On Electronic Sound Sculptures

Circuits and Aesthetics

Eirik Brandal
c012888

Master's thesis

Composition department
Royal Conservatoire of The Hague

April 2017

Abstract

This paper is first and foremost concerned with my methods for designing, constructing and composing with freeform electronic sound sculptures. It covers the topics of circuit modularity, network communication, interaction and sonification as a means to create nonlinear music, as well as architectural concepts that are either being utilized or that have been functioning as sources of inspiration toward the design of the sound sculptures. The reader will be guided largely through the perspective of my own work, but general ideas and concepts from similar artists will be discussed where applicable.

Contents

Introduction

During my years in The Hague I have switched between fields of interest at the same rate I have changed shoes. Whether the latter is a good thing remains to be seen (or smelled), but the former lead me to the art of electronics. Starting as late as in 2013, I have not had a long history in the field, but the addictive feeling of constantly learning new things kept me from abandoning this interest as quickly as I have done with others. It has been a chase for the ever-elusive state of all-encompassing enlightenment; there are always new and unknown territories to explore. There is also this 'futuristic nostalgia' to it, in the 60s sci-fi sense, with blinking lights and bleep-blop noises – an aesthetic that perhaps subconsciously plays a part in my sculptures. Already in the beginning, the notion of tailor-made objects for very specific purposes fascinated me – objects that would seem to be very complex, yet only do one simple thing. The idea of such contraptions resulted, after a couple of experiments, in my first freeform sound sculpture. And there were many to follow.

What perhaps drove me away from regular paper-music was the fact that the end result, the sound of a performance, is merely a reflection of the actual piece through the musicians' or conductor's interpretation (which of course might be half of the fun for some composers). I remember that I once, during the performance of one of my first pieces after arriving in The Hague, mumbled under my breath *"it sounded better in Sibelius".* Unfortunately it was snapped up by the ensemble's pianist, and I got an earful. It was, however, meant only as an innocuous remark about how far the performance sounded from what I had in mind during writing, but in hindsight I could have chosen a better phrasing. Nonetheless, it explains how deeply I care about the authenticity of the presentation of my works. As I considered the part of convincing humans to do their uttermost in the representation of my pieces in a performance that I ultimately would be disappointed in to be mildly challenging, I looked to a field of art where the final result had a closer resemblance to the actual artistic vision I had in mind.

In this thesis I wish to describe or formulate: 1.) concepts from architecture that help define the visual element of my sculptures; 2.) strategies for composing in a nonlinear domain; and 3.) ideas of an ecosystem where modules are working together to create something larger than the sum of its parts. With 'nonlinear' I mean a lack of direction; there is a nondeterministic element to the pacing of events and structure of contents.

Due to the double-sided nature of my research – i.e. visual aesthetics and sound synthesis – I will start off with this insignificant, yet fitting, quote:

> *"It is not easy to arrive at a conception of a whole which is constructed from parts belonging to different dimensions"*
>
> - Paul Klee (Herbert, 1964, p. 77)

Chapter 2

Design

> *The two great rules for design are these: 1st, that there should be no features about a building which are not necessary for convenience, construction, or propriety; 2nd, that all ornament should consist of enrichment of the essential construction of the building* (Pugin, 1841, p. 1).

In this chapter I will discuss my inspirations and influences in connection to the visual and practical design of my sculptures, as well as some background to the art of freeform electronics, its variety of shapes, and its limitations. The sources of my inspirations are not exclusive to electronics, but contain various examples from other visual art forms as well as basic concepts from architecture, particularly those of Functionalism.

2.1 Dissecting shapes

The visual aspect of my work is also connected to Suprematism and Constructivism because of their total abstraction and use of geometrical shapes – and in the case of the latter, because of its connection to science. The Suprematists believed in non-utilitarian, non-material and non-objective art, where *feeling* was of main significance. In contrast, the Constructivism art movement rejected the idea of autonomous art – art without instrumental value – in favor of art with a social function. I'm not claiming that my sculptures have a social function, but the idea of a dual purpose is intriguing: besides their intrinsic visual and auditory qualities, they are also live electronic devices capable of presenting, or perhaps sonifying, their internal communications.

To clarify the comparison between my work and these idealistic opposites in Suprematism and Constructivism: my sculptures obviously have a functional or “utilitarian” aspect to them due to being circuits, but the overall goal is not necessarily anything else than the *pure artistic feeling* from the visualization and sonification of processes in a complex system (i.e. a circuit). Solving a problem geometrically, as you would “solve” a circuit in the form of a sculpture, exhibits an *intellectual beauty:*

> *Just as elegant solutions are accomplished in mathematics or in the fugues of J.S. Bach, architecture can give rise to aesthetic pleasure because it exhibits the solution to a complex set of technical problems* (Illies & Ray, 2016).

Whether it appeals to the senses or to the intellect is of course subjective. Someone with no knowledge of electronics would most likely perceive the sculpture in its abstract complexity and approach it holistically – not entirely understanding the system of the circuit, but acknowledging the system's existence. Any person with a degree of technical proficiency might postpone or ignore the 'artistic pleasure' due to his initial analytical approach upon observing the work – similar to the *technological listening* of sonologists trying to dissect or rationalize acousmatic pieces of music. Regardless of expertise, both are, in my opinion, cases of intellectual beauty because there is a governing law (or system in the case of a circuit) that is discernible, or at least acknowledgeable, by anyone. According to Le Corbusier and Ozenfant in their essay *Le Purisme*, the concept of intellectual beauty is on the top of the hierarchy of aesthetical sensations:

> *With regard to man, aesthetic sensations are not all of the same degree of intensity or quality; we might say that there is a hierarchy. The highest level of this hierarchy seems to us to be that special state of a mathematical sort to which we are raised, for example, by the clear perception of a great general law (the state of mathematical lyricism, one might say); it is*

> *superior to the brute pleasure of the senses; the senses are involved, however, because every being in this state is as if in a state of beautitude* (Herbert, 1964, p. 60).

