SURFACING SILICON

Revealing the Underlying Material and Structure of Digital Electronics through Aesthetics

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ABSTRACT

Digital electronics are everywhere. We spend most of our days surrounded by them, but what most of us ever experience is their surface. The purpose of this work is to open up the black box of everyday digital electronics as a way to show what is hidden inside. This is done, not as a way to teach people how they work, but to reveal what has become the underlying fabric of our world so they can be seen and appreciated.

The shape of digital electronic technology over the past 50 years is characterized by the demands of efficiency and productivity. Transistors within silicone chips are smaller and more densely packed today than ever before. These advances have not been met with corollary modes of representation. We are faced with a technological landscape that exists outside of the realm of human perception. Transistors are too small to see, and even if they were visible, they are sealed inside protective cases.

The work presented here takes on digital electronics as a subject and medium for artistic expression. The goal is to use aesthetics as a way to show and call attention to what is otherwise not meant to be seen. The contributions are an in depth conceptual and material exploration that address the use of an opaque technology, one that is normally outside our realm of experience, as means of creative expression.

In the same way that uncovering the underlying fabric of our natural world reveals the hidden truths of nature, accessing the material of our fabricated world brings us closer to underlying truths of humanity. The effect reveals a certain beauty that would otherwise be lost to the highly efficient rational world.

**Thesis Supervisor : Kevin Slavin
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Special thank you to my partner Che-Wei Wang who inspires and brings smiles, energy and fearlessness to our lives. I love you.

This thesis is dedicated to my Mom who I love and appreciate more every day.

CONTENTS

1. INTRODUCTION

1.1 MOTIVATION

Developments in science yield abstract models that reveal underlying structures of the natural world[1]. Advances in technology make use of those developments, but often contribute to that hidden world[2]. With the proliferation of digital electronics, we are building up an entirely new natural landscape; elements that were never before part of our hidden world now form a substantial part of it. This new landscape is characterized by fields of nanometer scale transistors, arranged in a way that shapes our lives.

Technological advances over the past 50 years have made the production of digital electronics exponentially more efficient[3]. The great shifts in modes of producing digital electronics, have not been met with corollary modes of representation. This effect is amplified by a design practice that favors technological devices that are sealed in protective cases, where user engagement is constrained to a bare minimum set of pre-defined inputs and outputs. Today, the utility and ubiquity of digital electronics has increased, but so has our ability to see inside machines.

A significant portion of our fabricated world now operates on a plane that is outside the scope of human perception. As with any imbalance between those who have access, and those who don't, this has implications. The relics of human innovation should not just be hermetically sealed boxes. Instead, there should be a practice of surfacing the comprehensive history of human thought and innovation that is otherwise veiled in utility. The following is a series of artworks that present an exercise in surfacing this unseen portion of our constructed technological landscape.

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[1] To be clear, an abstract model is used as a way to represent something that is often impossible to present directly. In physics for example, this involves prescribing a mathematical model to a speculative theory as a way to prove its validity. The Rutherford-Bohr model of the hydrogen atom is an example of this. The hydrogen atom is impossible to observe directly, but by using a mathematical formula to support his theory, Bohr was able to model it as a positively charged nucleus with an orbiting electron.

[2] Revolutions in science spur advances in technology that contribute to the fabric of the hidden world. I'm not suggesting that a transistor is hidden in the same way as an electron once was; transistors were made by people. But as science attempts to render our shared world more visible, technology is making more stuff that we can't see. And like the underlying truths of the natural world, that stuff is there and it is beautiful.

[3] Moore's Law projected in 1975 that number of transistors that will fit on a densely packed Integrated Circuit will double every two years.

1.2 OVERVIEW OF RESEARCH

The following overviews three research trajectories that consider building a vernacular for presenting digital electronics in a way that they can be seen and experienced. Not as functional devices, but as art. With each trajectory, the site and resolution of inquiry shifts. It begins just below the surface, or the exterior skin of a device at the Printed Circuit Board (PCB)[4] and moves inwards to the Integrated Circuit (IC)[5] and then finally to the low-level digital logic gates that lie embedded and invisible to the naked eye within Integrated Circuits.

- *Cellular Telephone* is a line of inquiry where the exterior skin of a cellphone is removed and the functional components are presented as a diagram and a functional cellphone. Here the normally invisible traces of a PCB, usually encased within an opaque enclosure, become visible.
- *Quartz Wristwatch* addresses digital electronics at the scale of the Integrated Circuit. The goal here is to devise a way to reconstruct the functionality of the IC of a quartz wristwatch with discrete transistors so that it functions, but their logical arrangement can be viewed and appreciated.
- *CMOS Logic Sketches* considers the scale of digital logic gates. Logic gates are so deeply entrenched in our devices that very few people know that these simple structures exist and continue to be the fundamental building blocks of digital electronic technology today.

Presenting the inner workings of digital electronics in a way that renders them legible calls for new modes of representation, and therefore necessitates new modes of production. Both require building up a vernacular for presenting electronics that simultaneously function, convey meaning and require new ways of making.

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[4] PCB is an abbreviation of Printed Circuit Board. Both PCB and Printed Circuit Board are used interchangeably throughout this document to mean the same thing.

[5] IC is an abbreviation of Integrated Circuit. Both IC and Integrated Circuit are used interchangeably throughout this document to mean the same thing.

1.3 OVERVIEW OF THESIS

The first section of this document begins with a background overview of technology art. This starts with a definition of what is meant by technology art in the context presented here. This is followed by a section titled art as revelation, which considers art as a way to invoke an understanding of some aspect of the world that is otherwise hidden or doesn't exist. These sections establish a way to look at art once technology as a subject or medium is introduced. This foundation is then used as a framework for surveying selected artworks. These include artworks that come before and after the introduction of digital electronic technology. A brief section on educational toolkits comes next. This is meant to acknowledge work done in this field, but also to differentiate between work that is meant to teach you about electronics from artwork that is about surfacing electronics as a material to experience.

The second section of this document covers the new work presented here. This begins with an overview of how digital electronic technology as a medium is currently considered, from its origins leading up to its present state. Following that, the document presents the new material exploration, development and process implemented to realize this work.

In the third section, the three trajectories of research are presented. Each one begins with a short summary, followed by a discussion that covers design, engineering and material process.

The conclusion summarizes the contributions and proposes future work in this area.

2. BACKGROUND - TECHNOLOGY ART

2.1 DEFINITION

Throughout this work, technology art is defined as art that uses technology as a subject matter, a medium, or both[6]. With art that has technology as a subject, the challenge is to represent something that is not only hidden, but to address a complexity that you were never meant to see, let alone understand. With art that incorporates technology as a medium, the challenge is to dissolve its opacity into a material that is legible.

2.2 ART AS REVELATION

There is a history of work, notwithstanding technology, that is about surfacing the invisible. Renaissance painters rendered realistic scenes of historical or religious narratives intended to educate or religiously transport the viewer. The Impressionists captured the passage of time by demonstrating changes in light and movement with unprecedented painting techniques. The Futurists emphasized speed and violence embodying the changing technological and wartime landscape. And the Cubists made visible the theoretical concept of experiencing multiple perspectives simultaneously.

What is common throughout these examples is the role of the artist, who works to transport a viewer into a world that is too opaque to discern or otherwise would not exist. This is accomplished through a perceivable medium.

When working with technology, as a subject matter, or a medium, the artist's role is unchanged; to welcome a viewer into an otherwise indiscernible world. Paint, stone, pencils, steel, motors, electronics, film are media that could all be considered technological. If considered as such, these technologies all have varying degrees of opacity. Working with digital electronic technology is a particular challenge, because both as a subject and medium, it is imbued with opacity. Form does not necessarily predicate function. Moreover, the functionality of digital electronics are actively encased.

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[6] To further clarify what is meant by subject matter and medium, in *The Persistence of Memory* by Salvador Dali, the subject matter of the work is "time" and the medium is "oil on canvas".

When using an opaque technology as a medium or subject, art's revelatory objective should be closely considered. The central focus of the work presented here is to address the need to dissolve the opacity of digital electronic technology.

The following examples use technology as a subject matter, a medium or both. They begin with works that were made before digital electronic technology, and end with work that is being made today.

2.3 EARLY TECHNOLOGY ART

This first group of works represent the beginnings technology art - art that use technology as a subject or medium. The examples discussed here span up until the 1970s, covering the technological eras where trains, radios, televisions and cars were first introduced. It stops right around the point that digital electronic technologies first become available to the public. These examples show how artists have historically responded to their surrounding technological landscape. And how they've claimed authorship of it, whether as a subject or a medium.

Rain, Steam, and Speed - The Great Western Railway (1844) by JMW Turner is one of the earliest works of art that embodies an impulse to examine the relationship between the natural world and the industrialization of man. As one of the first paintings to have technology as a subject, it is not in any way a clear rendering of a train. Instead Turner uses abstraction to conjure the sheer speed and power of a massive body of iron cutting through a natural landscape. Nothing about this painting is static. Turner's use of abstraction, well before it was even a thing, establishes a stylistic vernacular that is in many ways technological. Similarly to how the Impressionists would come to represent light, and the Futurists speed, Turner captures the nature of this new technology and its impact.

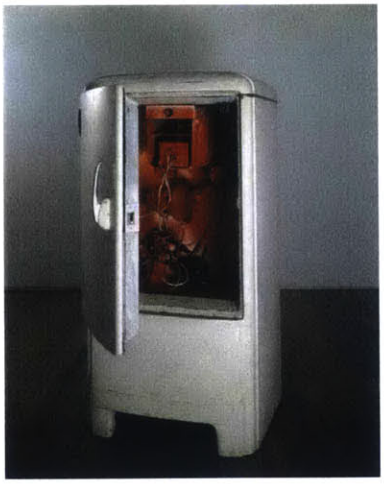
Rain, Steam, and Speed - The Great Western Railway, JMW Turner (1844)

Bicycle Wheel (1913) by Marcel Duchamp is considered the first kinetic artwork and also the earliest readymade[Burnham 226]. In this piece, Duchamp re-contextualizes a simple, functional technology so that it can be viewed in a new way. This work is important for numerous reasons. It is cited here because it calls attention to the implications of using a non-traditional material, specifically one that is technological, as art. The bicycle wheel carries with it layers of connotations from the outside world. It is a simple, functional machine, invented by man and manufactured by a different set of men. This technology is considered in a completely new way when positioned by Duchamp in the context of art.

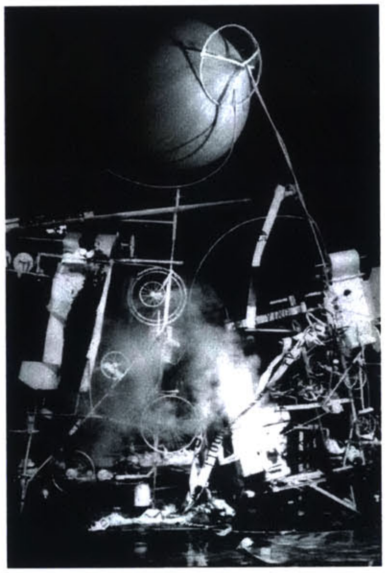
Bicycle Wheel, Marcel Duchamp (1913)

The bicycle wheel is a human-scale mechanical device. Although it is technological, its degree of opacity differs from electronic technologies. The relationship, embodied by the bicycle wheel, between form and function is clear and legible. With the introduction of electronic technologies into artworks, form becomes opaque and illegible.

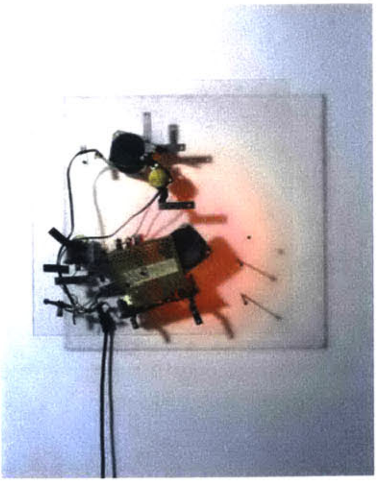
An appropriate segue here is into the work of Jean Tinguely with *Frigo Duchamp* (1960). Little is known about this work other than that the fridge was a gift from Marcel Duchamp [Museum Tinguely]. In this piece, an impenetrably massive refrigerator is set partially open for viewers to peek inside, not at food, but at a heap of electronics. The lit or painted red interior (you can't tell in the photograph) of the fridge suggests that we are looking, not at the electronic guts of a fridge, but into the body of technology more generally. We are privy to a glimpse past the opaque exterior of technology and into what seems to be its insides. The technological interior that Tinguely shows, effectively a mess of electronics, is alluring, but warns us that it's not something that people are supposed to know about or understand. The opacity of technology is reinforced.


