper, data can be defined locally, as a constant within the interface, or it can be imported from a Rhinoceros document or file on the computer. This feature allowed a connection to be made between the data in the .txt files collected from the modules at the CINC, and a Grasshopper definition. Once imported, the data is stored in parameters within the Grasshopper file. Using various list commands data can be organized, split, and eventually visualized.
The incoming data is organized in two columns, the first counts the number of seconds starting from 0, the second represents the correlating sound value that is read by the mic. With the 'split list' command, I was able to break down the data into minute segments, graph the sound value points along the Y-axis, and then create a curve running through the points. After a series of additional transformations, the result is a graphic that visually represents clear shifts in the sound quality of each space over time. The definition splits up each set of data for every 60 seconds and shifts the placement up the Y-axis, the spacing is controlled by a number slider.
Figure 31. Visual depiction of an hour worth of data collection in each space.
Figure 32. Graphical representations of the data points over one hour.
Figure 33. Photograph of 3D prints made from the data collected.
Data Materialization

To further represent the data, I created a series of three-dimensional forms using grasshopper. These forms were then materialized with a desktop 3D printer. The method of 3D printing is an additive manufacturing process where three-dimensional form is built up layer by layer. The fabrication process added an unplanned effect on the forms, the sound waves begin to feel like a landscape, and there is an element of tactility that is unique to the striations made by the 3D printer. This material texture was something I could not have fabricated intentionally, and was an example of how explorative materialization processes have the potential to yield unimagined results.

Figure 34. Close up of material detail as a result of production technique
Further Developments

With further resources, this project has the capability to become a real-time, responsive data-driven system. By adding a Bluetooth component to the module, it would have the capability to send live data to a computer that responds directly to and visualizes the incoming data. With further experimentation and technical resources, this project could go a step further, translating and responding to this data in an architectural way. The next step in this pilot project would be generating a fully integrated system loop, that takes input, analyzes the conditions, and reacts to the data intake at building scale. For instance, a wall paneling solution could be integrated with this system and react to varying sound conditions and variables of the space, driving material density, makeup, and location based on the inputs. A futuristic application could involve communication between the architectural elements of the space and humans inhabiting it through Bluetooth connects made between possible human wearables and building systems.

Within the last five years, technology such as desktop 3D printers have evolved at such a rate that they have moved from printing trinkets out of plastic, to constructing full scale bridges out of a structural composite.
Robots weave tensile carbon fiber structures, and biological systems are being 3D printed through custom material composites, the potential for these responsive systems to be integrated throughout not only the design process, but the materialization process and the life cycle of our buildings is endless. We have yet to reach the full potential of these technologies, but it will take an accumulation of many small projects to build a foundation for a paradigm that has few historical precedents.

Learning Outcomes

Achieving a working system that lives up to the theoretical concepts of advances in technology and computation proved challenging, considering the lack of accessible resources within my department. During the design and experimentation process, it became clear that in order for a true generative, responsive design system to be successful, it must involve collaboration between scientists, material engineers, computer scientists, and many other disciplines. Designing and building custom electronics components was not an easy task, and to some it might appear as a "plug and play" activity. However, in order to achieve a functioning collection system, it required extensive time spent testing and refining before implementation could occur.
This project was a starting point for integrating knowledge from areas outside my field of study, and enabled the integration of technology into my Environmental Design Education, a setting where experimentation with technology and advanced fabrication systems is not currently present.

**Contribution**

If experimental projects similar in nature to this work were explored as foundation courses in design education, and paired with collaboration from disciplines outside the field of architecture, the potential for development of an advanced computational design understanding over the span of an undergraduate career would be feasible. The pairing of computation and environmental design methodologies offers an exciting opportunity for contribution to a rapidly expanding field of design, and equips designers with knowledge and experience that, collectively has the potential to revolutionize the built world.
CONCLUSION
Looking to the future of computation within architecture, we must now imagine our tools with new "curiosities and sensibilities of authorship, signature, and with a new spectrum of artificial intelligence and autonomy (Gerber and Ibañez et al.2014, p.10)." In doing so there is the potential for great innovation and the production of a renewed Architecture (Lorenzo-Eiroa and Sprecher et al.2013).

This project is not only a small glimpse of a larger movement, but a case for a true experimentation and systems driven design process. In order to educate designers and scholars to solve future problems, a new way of design thinking that doesn’t limit experimentation or the integration of cross-disciplinary work is crucial. The aim of this project is to successfully integrate a new way of approaching design, specifically in the context of the Environmental Design Program, as a system where information is taken directly from a surrounding environment and translated through computational steps to generate forms that represent the incoming data. By redefining the process in which we design, harnessing emergent technologies and designing through systems that are built from advanced experimentation, the process will inherently generate entirely new designs and theories.
CADemiurgy – An Open Theory of Design-Research in Architecture, Design Research in Architecture, “the possibility of digital technology to model but also to fabricate new worlds.”

CNC Milling – a fabrication technique that utilizes a multiple axis router, and computer software to mill computer generated forms.

Computation – (most basic), refers to the processing of information

Computational Design – Visual programming that drives a design output or system.

Computational Geometry – a type of computational design that focuses on algorithms that create geometries.

Computer Aided Design (CAD) – the use of computer software for design and design representation, AutoDesk’s popular program AutoCad is an example.

Design Method – Steps taken to create and come to new findings through both qualitative and quantitative measures.

Digital Model – a software based, digital representation of a designed object or system.

Digital[ly] Fabric[ated][ation] – a fabrication process in which digital models of designs are transformed into three dimensional scaled objects.
Emerging Technologies – technologies that are expected to change the state of the field [ex. In design, 3D printing, CNC milling, robotics]

Generative Design – is a design typology that mimics nature’s evolutionary approach to creation, and

Information Design – the graphical ordering and presentation of information.

Materiality – The physical state of a design or object, often varying due to the process through which the object was produced.

Material Ecology – “is an emerging field in design denoting informed relations between products, buildings, systems, and their environment.

Parametric Design – a design process based on algorithmic thinking that responds to set parameters and definitions that drive an end product.


FIGURES CITED

Figure 1.

Figure 2.
http://news.yale.edu/sites/default/files/Lewis-Residence_YaleNews.jpg

Figure 3.

Figures 4 & 5.
http://www.blackmountaincollegeproject.org/ARCHITECTURE/CAMPUSES/LAKE%20EDEN/FULLER11.gif
https://hammer.ucla.edu/fileadmin/media/programs/2016/Winter-Spring/Hammer_Workshop_Explorations_Bucky_1280x1002.jpg

Figure 6.
https://s-media-cache-ak0.pinimg.com/originals/97/d1/0b/97d10bd8bf8f30e7c6900f2168a2dbfc.jpg

Figure 7.
http://images.adsttc.com/media/images/5501/96fb/e58e/cee4/f100/01bf/large_jpg/frei-otto_film-de-savon.jpg?1426167541

Figure 8.

Figure 10.
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Figure 11.
http://matter.media.mit.edu/assets/projects/Pneumatic_Biomaterials_Deposition_06.png
Figure 12.
http://matter.media.mit.edu/assets/projects/Pneumatic_Biomaterials_Deposition_06.png

Figure 13.
http://68.media.tumblr.com/8e4cb04af93157c4a1b344f6f0de62c5/tumblr_nn6fa7fx5z1qa65mxo1_r1_500.png

Figure 14.

Figure 15.

Figure 16.
https://c1.staticflickr.com/9/8435/29020764630_1ca624ff99_b.jpg

Figure 17.

Figures 18-34.
Courtesy of the author