Frigo Duchamp (1960), Jean Tinguely

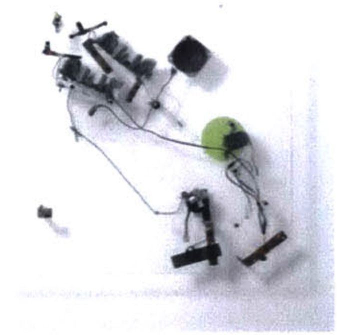
Jean Tinguely's work is instrumental in developing a vernacular for using electronics and machines as an expressive medium. And also for characterizing the challenges of working with technology in such a way. When discussing his work, Tinguely speaks to the difficulties of producing a physical system that strives towards psychic ambiguity, while being conceived under the physical precepts of a mechanical artifact [Burnham 218]. In the everyday experience of the machine, there isn't room for ambiguity. Either it works or it doesn't. *Homage to New York* (1960) destroys this notion. The piece, a machine that destroys itself, dissolves the constraints imposed by functionality. Tinguely designates a space for ambiguity to emerge, setting the stage for his lifetime of work with technology as a means for expression.


Homage to New York, Jean Tinguely (1960)

In his Radio Series, Jean Tinguely takes apart radios and displays their inner workings. There are several pieces in this series called radio *drawings* [Artnet] that are of particular interest (no. 7, no. 8, no. 9, no. 15). These are compositions that splay out the interior electronics of radios onto transparent plexiglass. In a normal radio, components would be arranged so that they take up as little space as possible within the device. Tinguely inserts space in between them and arranges them in relationships that direct a viewer's gaze.

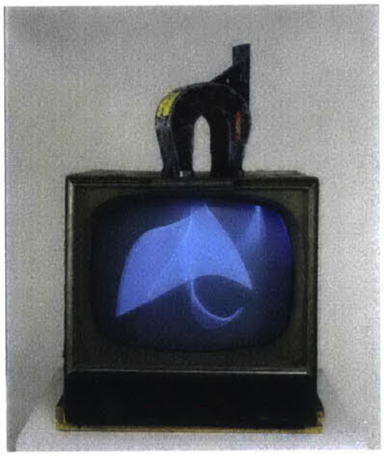

Radio WNYR No. 15 (1962), Jean Tinguely

Tinguely dissolves technological opacity by displaying only the essential components of a radio and disregarding its outer shell. Wires, knobs, speakers, electronic components, and other radio components are sometimes displayed alongside nails and colored acrylic disks. These raw, non-electronic materials live naturally alongside the radio components. Radio becomes raw material.

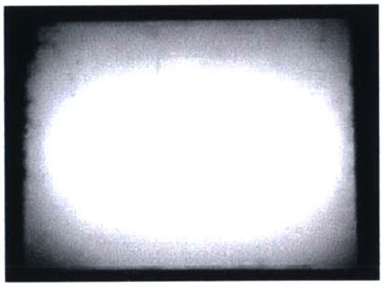

Radio WNYR No. 9 (1962), Jean Tinguely

The suggestion that these pieces are drawings, even though they are 3-dimensional, is appropriate. Tinguely reduced the technology of radio down to a material that is as legible as a pencil. In the same way that modernist painters sought out and surfaced the material of paint, Tinguely sought out and surfaced the material of the current technology of his time.

Nam June Paik's work renders the Television into an expressive material. In *Magnet TV* (1965), Paik uses a horseshoe magnet to manipulate the flow of electrons in a television set before they reach the image plane. With keen insight into electronic technology, Paik surfaces the material of an opaque technological medium. By gaining access to the core material of an electronic image, Paik seizes the television as a medium for artistic expression.

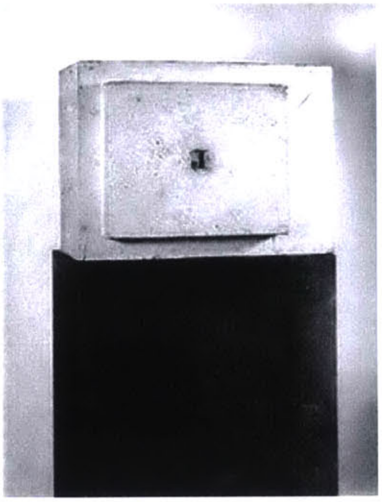

Magnet TV, Nam Jun Paik (1965)

While televisions were the current technology of the time and at the forefront of visual media, Tony Conrad's *The Flicker* is an example where a current, but not new, technology is used as a medium. This piece is constructed using only alternating black and white images. Conrad successfully reduces the medium of film into its fundamental components: light, darkness, film and a projector. By composing fluctuating patterns of light and darkness, Conrad elicits a physiological effect on the audience. The rapidly switching frames are known to trigger neural reactions in viewers [Media Art Net - Conrad]. When viewed appropriately with a film projector in the same room, this visual effect is accompanied by the projector's sound. With this work, the technology of film is reduced to its fundamental components. Film is stripped of its technological opacity, even the projector becomes part of the work. Technology is not really the subject of this work, but it is very much the material.


The Flicker, Tony Conrad (1965-1966)

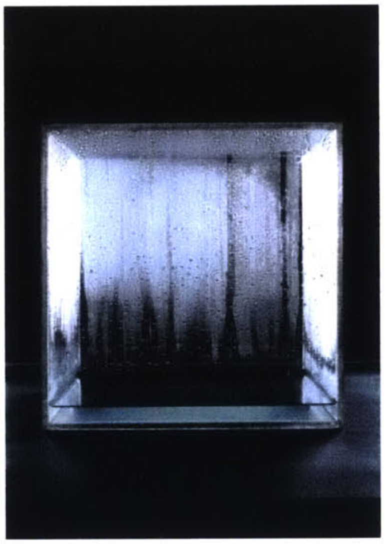
Wolf Vostell's work takes on technology as a subject with a more forceful, reactionary approach. *Stationary Traffic* (1969) is a piece where Vostel casts an entire car in concrete. In *Concrete TV Paris* (1974-1981) a functional TV is cast into concrete leaving a tiny window onto the screen. This approach to technology differs from Paik and Tinguely in that through the use of concrete, Vostel reacts to technological opacity by reinforcing it.

Stationary Traffic, Wolf Vostell (1969)



Concrete TV Paris, Wolf Vostell (1974-1981)

In *Condensation Cube* (1965) by Hans Haacke, a small amount of water is enclosed in a sealed plexiglass cube and exhibited in a museum where the temperature is usually around 65 degrees fahrenheit. As the temperature within the cube rises, and the humidity is at effectively 100%, the dew point is reached and condensation appears as water droplets on the inside walls [Jarzombek].

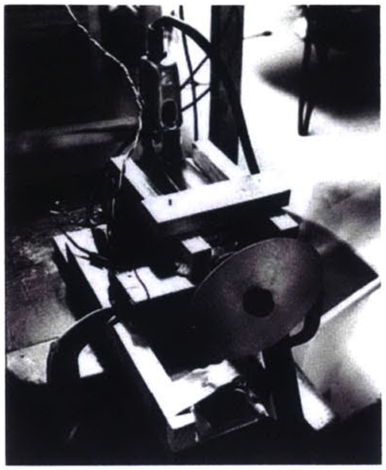


Condensation Cube, Hans Haacke (1965)

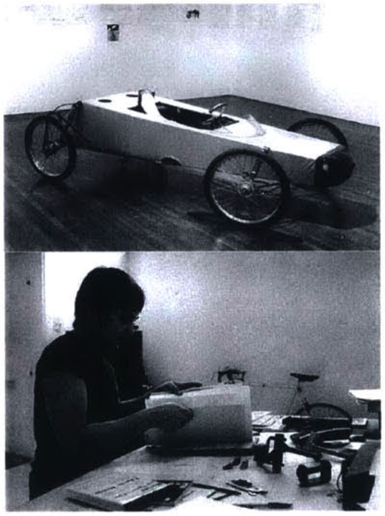
Aside from plexiglas being a new material at the time, the medium of this piece is non-technological but the subject matter very much is. The materials used are simply water and plexiglass. But they are arranged in a way that surfaces the dynamic interplay of systems within the natural world. This act of surfacing an otherwise hidden system, is very much motivated by technology.

In *Beyond Modern Sculpture*, Jack Burnham attributes the rise of systems into consciousness in the 1960s to our increased participation in them. He uses buying a car as an example of this. We no longer buy an object, in the old sense of the world, instead we buy a lease to temporarily participate in a transportation system, a traffic safety system, a highway system, an industrial parts-replacement system, a drive-in eating system, etc. [Burnham 11]. Yes, advances in technology prompt our participation in broader systems. But they also let us see and understand the broader systems that we are a part of already.

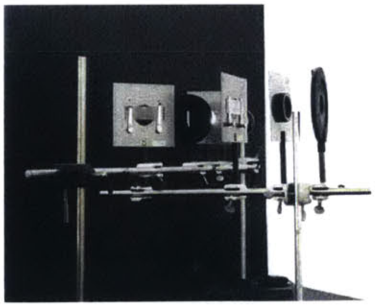
Chris Burden's work is very much about the broader systems that we participlate in, specifically the ones brought about by power, which is a characteristic of technological opacity. Burden's approach to these presiding systems is to take technology out of them. He does this by reducing technology to a scale that a single human can construct and experience. In doing this he removes technological devices from their broader accompanying systems, so that they can be experienced in isolation.


C.B.T.V., Chris Burden (1979)
IMAGE : http://www.feldmangallery.com/pages/exhsolo/exhbur77.html

C.B.T.V. (Chris Burden Television) (1977) is a piece by the artist Chris Burden. In this work, Burden recreates and demonstrates the original apparatus that led to the invention of television. By duplicating and demonstrating television in its original mechanical and simple form, Burden was able to construct a television with relatively simple and accessible materials. He doesn't need a cathode ray tube, or a custom glass vacuumed enclosure, those would require a specialized manufacturing facility. In a press-release from the Feldman Gallery where this work was first exhibited, Burden's hopes that *C.B.T.V.* would enable people to understand the technological principles behind current electronic television [Feldman]. It is no longer a device eclipsed by fleeting images generated by mass media, but allows people to experience television as pure material.


B-Car, Chris Burden (1979)

In *B-Car* (1979), Chris Burden designs, engineers and constructs a car that travels at 100 mph and consumes 1 gallon of gas per 100 miles travelled. Burden kept all of his sketches and construction notes for the car. These are meant to be viewed alongside the car as documentation of the car's construction. Burden reduces the car to just the requisite material for it still to be considered a car. Like with *C.B.T.V.*, the car becomes raw material scaled to meet the needs of and be constructed by single individual.


The Speed of Light Machine (1983), Chris Burden

The Speed of Light Machine (1983) is a working reproduction of the original late 19th century scientific apparatus used to measure the speed of light. A beam of light is projected through a series of lenses and bounced off a small mirror spinning at 500 times a second. By controlling the apparatus, viewers can observe physical evidence of light's finite speed. The speed of light is normally represented by a number that we take for granted and that is too big to truly grasp. Here, Burden instantiates this opaque physical concept as physical material.

Even though Chris Burden had many precursors and worked with assistants, his work single handedly confronts technological complexity and the broader systems that accompany it. He reduces technology to the scale of a single human, for us all to experience. The television, the car and the speed of light are removed from the broader context where they normally exist. The television is stripped free of the broadcasting system, image standardizations and communication protocols. The car is taken out of the system that governs industry standards of car design, construction and safety. The speed of light is rendered in a context accessible not only by physicists, but by everyone.

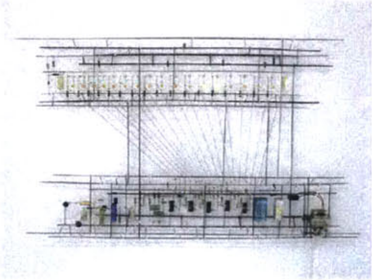
2.4 CONTEMPORARY TECHNOLOGY ART

Digital electronic technology brings a new set of challenges for the artist with respect to technological opacity. The technologies that were referenced in earlier artworks had not been subject to the mass miniaturization that accompanies and enables digital electronics. Early mechanical technologies are visible to the naked eye. You could tell how something worked by looking at it. Cars had hoods that your could open up and fix something broken. With electronic technologies, appearance no longer necessarily relates to function. Original CRT televisions had cases that you could pry open to find discrete electronic components soldered to a PCB. Here, unless you have prior knowledge about electronics, it becomes harder to glance at something and know how it works. An enclosed metal canister with two metal leads sticking out of it in no way embodies the functionality of a capacitor. This abstraction between form and function is exacerbated with the introduction of digital electronic technology. Components are no longer discrete, let alone visible.

In addition to miniaturization, the scale shift embodied throughout digital electronic devices is another challenge that this technology brings to the artist. Here we have nanoscale transistors within a device that we can manipulate with our hands. When the nanoscale is rendered visible, suddenly the milli and even micro scale are out of scope.

Similar to how earlier artists responded to their technological landscape, the following group of works demonstrate how artists use current technology as a subject and/or medium. A focus is placed on the challenges raised by the opacity that is coupled to a world with digital electronics.

Peter Vogel creates some of the earliest interactive artworks with analog electronic components. In *Moving Lights* (1980), photocells respond to changes in light as viewers move past the work and corresponding LEDs light up. Attention is also paid to the formal qualities of analog electronics as material. Components are carefully composed, to provide both a physical scaffolding and also to convey a legible, inviting aesthetic. Here the electronics are functional, and are also considered as an expressive medium.

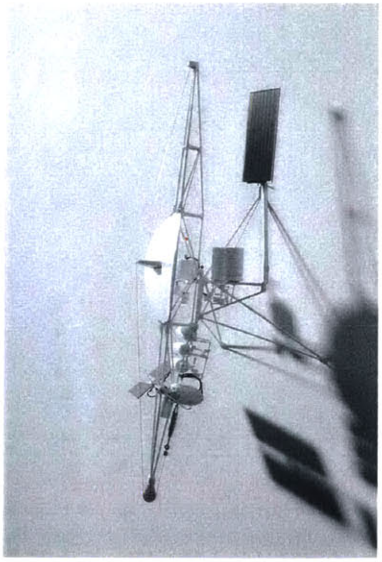


Moving Lights (1980), Peter Vogel

Technological Mandala 20 - Resonator (2014) by Leonard Ulian is part of a series of work where electronic components are used as compositional and structural elements. Copper wires radiate outwards from an Integrated Circuit in a resonant wave pattern, perhaps suggesting the chips' embedded functionality. Components are splayed into a pattern where their potential to function will never be realized.

Technological Mandala 20 - Resonator (2014), Leonard Ulian

Bjoern Schuelke uses electronic components as structural and functional elements in his work. *Transmitter* (2011) is part of his photovoltaic series. As light in a space hits a small solar panel, the energy captured powers a motor to subtly reposition the work. The electronic components along with any additional structural material is uniformly cloaked in white automotive paint. The effect deletes superficial features of individual components, such as capacitor values, and focusses our attention on components as formal elements. Even though Schuelke's uniform coat of paint partially obscures the electronic components, this technique reinforces the idea that their markings are an added notation. By removing that layer, the emphasis is placed on form. These works use primarily analogy electronic circuitry, but they are important to show because they establish a well defined use of electronics as material.



Transmitter (2011), Bjoern Schuelke

Info Glut (1997) by Alan Rath lives at the intersection of technology and the body. CRT monitors show hands signing non-sensical ASL extend from a mouth. The superimposition of the raw aesthetic of bare electronics with pre-recorded video of human body construct a space where the two can exist simultaneously. Using video, and an anthropomorphic composition, the material of electronics is merged with the material of the body.

Info Glut II, Alan Rath (1997)

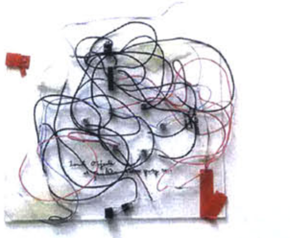
Radio in a bag (1981) is a work by industrial designer and architect Daniel Weil. Here, the inner workings of a radio are removed from their ordinary, hard plastic and opaque enclosure and packaged inside a transparent plastic bag. The components are placed in a visual composition alongside graphic surface treatments of the bag. In this work, Weil calls for the same care and attention to be paid to the design of the electronics, in the same way that normally just the surface of devices are treated.

Radio in a bag (1981), Daniel Weil

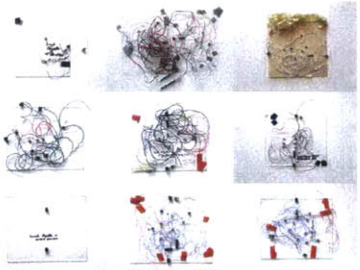
This idea is extended in *Tube Map Radio* (2012) by Yuri Suzuki. In this work, the electronic components and the PCB is the complete functional radio. There is no protective enclosure that shields the electronics. Here is an assembled Printed Circuit Board (PCB) of a functional radio overlaid onto a map of the London Underground. Here, the PCB itself is the stand-alone functional device. What is normally hidden away within a protective case is now material that can be touched and handled. The electronics are arranged so that landmarks correspond to functional components, there is a speaker at Speaker's corner and a battery at Battersea Power Station.

Tube Map Radio (2012), Yuri Suzuki

Loud Objects is a New York City based trio (Kunal Gupta, Tristan Perich, Katie Shima) formed in 2005. The group stages performances that construct noise with minimal electronic components. As the performers live solder custom audio circuits on top of an overhead projector, the audience can experience the sound and also see how the sound is constructed. The effect draws you closer to the physical, raw material of digital sound than you would get through a laptop [Loud]. Each instrument is a single microchip. The output pins are pre-programmed to switch off and on (from 0 to 5 volts) at a frequency that is audible. Throughout the performance, microchips are taken out of a bag and indiscriminately soldered together live. You can't tell what sound will emerge based on the appearance of each chip. Sound gradually accumulates until the performers decide to stop.



Loud Objects (2005-PRESENT)
Sound circuit board from a performance.



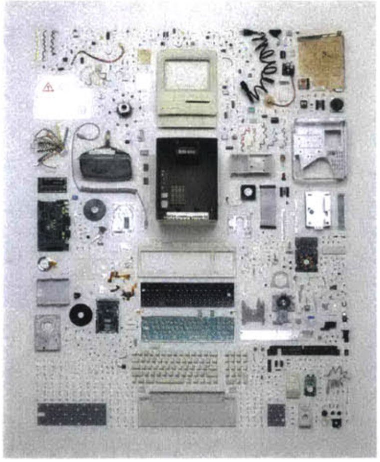
Loud Objects (2005-PRESENT)
Series of sound circuit boards from performances.

Along with Tinguely's Radio Drawings, these projects are inspirational. Loud Objects is also reminiscent of Tinguely's Radio Drawings because of how they reduce technology to raw material and manipulates it in a way that is fluid and expressive. The way that Loud Objects works with electronics elevates them as a raw material. Instruments are not precious. And the rules of the electronics, the requirements of power, ground, and an output pin to be connected, are not constraining. The chip's pins are deformed to make them easier to solder, they are tossed around and manipulated in a way that reminds you of a kid gluing macaroni.

Hecho en Switzerland (1995) - Tom Sachs

Tom Sachs is a contemporary artist who reconstructs technology out of a well honed material palette of plywood, white paint, resin and tape. In doing this, he reduces technology to raw, accessible material. Over the years he has constructed a piano, a series of boomboxes, a lunar module, a mars rover, a refrigerator and even functional guns. *Hecho en Switzerland* (1995) is the first gun exhibited by Sachs. It is said that Sachs originally made these pieces as a way to make money with the NYPD's gun buy back program in the 90s that would pay you $300 if you turned in a working gun [Boing Boing]. The gun series is important to show here because these objects use simple, legible materials to construct functional technologies.

Todd McLellan's Things Come Apart is a series of photographs where everyday technologies are disassembled into individual parts and then photographed. These works expose the inner components of everyday devices, an old macintosh computer, a telephone, a pen, a fire extinguisher are all broken down and set into arbitrary rectangular compositions. The hierarchical interconnections of components are broken down so that each is assigned an equal weight. These technological objects are no longer operational. And are made visible as standalone objects, but also as parts belonging to a whole. This piece raises the important issue of establishing a new sense of order once the hierarchy of a technological object is dissolved.

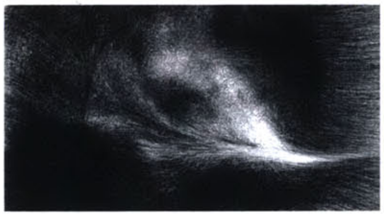


Things Come Apart (2013), Todd McLellan

Tauba Auerbach's *RGB Colorspace Atlas* (2011) is a material representation of an abstract color model. The RGB Color model is used by computers to represent and display color. Here, that model is rendered as physical book. All possible gradients of color within the RGB color model are realized in material at human scale.

RGB Colorspace Atlas, Tauba Auerbach (2011)

Casey Reas writes software to explore conditional systems as art [Reas]. In *Tissue Software* (2002), Reas models synthetic neural systems based on the ideas of neuroanatomist Valentino Braitenberg [Reas - Micro]. This work makes visible the emergent properties of hidden systems that would otherwise be impossible to experience. It also renders a systematic hierarchy that is scaleless. This work carries an aesthetic of complexity that is immediately associated with computers. It lives both as software, on a computer screen and as digital prints.



Micro Image - software 1(2002/2014), Casey Reas

An interest in systems persists today, but is motivated not only by our participation in them, but in our unprecedented ability to visualize and model them. Today, everyone has access to the technology required to model the behavior or emergent properties of a complex system[7]. However, this unprecedented ability to model complexity through digital computation, is not met with a corresponding ability to physicalize that complexity.

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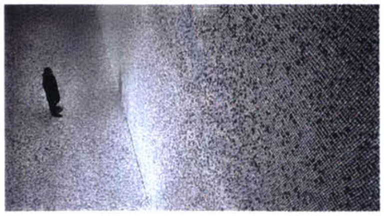
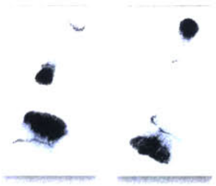
[7] Easy to learn programming environments like Processing (processing.org), an open source programming environment by Casey Reas and Ben Fry, can have you modeling a complex particle system with just a few lines of code.

In Ryoji Ikeda's work, viewers are literally immersed in the infinitely vast universe of data[Ikeda]. *data.tron* (2008-2009) is not intended to be experienced through a conventional screen or a physical print, but instead as a fully immersive installation. Using projected light, this work materializes computer data at a scale that people can inhabit. The experience of this work is physically overwhelming in a way that recalls Tony Conrad's *The Flicker*. We are surrounded and dwarfed by data, but it is unclear what the data is, and where it comes from. This reminds us of the overarching challenge of representing vast differences in scale simultaneously. The effect reinforces our disconnect with the material of digital technology.



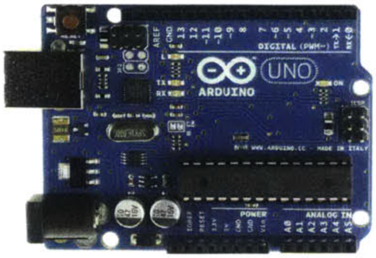
data.tron, Ryoji Ikeda (2008-2009)

Zoom In Zoom Out (2013) is a piece in Evan Roth's Multi-Touch Painting series. In this work, the point of contact between people and the surface of digital electronic device (a smart phone) is captured, enlarged in scale and rendered as physical material. This piece calls attention to the opacity of digital electronics, to the surface of the black box, the boundary that keeps us out.



Zoom In Zoom Out (2013) - Multitouch Painting series, Evan Roth

2.5 EDUCATIONAL ELECTRONIC TOOLKITS


Arduino UNO


Little Bits (2008-PRESENT), Ayah Bdeir


Denki Puzzle, Yuri Suzuki + Technology will save us (2012)

While the work presented in this thesis is about granting access to the hidden material and structure of digital technology, it is not meant to teach people about electronics. The difference is subtle, but it is important. There are a variety of highly innovative electronic toolkits where the main objective is to give people access to technology as a tool for making as quickly as possible. New vernaculars that surround electronics as a material are presented to facilitate engagement. So it is important to mention these works as references. It is also worthwhile to note that often black boxing, such as hardware and software encapsulation that contribute to the opacity of technology, are often used as techniques to make working with electronics easier.

Arduino is an open-source software and hardware platform meant as an introductory tool for working with electronics. This platform provides a programmable microchip on a breakout board for easy access to input and output pins. The high level software environment that lets you write programs is written on top of C[8], takes you further away from the material of the machine.

LittleBits lets people build electronic circuits with a kit of magnetically linkable parts.

Denki Puzze (2012) is a kit of PCBs that can be assembled in 3-dimensional space as a physical circuit and functional device. The form of each PCB indicates a particular function. This piece lifts electronics from their 2-dimensional plane and introduces a new layer of tactile syntax to help understand how they work.

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[8] C is a general purpose computer programming language developed in the late 60's [Wikipedia C].

3. DIGITAL ELECTRONIC TECHNOLOGY

3.1 A MATERIAL HISTORY

Technological innovation happens around the premise of utility, and at the expense of legibility. Designs are engineered to be functional, but not necessarily understood. This is not only a result of technical complexity, but also a result of a design practice that favors limiting engagement with a machine to its bare essential points of input and output. This methodology begins with Dieter Rams in the 60's and continues today with Apple Computers. The intentional black boxing of digital electronics by designers is one aspect that disengages us from electronics as material, and makes them difficult to understand.

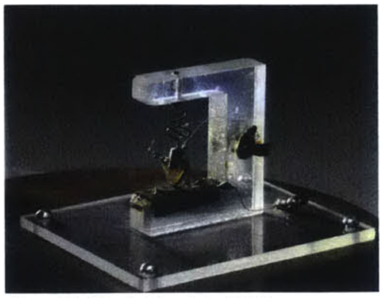

Figure 3.1.1The first transistor (1947)

Other factors contribute to the opacity of digital technology such as the irreconcilable confluence in scale within a single device. Even the laws of physics change between a device that you can hold in your hand and the nanoscale semiconductor material that makes it work.[9] This shift in scales, is what contributes to the opacity of digital electronics. This wide range of scale within a single system also happens to be a reason why the brain is so hard to understand [Boyden].

Figure 3.1.2 The first Integrated Circuit (1958)

The test-rig of the first transistor [Figure 3.1.1] along with the first Integrated Circuit [Figure 3.1.2] instantiates a certain truth to materials that is completely disconnected from our experience of digital technology today. The inventors of the transistor worked at the scale of physical matter while simultaneously manipulating volumes of electrons [Dunne 7]. Today the material of the transistor has been conditioned by the demands of mass manufacturing. Transistors are sized at the nano-scale and encapsulated in protective blocks of plastic [Figure 3.1.3].

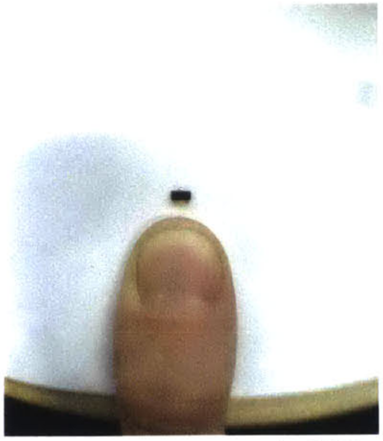

Figure 3.1.3 A single outline transistor in a SOT-23 package with my thumb for scale. It is important to note that the actual transistor is at the nano-scale. What you see here is the outer plastic casing.

The solid-state transistor and the Integrated Circuit are the physical, material bridge between a theoretical possibility and a physical, real world application. Up until the invention of the solid-state transistor, and following that, the Integrated Circuit, the theory behind computation was mapped out, but computers were impossible to build. Mechanical relays weren't robust enough and even with the invention of the solid-state transistor, it was

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[9] As transistors are miniaturized to the nanoscale, suddenly things like the percentage of atoms at the surface of a material become significant; at the micro-scale that didn't matter [Mesoscopic].

impossible to reliably wire hundreds and thousands of components together to realize more complex designs [Reid].

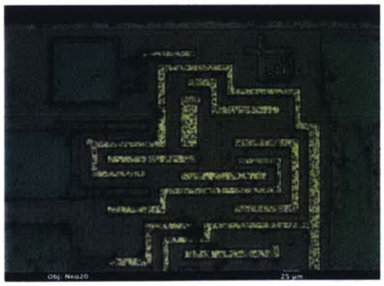
At the time, to build anything you needed to wire wrap or hand solder individual components. Wiring hundreds and thousands of components together made it impossible to manufacture devices in an efficient way. The first Integrated Circuit, invented in 1958, demonstrated that it was possible to build multiple components, transistors, resistors, capacitors onto a single chip. This was revolutionary.

The initial prototype of an Integrated Circuit showed less than a handful of components on a single chip. As of 2014, over 5.5 billion transistors can fit onto an chip that is 661mm^2 [Transistor Count].

A look today into the actual material of digital electronics requires a delicate and caustic process of reverse engineering. There is a small community of electronics hobbyists who reverse engineer chips. The process involves extracting it from its plastic casing, etching away at it with toxic chemicals, photographing it with a microscope and then performing an analysis to try and figure out what stuff is. This method of reverse engineering a chip is a destructive process. Once you are inside, the chip no longer functions. Two wiki sites that provide tutorials and an archive of reverse engineered ICs are siliconpr0n.org and siliconzoo.org. Much of this work is done with older ICs since the transistors are larger and visible with an optical microscope. This is another limitation of this technique. The transistors in today's chips can measure down to 10nm [22 Nano]. Features of this size are not visible with an optical microscope where the resolution limit is 250nm [Micro]. Instead you need a scanning electron microscope, a much more expensive piece of equipment that is difficult to access.

This technique of reverse engineering produces beautiful results, and effectively lets you see into a chip. Once we see inside, it is really hard to decipher what is going on, unless you are a well versed electrical engineer.

An archive of reverse engineered Integrated Circuits are hosted on siliconepr0n.org. There are currently 18 individuals who have posted their microscope die images to the collection. A zoomed in image of a classic 74 series six element logic IC is shown in [Figure 3.1.4]. The elements within this 1970's technology are at the micron scale.



3.1.4 Azonenberg's optical microscope images of the 7404 IC [Azonenberg]. This Integrated Circuit features six inverter gates.

The core material unit of this work is the transistor, specifically the Mosfet[10] (metal-oxide-semiconductor field-effect-transistor), and the technology that stems from it. Starting with the discrete Mosfet shown in [Figure 3.1.3] and extending outwards, the work begins with CMOS (Complementary Mosfet) logic, next the IC and finally the PCB.

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[10] Mosfets and Transistors will be used interchangeably throughout this document unless otherwise specified.

3.2 NEW MATERIAL DEVELOPMENT

The material process developed for this work was motivated by a desire to lift electronics out of their everyday vernacular. This process is intended to call attention to and reveal aspects of electronics that are otherwise hidden, and also to forge a setting to come in contact with the material of electronics.

The fabrication technique required for this work must allow electronic traces to be considered as volumetric objects, and also for circuits to be constructed at human scale. In order to do this, several techniques for constructing transparent circuit boards were investigated.

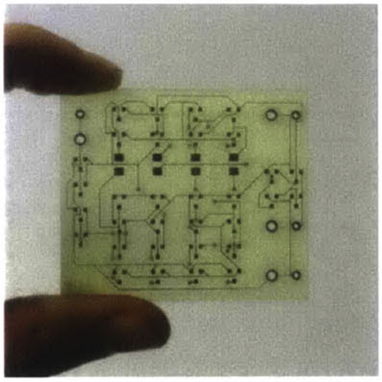
Figure 3.2.1 Bare-bones PCB.

Ordinary printed circuit boards are fabricated with photomasks onto a substrate with a conductive coating. They are then coated with a colored (usually green) solder mask, leaving the solder pads for components exposed. This also makes the traces between components difficult to see. A bare-bones PCB [Figure 3.2.1] is a PCB without solder mask. The material is usually some type of glass-reinforced epoxy laminate that has a semi-opaque yellowish tint. Barebones PCBs have a certain crude aesthetic quality to them, but they are limiting since they are not transparent, and also don't easily scale.

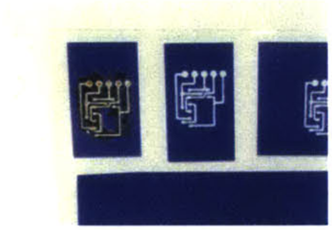
Figure 3.2.2 Test with Circuit Scribe conductive ink pen.

Techniques to fabricate glass circuit boards were also considered. A DIY tutorial on Hackaday by Kevin Dady uses a method where a copper laminate is cemented to a glass microscope slide and then photo-etched with chemicals[Dady]. This process would not work at the scale required for the work presented here. It also doesn't easily allow for the fabrication of vias[11] needed for double sided circuit boards.

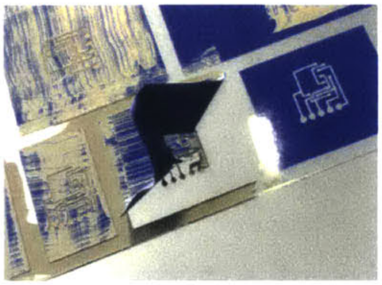
Figure 3.2.3 Test with conductive ink and vinyl cut traces.

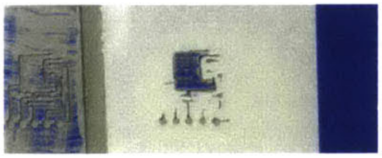
Figure 3.2.4 Test with conductive ink and vinyl cut traces after the vinyl stencil is removed.

Several circuit fabrication methods were experimented with that involved using the vinyl cutter to mask out the negative space between electronic traces. The first used the Circuit Scribe conductive ink pen[12]. This pen is meant to be used on glossy photo paper and does not soak into the acrylic enough in order to make an electrical connection, regardless of how many layers were applied [Figure 3.2.2]. Another limitation was that the vinyl cut traces had a limit on how small they could get without warping, so the lines

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[11] A via is an electrical connection between layers of a circuit board.

[12] https://www.kickstarter.com/projects/electroninks/circuit-scribe-draw-circuits-instantly

were not very precise. The next test used conductive ink from Conductive Compounds part number AG-610. In this case the ink did not adhere well enough to the acrylic surface and came off with the vinyl stencil[Figure 3.2.3]. This was the result [Figure 3.2.4]. The third method attempted was to use gold leaf as electronic traces. An advantage of gold leaf (as opposed to the conductive ink) is its high conductivity. However, the gold leaf did not stick well enough with the adhesive and also came off with the vinyl stencil[Figure 3.2.5].

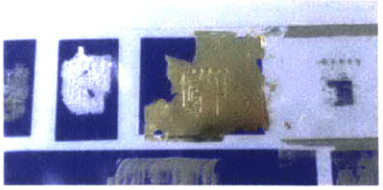

Figure 3.2.5 Vinyl cut with gold leaf.

The next method attempted was based off of Hannah Perner-Wilson's *A-Kit-of-no-parts* experiments with laser engraved traces [Perner-Wilson]. Perner-Wilson used the technique where she laser etched the surface of plywood covered with masking tape and filled those traces with conductive ink [Figure 3.2.6]. Once the ink was dry, she removed the masking tape.

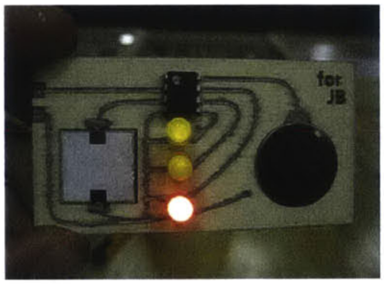

Figure 3.2.6 Laser etched traces in plywood from Hannah Perner-Wilson's A-kit-of-no-parts.

The technique used here is similar. However masking tape is not needed around the etched wells because acrylic is non-absorptive,. Once the ink is dry any excess ink on the surface is scraped away to electronically isolate the traces [Figure 3.2.8].

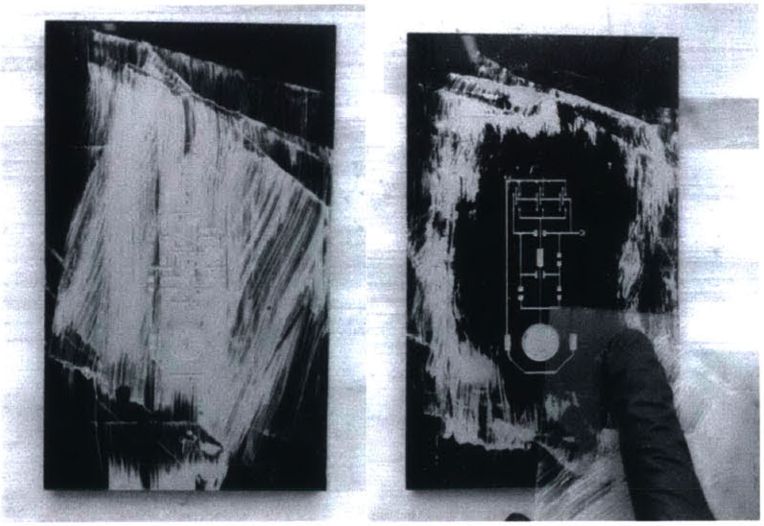

Figure 3.2.8 Close up of conductive paint on etched acrylic (Left). Close up of the process of removing excess conductive paint from the etched acrylic (Right).

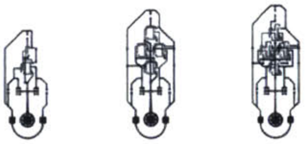

Figure 3.2.7 Vector file used for laser etching.

These electronic schematics were designed initially using Eagle[13]. The board traces were exported as high-resolution images and imported into Adobe Illustrator [Figure 3.2.7]. The images were converted into vector

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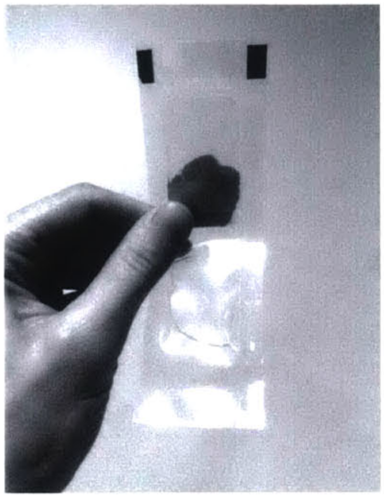
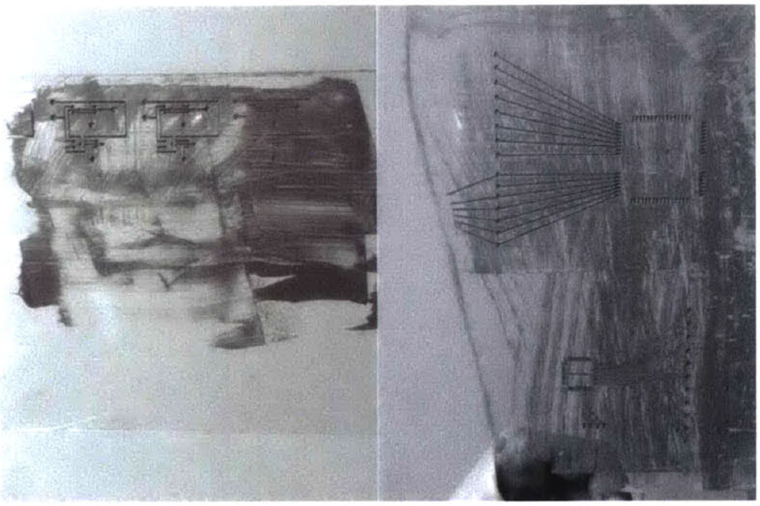
[13] Eagle is PCB design software [http://www.cadsoftusa.com/].

drawings; the lines and traces were cleaned up in order to meet the laser specifications. The traces were etched to an approximate depth of .4mm +/- .1mm. It is important the traces are not too deep because the electronic components need to sit on a flat surface. Other tests were done to make sure that this process could accommodate the footprint of some pin pitch[14] ICs.



Atom Adhesives 902-LP 2-part conductive epoxy.



Some early laser tests to determine the laser etch depth (left). Tests to determine the component footprint pin pitch (right).

23 ga. blunt tipped syringe filled with conductive epoxy.

Components are mounted to the surface using 2-part conductive epoxy. This epoxy is 1 time use and has a 90-minute pot life. Once the two parts are mixed, it is loaded into a blunt tipped syringe and applied to the component pads. The epoxy has some thickness to it and helps to support components even if they are not lying perfectly flat.

The main challenge with this method is that conductive ink is not an ideal conductor. Traces as small as 1" in length and up to .04" in thickness have a resistance of between 2 and 5 ohms. This resistance accumulates over the span of an entire circuit and can add upwards of 100 ohms of resistance to a circuit depending on its size. Depending on the type of circuit, these resistive loads can impact whether or not it will function. The resistance of conductive ink presents even greater challenges when working with high current applications, or when transmitting complex digital audio signals because the signal is truncated.

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[14] Pin pitch refers to the space between the contact pads of the leads of an electronic device.

This technique is effective in terms of an aesthetic quality but has limitations with more complex electronics applications. It is nonetheless a fruitful technique for many use cases.

4. SURFACING THE INTERIOR DIGITAL ELECTRONICS

4.1 CELLULAR TELEPHONE

4.1.1 SUMMARY

The focus of inquiry here is just below the protective enclosure of a digital electronic device.

A diagrammatic representation of and also a functional cellphone live as an assembly of electronic components suspended on a transparent acrylic plane. The buttons, microphone circuit, charging circuit, GSM module, etc. are arranged as objects in space so that you can see their relationships to each other. Their connections are no longer invisible traces on a PCB, but lifted up and made explicit with wire.

Once that enclosure is stripped away, the goal here is to capture a moment when components are wrenched from their circuit board. The most prominent feature that remains are the hand wired connections that hold components in a delicate balance that culminate as a functional cellphone.


Figure 4.1.2.1 David Mellis's DIY Cellphone.

4.1.2 DESIGN, ENGINEERING + MATERIAL PROCESS

The circuit for this work is based on David Mellis's DIY Cellphone [Figure 4.1.2.1][15]. Mellis's bill of materials and schematic designs are used as a technological framework and starting point. Throughout the research process, this is modified based on aesthetic and technical requirements.


Figure 4.1.2.2 Initial design schematic with through-hole components. Here the overall compositional relationships are unresolved.

The initial design for this piece was conceived of using wire wrap and through-hole[16] components. It was important that the components were viewed exploded on a spacious plane, as opposed to a densely packed circuit board. Holes were to be laser cut into 1/16" transparent acrylic. The components are mounted in the holes, connected with brightly colored wire wrap and held in tension with fine brass pins epoxied into place [Figure 4.1.2.2].

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[15] http://web.media.mit.edu/~mellis/cellphone/

[16] Through-hole refers to a way that electronic components are packaged and mounted to printed circuit boards. Through-hole technology is older and takes up more space on a PCB than newer package technologies.

The electronics that make up the cellphone were substituted with through-hole components and redrawn in Adobe Illustrator. From here they were arranged, not so that they cram into the smallest possible space. But so that instead their arrangement defines the space they inhabit. Several different organizational paradigms were considered here. Components could have been ordered based on their size or color. Or their placement constrained to a strict 1 square inch grid.

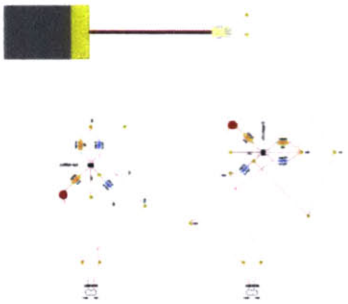

Figure 4.1.2.3 Detail view of the charging circuit.

The GSM module, the micro-controller, the microphone circuit, the speaker circuit, the charging circuit, the keyboard buttons are all functional divisions that make up the cellphone. Keeping in line with the themes throughout this work, the components are organized in a way that most clearly reveals their functional and hierarchical relationships most clearly [Figure 4.1.1.3,4]. The paradigm chosen clearly presents and articulates the connections between components. The geometric, graphical aesthetic helps guide a viewer's eye through the work.

Figure 4.1.2.4 Detail view of microphone and speaker circuit that extend from the micro-controller.

Before producing the through-hole version of this work, work began on a new technique for working with surface mount[17] components and conductive ink. Switching back to surface mount components was important because this technology is more aligned to current electronic technology. If you were to actually open up a digital electronic device today, you would never see a through hole component.

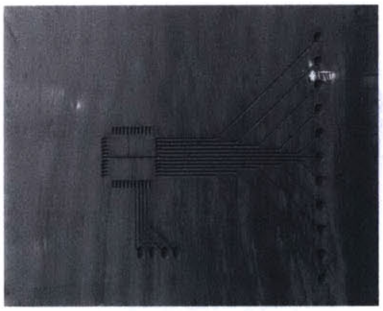

Figure 4.1.2.5 Conductive ink test for the Atmega1284 pinout testing smallest footprint feature.

The Atmega 1284 used as the micro-controller for the cellphone is has the smallest footprint. Tests were done with the technique of laser etching acrylic and filling it with conductive ink to see if the traces could be electronically isolated [Figure 4.1.2.5]. Modifications were made to the trace width to make sure that the traces would be as thick as possible, so that they could conduct while also be electronically isolated.

The circuit for this piece was made first in Eagle and then brought into Adobe Illustrator so that the lines could be adjusted according to the limits of the production process [Figure 4.1.2.6, 7].

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[17] Surface mount refers to a technology where electronic components can be mounted directly to the surface of a PCB. There are various types of surface mount packages that reduce the footprint of components and save space on a PCB.

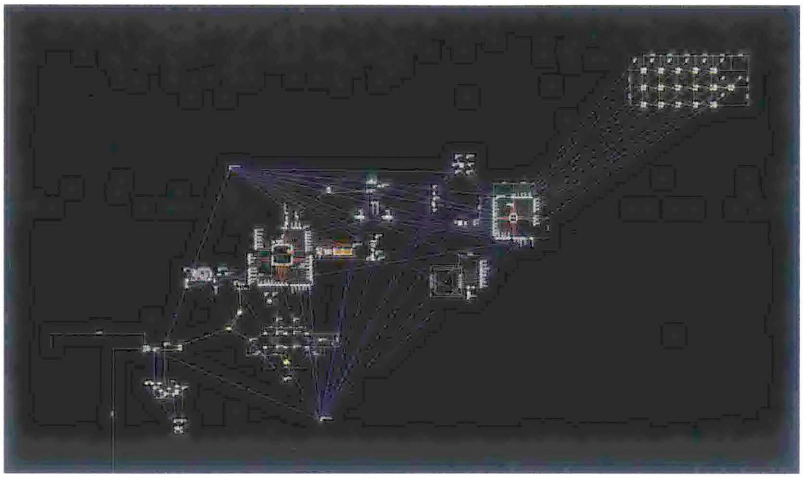

Figure 4.1.2.6 Design schematic view in Eagle with overall composition.

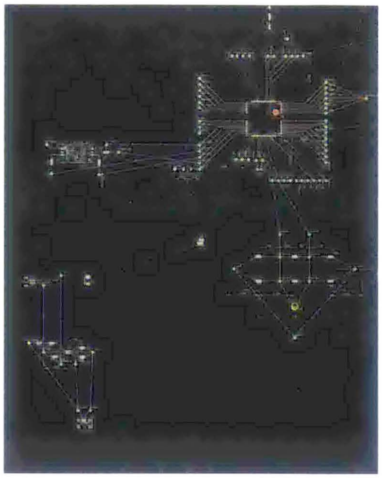

Figure 4.1.2.7 Detail view of Design schematic in Eagle.

It is important for the final version of this piece to be considered as a standalone object, in the same way as the cellphone itself. With this piece however, the boundary between a user and a device is not a clearly defined as with an ordinary phone. Here the barrier between the phone and the technology that is the phone is more porous and open to interpretation. With the electronics suspended onto a sheet of transparent acrylic, there is no definite boundary between what is inside and out.

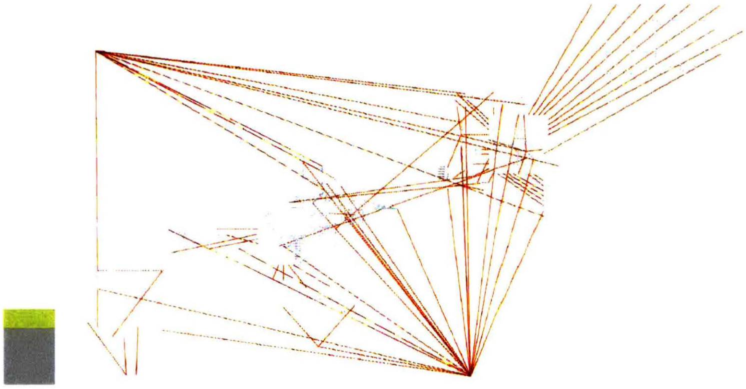

Figure 4.1.2.8 Design schematic with surface mount components with overall composition resolved. This just shows the part footprints in grey and the wire wrap lines in orange.

A variety of designs for a sculpture base were considered as a way to think about how the work interfaces with the world. The first shown in [Figure 4.1.2.9-11] was for a steel base that would wrap the bottom of the work and allow it to stand freely. After more consideration, this idea of wrapping wasn't in line with the overall work because it would let the piece free stand in way that seemed magical, but it was difficult for a viewer to understand.

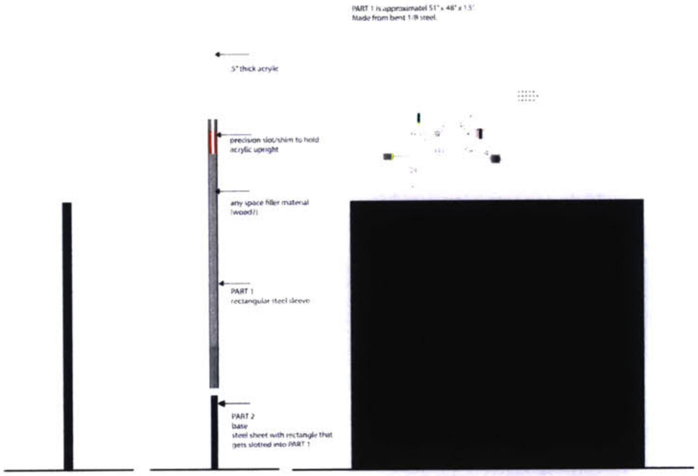

Figure 4.1.2.9 Sketch of base construction. Acrylic wrapped in steel that slots into a steel platform to stand upright.

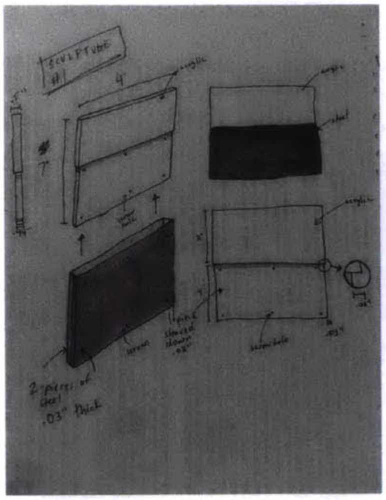

Figure 4.1.2.10 Early sketch of base construction. Acrylic is wrapped in steel.

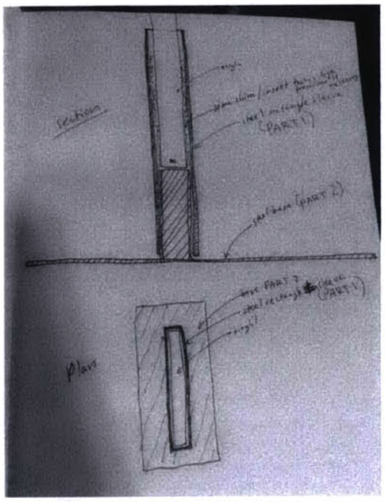

Figure 4.1.2.11 Early sketch of base construction. Acrylic is wrapped in steel. Fabrication section.

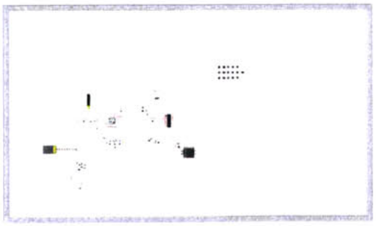

Figure 4.1.2.12 Sketch of an early version with a steel frame as a base.

Other methods were considered such as a steel tube frame [Figure 4.1.2.12] and also as a plane that hangs from the ceiling. The latest iteration of the piece is set to be etched on the upper part of a 60"x48" sheet of acrylic that is held standing upright with a base constructed using 3/4" square tube stock welded into a minimal support structure [Figure 4.1.2.13].

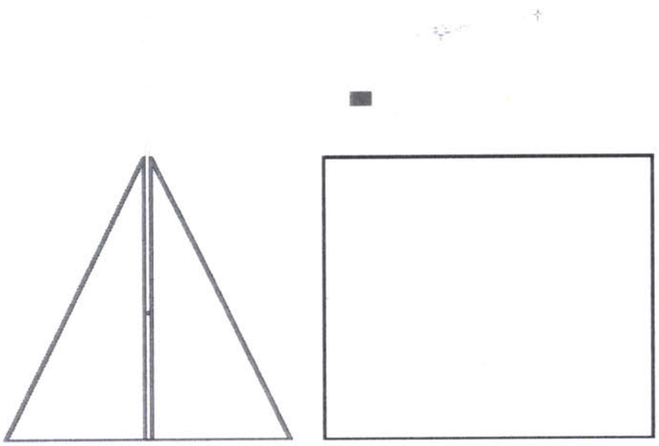

Figure 4.1.2.13 Sketch of option for base with 3/4" square steel tube stock.

4.1.3 DISCUSSION

In this piece, the cellphone is stripped of its protective enclosure. The components that are normally arranged on a circuit board to take up as little space as possible, here are composed as material in space.

The primary scale shift in this work amplifies hidden wire traces on a PCB into perceivable material. The scale of the other components are maintained.

The entry points into this work are similar to how you would normally engage with a cellphone. The keypad maintains its familiar arrangement of buttons, even though it is rotated 90 degrees. These buttons are normally covered in a protective layer with screen printed numbers, here they are left raw. Other familiar aspects of the phone are the screen, the USB charging circuit and the battery. This phone, unlike many today, has a replaceable rechargeable battery. These familiar elements are stripped bare to reveal their connections to the Integrated Circuits and other electronic components that make the phone work. The familiar is placed in relationship to the unfamiliar, to what is normally hidden. This technique of showing the familiar and unfamiliar simultaneously orients a viewer within the work. It is also a starting point for engagement.

It is important to note that the phone rendered in this work is not current phone technology. It is a GSM device, which is outdated today, even though those networks are still in operation. It would be interesting to iterate several more times on this work to try and get closer to current cellphone technology. A lot would surface once different cellphone makes and models were visible in relationship to each other using the same material techniques.

For this work, the material qualities are mostly resolved, but work must be done to test the limits of the conductive ink with an audio signal and high current application.

4.2 QUARTZ WRISTWATCH

4.2.1 SUMMARY

Modern quartz watches have a tiny blob of black plastic stuck to their circuit board [Figure 4.2.1.1]. Underneath this black plastic is an Integrated Circuit made up of hundreds of microscopic CMOS transistors. These transistors are arranged in a way to make a piece of fine-tuned quartz resonate at 32,768 times a second, and then reduce that signal down to a 1Hz vibration. Down to human time, time that we can carry with us.

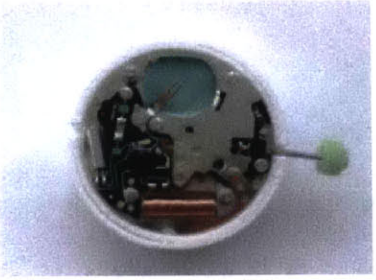

Figure 4.2.1.1 Quartz Watch movement with Integrated Circuit callout.

This next piece titled *Quartz Wristwatch* is a working wristwatch where the opaque Integrated Circuit is reconstructed with discrete transistors in a way that is legible and surfaces the beauty that lies within its simple, logical organization.

The electronics and watch movement are displayed on a 36x60x1/2" freestanding sheet of transparent acrylic. At the top is the familiar watch dial that displays the current time. Below are the electronics required to make the watch tick. Power and ground emerge from the lower portions and sides, feeding into an array of distinct and repeating medium scale circuits. In approaching this work, its resolution increases. What from far looks like an unreconcilable blur of black transistors, from close becomes unmistakably intentional. The signal flow can be traced from bottom to top where an everyday watch dial tells time.

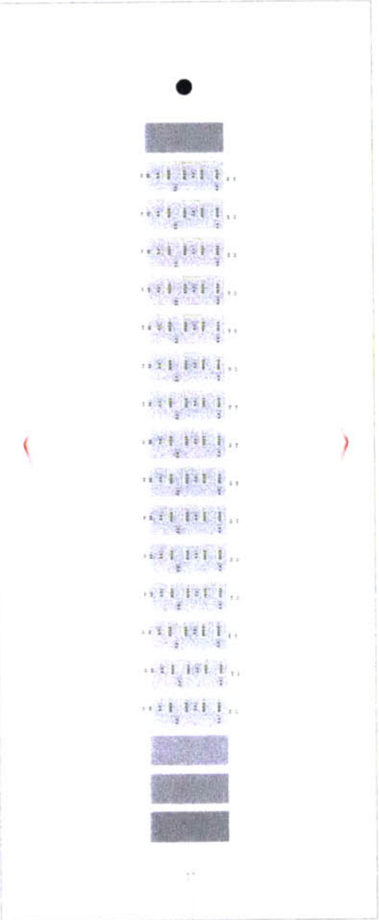

Figure 4.2.1.2 Abstract Diagram of quartz wristwatch. The watch dial and movement are represented at the top and the electronic stages That make it operate are below.

4.2.2 DESIGN, ENGINEERING + MATERIAL PROCESS

Below is a brief overview of how a quartz watch works. The Integrated Circuit of a quartz watch can be reduced into 3 functional units :

1. An *oscillating circuit* that causes a piece of quartz to vibrate at its resonant frequency (in this case 32,768Hz).
2. A *divide-by-two circuit* takes the 32,768Hz waveform and divides it by 2. This circuit is repeated 15 times within a watch in order to reduce a 32,768Hz waveform down to 1Hz. If you divide 32,768 by 2 fifteen times you get 1. It is likewise $2^{15} = 32,768$.
3. Then a *wave shaping circuit* interfaces the resonant 1Hz signal with the mechanism of the watch movement.

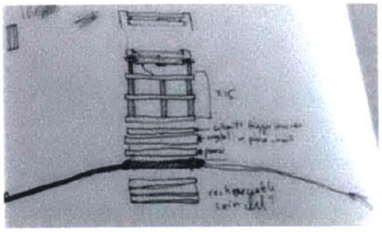

Figure 4.2.2.1 This is a sketch of an "exploded" model of a quartz watch would look like. Each layer is a distinct part of the technical system. power, crystal, inverter, divide-by-2 (x15), interface with mechanical rotor. (Still need to add motor signal conditioning layer.)

An early design of this piece was of a functional and wearable exploded quartz wristwatch. Sandwiched between the dial and the battery is all the functionality that is necessary for a quartz watch to keep time [Figure 4.2.2.1].

Kabtronics's DIY transistor clock was used as a reference for building the electronics for this piece. KABtronics is an engineer and hobbyist who makes a well known DIY discrete transistor clock. A kit to build this clock along with thorough documentation is available at transistorclock.com. The KABtronics transistor clock is pictured in [Figure 4.2.2.2]. It uses 120V 60Hz AC wall power to power the clock and keep time and 7-segment LED units as a display.

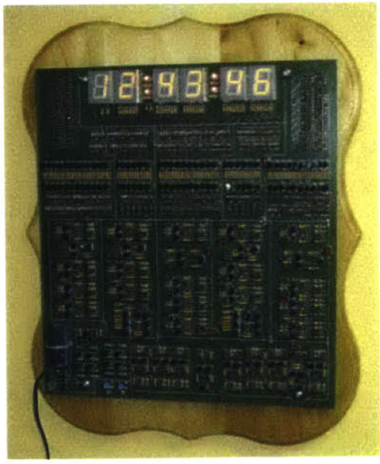

Figure 4.2.2.2 KABtronics DIY transistor clock kit.

The divide-by-two circuit was built based on based on the JK flip-flop described in KABtronics's documentation. After building a working version on a breadboard [Figure 4.2.2.3], the circuit was translated into a PCB schematic for surface mount components [Figure 4.2.2.4]. A lot of time was spent considering the layout of the components on the breadboard and the PCB. It was important to ensure that the schematic was as clean and legible as possible. The board inputs a square wave and outputs a square wave at half the frequency. The front side of the board features the JK flip-flop wired as a divide-by-two circuit. The back side features a circuit to convert a square wave into a pulsed shaped waveform of the same frequency. In order for this type of JK flip-flop to function as a divide-by-two circuit, it requires a pulse waveform as an input. Power and ground are at the top and bottom of the disk-shaped circular profile. Input and output on the left and right. The discs are designated to be mounted together with conductive standoffs. Power and ground rails pass through the entire piece. Alternating PCBs flip on the horizontal axis so that inputs and outputs could be connected [Figure 4.2.2.3].

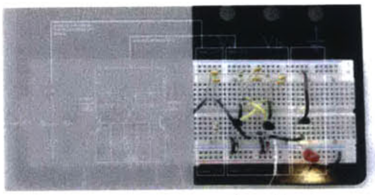

Figure 4.2.2.3 This is a schematic and corresponding circuit of a JK flip-flop using discrete passive components and BJT (bipolar junction transistors).

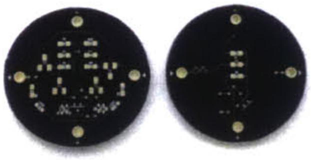

Figure 4.2.2.4 This is a schematic and corresponding circuit of a JK flip-flop using discrete passive components and BJT (bipolar junction transistors).

The KABtronics clock uses DTL (Diode-Transistor Logic)[18], which is an early type of digital circuit. However, the quartz wristwatch, was made possible specifically because of the introduction of CMOS (Complementary Symmetrical Metal Oxide Semiconductor) logic in the 1960s [Wikipedia CMOS]. This style of logic uses Mosfets (Metal-Oxide-Semiconductor Field-Effect-Transistors) as opposed to other transistor types.

There are several characteristics of CMOS logic that make it the most common style of digital circuitry in use today. The complementary pairing of N-type and P-type transistors make it so that one type is always off and power is consumed only in the moment of switching states [National Semiconductor]. This makes CMOS more power efficient, and therefore more practical in applications where portability is important. CMOS logic also allows for the highest density of logic functions on a chip. Another interesting characteristic of CMOS logic is that it doesn't require additional components such as resistors, capacitors or diodes. Everything is built with transistors alone.

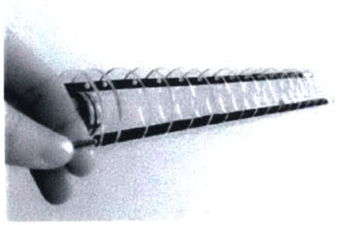

Figure 4.2.2.5 Sketch model of an early version.

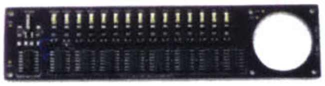

Figure 4.2.2.6 Proof of concept to visualize the reduction of 32,768Hz into a 1Hz signal before it goes to the motor. Built with CD4013 and CD40106 ICs.

It was important to start over and build my circuits with CMOS as opposed to Diode-Transistor Logic. The implications of this was at first a bit jarring. A theme that was being explored was the idea of some implicit hierarchy that existed within the world of discrete components. The varying relationships between resistors, capacitors, diodes and transistors had both a functional and formal significance that I was hoping to uncover. Suddenly the material became reduced to these millimeter scale, discrete transistors encased in three legged black plastic rectangles.

Figure 4.2.2.7 Version using single function Integrated Circuits. D-flip flop ICs are wired to divide-by-2.

Moving forward, the goal was now to figure out how to surface meaning within these homogenous fields of tiny black rectangles. This is where work began with *CMOS Logic Sketches* [Section 4.1] a crucial step in working out some of the basic formal qualities of the material.

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[18] With DTL (Diode-Transistor Logic), diodes are used to perform the logic function (such as a NAND gate) and bipolar junction transistors (BJTs) to do amplification. This form of logic was used in the earliest electronic computers, including ENIAC in the 1940s [DTL].

With *Quartz Wristwatch*, the investigation shifted to a higher level. Instead of working at the transistor level, standalone Integrated Circuits were used for a series of prototypes. This was a way to get a feeling for the complete system of the watch before breaking it down further into transistors.

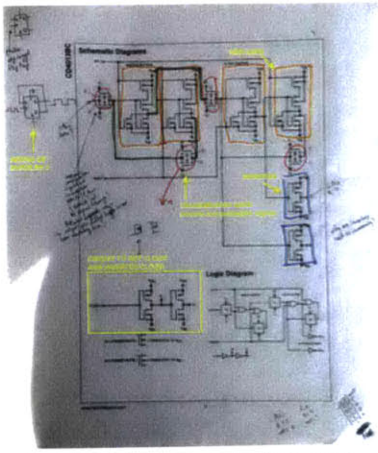

Figure 4.2.2.8 Schematic + logic diagram of the CD4013 CMOS D flip-flop. I used this diagram as a starting point for building a D flip-flop wired as a divide-by-2 circuit.

The first board that was made used the CMOS CD4013 D-flip flops as the divide-by-2 stages. Each CD4013 has 2 D-flip flops, which is why there are only 8 of them on the board for the 15 divide-by-two stages. For the oscillating circuit, only 1 of 6 Schmitt trigger inverters on the CD40106 CMOS IC was used. This inverter is used to help make the crystal resonate.

In the next prototype, individual boards were made for each discrete aspect of the watch system. One for power, an oscillating circuit, a dividing stage, a motor driving stage and output clock dial. For this circuit, single element D flip-flop ICs were used. This exercise was meant to provide a sense of what the overall system would feel like. An LED indicator was used to visualize the output at each stage, showing the 32,768Hz waveform slow to 1Hz.

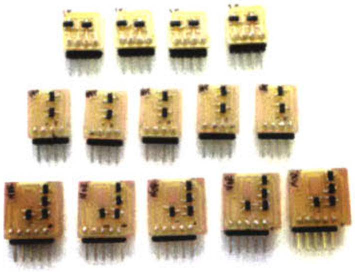

Figure 4.2.2.9 Breakout boards for 5xNOR Gates, 5xNOT Gates, 4xTransmission Gates to use to prototype D flip-flop pictured in CD4013 datasheet.

The next step was to build a CMOS D flip-flop out of discrete Mosfets[19]. The first attempt at this was to reverse engineer the circuit used in the CD4013 IC. With this very old class of 4000 series[20] component, the datasheets often come with an electronics schematic. [Figure 4.2.2.8] is a printout of the schematic and logic diagram from the CD4013 that was used as a working document. Ordinarily, the datasheet isn't meant to be used as a document to reverse engineer the component. It doesn't have enough information to do that accurately, but it was used here as a starting point nonetheless.

The flip-flop pictured in the CD4013 datasheet contains 4 NOR gates, 2 NOT gates and 4 transmission gates. It is important when working with CMOS logic that complimentary pairs of N and P-Type components match as closely as possible in terms of their operating characteristics. The

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[19] Mosfets and transistors are used interchangeably from here on.

[20] 4000 series Integrated Circuits were introduced in 1968. This industry standard family of CMOS logic functions are still in use today [4000 Series].

components used throughout most of this work are N-CH[21] and P-CH[22] SOT-23[23] mosfets. To get a perfect match, you need an Integrated Circuit that contains a matched pair. The ones used here are approximate. [Figure 4.2.2.9] is an image of CMOS gates built to prototype the CD4013 flip-flop on a breadboard.

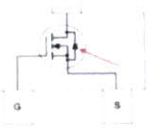

Figure 4.2.2.10 Schematic that shows internal diode on N-type Mosfet.

One characteristic about discrete mosfets is that they have a built in drain-source internal protection diode [Figure 4.2.2.10]. In normal use cases, this is internal diode helps protect the rest of the circuit, specifically the transistor is being used to amplify a signal. It is otherwise negligible. However, when using these mosfets to build a CMOS transmission gate, the internal diode must be bypassed in order for the switching characteristics to work.

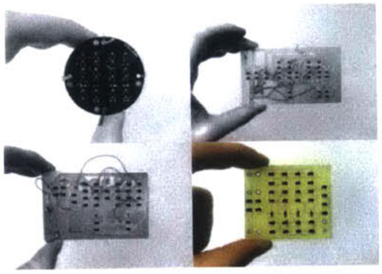

Figure 4.2.2.11 4 attempts at uncovering and then solving the internal diode problem.

[Figure 4.2.2.11] is a series of prototypes made in attempt to solve the problem of bypassing the internal diode. A hack was to put a resistor at the output of each transmission gate, however this caused a new problem. The resistors slowed down the divide-by-two so that it would not work reliably at frequencies approaching 30KHz. It wasn't fast enough for the 32,768Hz crystal.

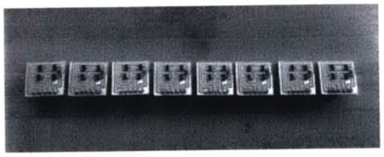

Figure 4.2.2.12 8 NAND gates for Master-Slave D flip-flop.

Since the CD4013 configuration of a D flip-flop with discrete mosfets wouldn't work, the next prototype was made with another configuration of a D flip-flop. This one requires 8 NAND gates and 2 NOT gates [Figure 4.2.2.12] and is diagrammed in The Art of Electronics [Figure 4.2.2.13]. This new circuit worked at speeds up to 65KHz where, the sharp edges of the square wave start to breakdown [Figure 4.2.2.14].

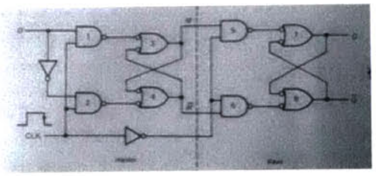

Figure 4.2.2.13 D flip-flop schematic from The Art of Electronics [HH 508].

After working out the divide-by-two circuit, the next step was to consider how the electronics would be represented. The original intention to make this piece wearable was potentially hindering its legibility.

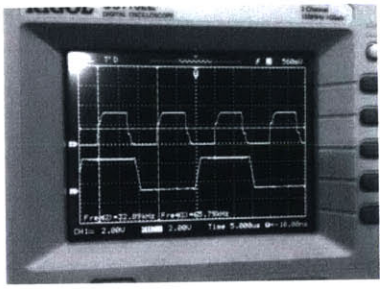

Figure 4.2.2.14 The waveform breaking down above 65KHz while testing the divide by 2 circuit.

The best way to surface the inner workings of a quartz watch Integrated Circuit was not under the paradigm of a wearable timepiece. Instead, all of the electronics are laid out on a freestanding 60x36x1/2" piece of

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[21] Fairchild Semiconductor part number NDS355ANCT

[22] Fairchild Semiconductor part number NDS356APCT

[23] SOT-23 (small outline transistor) refers to a package configuration of a discrete transistor.

transparent acrylic.

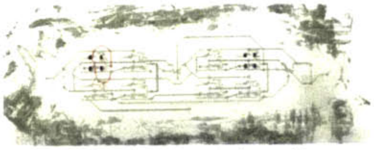


Figure 4.2.2.15 Divide-by-2 circuit material prototype.

A similar process is used here as in the other work where electronic traces are laser etched and then filled with conductive ink. Excess ink is rubbed away to isolate the traces. Transparent material is used and etched on both sides since it is not possible to build this circuit on a single side. Brass pins are used as electronic vias to electronically connect the front and back of the board. Wire wrap is used for longer traces and in places where the resistance of the conductive ink is too high. The brass vias and brightly colored wire wrap add an additional layer of information to the piece [Figure 4.2.2.15].

The LED dims progressively but not in a way that is necessarily obvious. For the final piece, I also need to consider the use of an indicator such as an LED. Since this component is not native to the system, it is instead used as an additional layer to add legibility, it should be differentiated in some way.

4.2.3 DISCUSSION

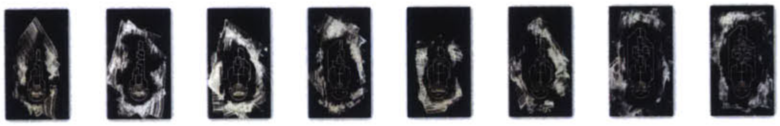
Out of all of the works, *Quartz Wristwatch* presents the biggest challenges from a technical and aesthetic standpoint. A reason for these challenges is the attempt to make visible a wide range of scales, simultaneously.

The smallest unit of scale in this work is the individual Mosfet. Upwards from there are the fundamental units of digital CMOS logic. The vernacular used to present digital CMOS logic is borrowed from *CMOS Logic Sketches*. From here, CMOS logic gates are arranged in a way to construct higher level functional modules, such as the divide-by-two circuit. These modules are then tied together to form the system that completes the functionality of the quartz watch Integrated Circuit. This is then interfaced with the physical mechanism of a watch that drives the watch hands to show time.

In this work, all of these scales, from the discrete Mosfet up to the watch dial are viewed simultaneously. To do this, a hierarchy must be established so that the complexity is not overwhelming. Additionally, a material technique that works at this variety of scales must tie it all together.

While the technique using conductive ink works at a small scale, the sensitivity of discrete components, along with the resistance of the ink makes scaling difficult and unreliable. In order to complete this work, a different type of conductive ink must be used that has a lower resistance. RIght now, these are available but require high temperatures for curing. Alternatively, a new material technique can be developed that will reliably scale.

4.3 CMOS LOGIC SKETCHES



CMOS Logic Sketches (2015), Taylor Levy

4.3.1 SUMMARY

Not only is boolean logic the underlying principle behind digital electronics, it is also what informs its physical structure. In *CMOS Logic sketches,* the fundamental logic gates that are normally embedded deep within the functionality of Integrated Circuits are surfaced.

CMOS logic gates are displayed in sequence. Each 5x7" panel is a functional presentation of a logic gate. Electronic traces are laser etched into glossy black acrylic and filled with conductive ink. Each gate is powered by a single coin cell battery, has a single or set of switches as input, and a white LED as output. The state of the LED (on/off) is determined by the state of the input switch/es. The pieces are displayed in sequence on a wall. Beginning with a CMOS inverter on the far left, followed by a buffer, NAND gate, AND gate, NOR gate, OR gate, XOR gate and XNOR gate. They are displayed on a wall so that they can be viewed as a whole, in relationship to each other. But they are mounted in a way that invites people to handle them individually, to engage with and discover the varying behavior of each tiny system.

4.3.2 DESIGN, ENGINEERING + MATERIAL PROCESS

The motivation behind this piece was to make visible the subtly distinct spatial relationships between complementary N and P-type mosfets when arranged as functional logic gates.

The earliest attempt in this series was to fabricate standalone PCBs that could serve as functional but also legible logic devices. This was problematic because they were designed to be made as conventional

PCBs. PCBs are most commonly seen in a context where something is broken, when a digital device needs repair. It was important to remove the work from this vernacular. Another problem was that they incorporated a layer of additional graphic symbols to give the gates meaning. Instead of surfacing the invisible, this added a layer of information on top of the invisible.

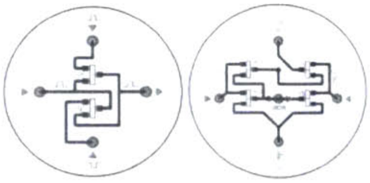


Figure 4.3.2.1 Early logic sketches for PCB discs.

The next attempt was to remove the work from the vernacular of electronics. In this series of mini-sculptural sketches of a CMOS gates [Figure 4.3.2.2] components are not mounted to a board, but are suspended in space by the thin wire wrap that also forms their connections. A button allows you to provide input to the inverter, and an LED provides output. When the button is pushed, the light turns OFF. When the button is in its off state, the light remains ON. The input signal is inverted. This work starts to be interesting because it steps outside of how electronics are normally presented. Here, electronics are not constrained to the 2-dimensional plane of a circuit board. They occupy and define 3-dimensional space, allowing digital circuits to become volumetric objects.


Figure 4.3.2.2 First logic sketch

In the previous attempt, layers were added as a way to surface the invisible, but in reality obfuscate it. This attempt lifts the traces up from the circuit board so that you can see around and see through them.


Figure 4.3.2.3 Laser etched circuit traces of logic gates.

For the next set of *logic sketches*, a novel PCB fabrication process was used that was developed specifically for this work. Here this process involved laser etching 1/4" black acrylic and filling the etched lines with conductive ink. Once the ink dried, excess ink is scraped away to reveal and isolate electronic traces. Ink is left behind as residual evidence of surfacing and uncovering the electronic pathways[24].

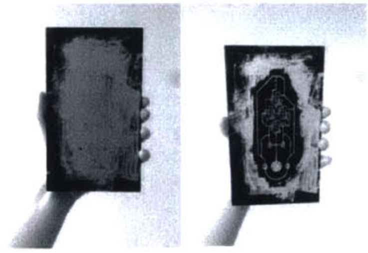


Figure 4.3.2.4 Etched traces filled with conductive ink (left). Traces once excess ink is removed (right).

The materials used were N-CH[25] and P-CH[26] SOT-23[27] mosfets, white LEDs, toggle switches and a 3V coin-cell lithium ion battery, conductive ink[28], conductive epoxy and acrylic.

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[24] This process is outlined in the section titled 3.2 New Material Development.

[25] Fairchild Semiconductor part number NDS355ANCT

[26] Fairchild Semiconductor part number NDS356APCT

[27] SOT-23 (small outline transistor) refers to a package configuration of a discrete transistor.

[28] Conductive Compounds part number AG-610

A series of prototypes were made first on transparent acrylic and later on black acrylic of an inverter, a NAND and a NOR gate. With the transparent acrylic, the traces were too thin and didn't conduct. The file was altered and black acrylic was used from here on because the effect of the ink was far more visible and dramatic. With these, momentary switches were used as inputs [Figure 4.3.2.6]. This had a really nice tactile quality, but didn't allow a viewer to observe the device's current state. In the final version these were switched for toggle switches so that the state of the gate was legible, and so that it could hold its state without someone holding down the buttons.

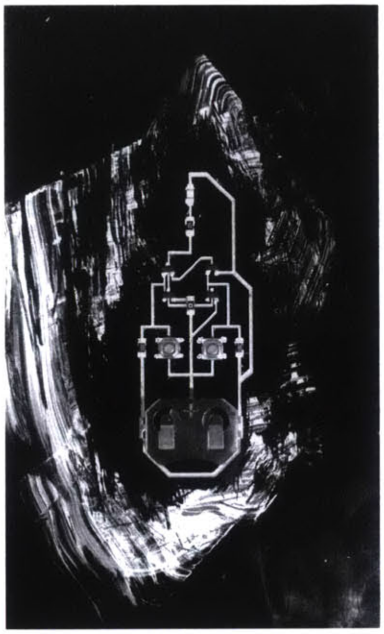


Figure 4.3.2.5 Early NOR gate prototype.

After the first series of tests were made of the inverter, NAND and NOR gate, a full set of 8 gates were made. As the circuitry became slightly more complex, they didn't work as well because of increased resistance of the conductive ink. In order to isolate this as a problem, and test the functionality of the circuit, the AND and OR gates were remade using a different process using vinyl cut copper traces [Figure 4.3.2.6]. In the next version, the traces needed to be shortened, thickened and multiple passes of conductive ink needed to be applied.

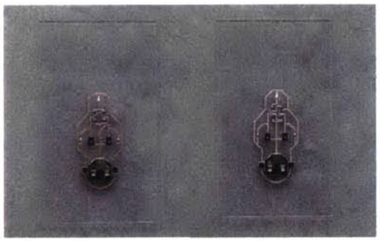


Figure 4.3.2.6 NAND and NOR gate prototypes with copper traces on transparent acrylic.

4.3.3 DISCUSSION

CMOS logic sketches makes visible a hidden aspect of digital electronics. The new material process developed to make these pieces establishes a vernacular for electronic artwork that is both functional and grants access to the hidden material and structure of digital electronics that is otherwise invisible.

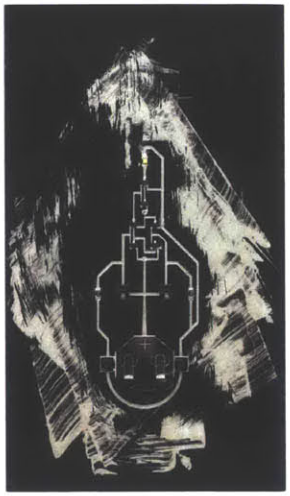
Sketching at the scale of digital logic is a crucial exercise for everything that follows. It is a necessary to exercise a material process in the most basic, iterative way before moving onto more complex designs. It is in these studies where subtleties in the material emerge and discoveries are made.

In the future I would like to continue building out more 8 piece series of logic gates under varying material paradigms. One that I am interested in exploring is a series of gates where wired connections are considered as solid volumes, instead of as thin traces. Here, all of the connections that comprise a gate are solids that space fill a fixed cubic volume.

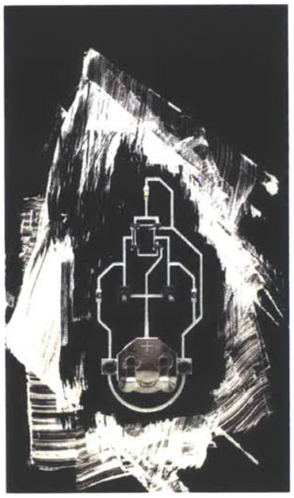
NOT

BUFFER

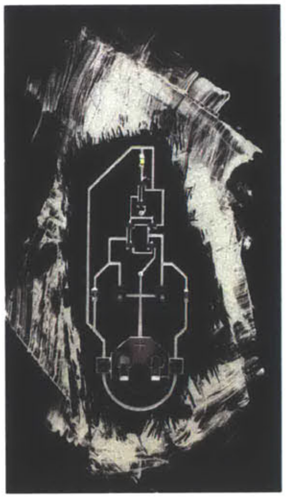
NOR



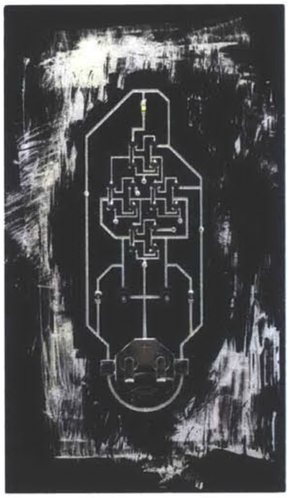
OR



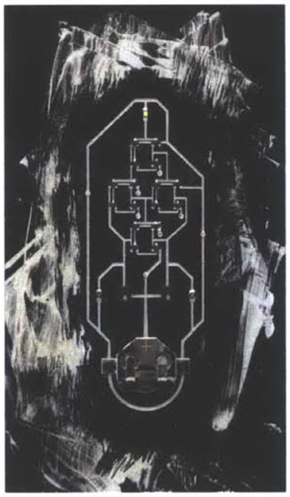
NAND



AND



XNOR



XOR

5. CONCLUSION

The work presented here uses current technology as a subject and medium in an attempt to surface the material of digital electronics. The contributions are an in depth conceptual and material exploration that surround the use of technology as means of creative expression.

This is done through three trajectories of research where the site of inquiry into digital electronics shifts. This begins just beneath the exterior skin of a device with *Cellular Telephone*. Following this, the scale of the Integrated Circuit is explored with *Quartz Wrist Watch*. And in *CMOS Logic Sketches* the focus is honed at the resolution of digital logic gates, the building blocks of all current digital electronic technology.

By probing digital electronics at these resolutions addresses the mesoscopic nature of digital electronics that makes them so difficult to understand. This idea is also what presented the biggest challenge in realizing this work. The difficulty in rendering functionality at the nano-scale and human scale simultaneously. Material processes that work at one scale, don't necessarily translate upwards.

The new material process developed to make these pieces establishes a vernacular for electronic artwork that is both functional and descriptive. But this is just one technique. Future work will involve iterating on new material processes under a similar paradigm. This begins at the scale of the discrete transistor, as the raw, perceivable unit and builds upwards from there.

There is still a lot of room for development in the space between *CMOS Logic Sketches* and *Quartz Wristwatch.* Even though the Integrated Circuit on a quartz wristwatch has relatively simple functionality, there is still work to be done at the scale right above CMOS logic gates, before reaching the complexity of a quartz wristwatch IC.

A challenge when working with technology as a medium is that it requires technical and aesthetic requirements to be fulfilled simultaneously. Sometimes these two things can be developed independently, but more often there is a back and forth process in which an aesthetic emerges once technical requirements are resolved and vice versa.

As technology evolves, we cultivate a portion of our fabricated landscape that lives outside the scope of human perception. With digital electronic technology and whatever new technology follows, the practice of surfacing the invisible portion of our world must continue. This practice reveals a certain truth to materials, and more so a truth to human ingenuity, that is otherwise lost to the highly efficient rational world. Without new ways of rendering the hidden fabric of human innovation, this poetry is lost.

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