I would also like to draw parallels between Functionalist architecture and my own work. In his essay *Ornament and Crime*, published in 1913, Adolf Loos criticized the use of ornaments in useful objects, claiming ornaments accelerated the process of an object becoming unfashionable, and that the time and effort put into ornamentation was a waste of time, and thus a 'crime' (Hopkins, 2014). This, along with Louis Sullivan and his phrase "form follows function" – meaning that "*beauty might arise naturally, or even necessarily […] if the functional aspects are satisfied*" (Illies & Ray, 2016) – in broad terms helped define Modernist ideals in the 20th century, rejecting the traditional and embracing the spirit and industrial aesthetic of the modern age. In Functionalist architecture, the form of a building was "*merely a consequence of the building's spatial requirements*" (Hopkins, 2014, p. 169), and we will see how these Modernist tenets are very much relevant to freeform electronic sculptures, and even to electronics in general. Each wire and component in a sculpture accommodates the functionality of the circuit, be it in structural support or transport of electric current. The electrical design of the circuit determines the design of the sculpture: the size is often determined by the circuit's complexity due to the space required to mount the various components and the amount of connections needed to be made between each module. As the physical construction is more often than not solely based on the circuit design's requirements, it is comparable to archaeology. If you are digging up a dinosaur you want to reconstruct, you know that each joint and knuckle has a specific function, and that it's just about collecting them and finding the right spot for them to be put together. Likewise, electronic circuits use components and wires for specific purposes, and after the circuit has been designed on paper, they also need to be placed at the right spot in the electrical ecosystem in order to make the current to flow through them in a meaningful way. Of course a dinosaur is less flexible when it comes to interconnecting its parts, so my hypothetical archaeological career would probably be short lived. The bottom line is that once the circuit's electric characteristics are decided upon, the visual design of the sculpture is already there. It's about finding the best way to put it all together.

2.2 Freeform electronics

There are various fields within the category of freeform electronics. *Dead bug*, *Manhattan style*, *air-wired*, or simply *ugly*, to name a few. The actual definition of each term might vary, but what they have in common is that none of the components are absolutely fixed to a substrate which takes care of the routing of electric currents, like the *through-hole* or *surface-mounted device* filled *printed circuit boards* (PCBs) we see in modern devices like our computers and phones. For simplicity's sake, I will refer to all non-PCB styles as *freeform.*

The advantage of the freeform style is that the road from an idea to the finished product or prototype is short. No need to plan and etch a printed circuit board, as you simply connect all leads in a point-to-point manner. Because of the fact that the leads are short and not in parallel – and because the circuit often rests on a huge grounded copper plate offering efficient grounding – radio interference and stray capacitances are reduced. These points made freeform styles popular among ham radio enthusiasts and other amateur hobbyists during the 80s (Maloney, 2016). The *Manhattan style* is perhaps the most fascinating one out of the bunch, and certainly the one that resembles a piece of art the most. The name comes from how a finished product looks like a busy skyline of tall buildings, and it lines up well with how many a child fantasize about electronic components being small houses in a complex city layout. It is also the most mechanically solid technique of all the freeform styles, utilizing small soldered pads that are glued to the copper plate for its connections, providing extra support (ibid.).

I personally refer to the style used in my sculptures as *air-wired*. The categorization might be questionable, but due to the lack of institutionalized definitions of freeform styles, it will do for this paper. Air-wired electronics also uses the point-to-point connections seen in other variants, but omits the grounded copper plate. Instead, thick tinned copper wires are being used for grounding, simultaneously functioning as support for the circuit.

There are, in relative terms, quite a few artists who have ventured into this air-wired approach to electronic sound sculptures. However, there are three particular artists I consider to be “senior artists” or pioneers within the field. Anyone who has witnessed the works of Peter Vogel undoubtedly has been amazed by the attention to detail, structural complexity and balance his pieces contain. I am evidently no different, having spent large parts of the last year trying to learn his trade by meticulously pausing videos and zooming in on low-resolution images of his exhibitions, attempting to get a grasp of the logic behind it. Vogel's philosophy as an artist has always been about instilling a notion of time onto his art. Originally a painter, he did various experiments trying to introduce a temporal dimension into his work, interpreting his paintings as graphical notations of dance or music. In 1969, while he was working on brain research for Hoffmann-La Roche, a Swiss health-care company, he was inspired by his readings in neurophysiology to create cybernetic objects, thus starting his sculpting career. Besides time, Vogel's work relies heavily on human interaction – a 'side effect' of dealing with time, according to the artist himself (Martin, 2013) – as a compositional tool.

Walter Giers, who recently passed away, was another artist in the field of freeform electronics. Like Vogel, he wanted to transcend the two-dimensional artwork by creating a dynamic piece that – unlike a recording that would be unchanged if you put it on repeat – would be different each time you played it. Giers' earlier works were also driven by human interaction, but after a discovery in the 70s, he started to automate his art, as he was more interested in it having a life of its own.

> *Integrating chance was an extremely significant development for me. In the beginning you had the interactive objects since there was no other way to do it. When I built a tone generator and I wanted it to produce different tones, I had to put a couple of switches on it, and then I brought a person into the mix, who operated the switches so that the picture would change and practically reach the dimension that I was going for. And then at the beginning of the 70s I realized that I could also do these things with the random generator automatically of course, well not automatically in the sense of a program, but the objects would become autonomous* (Telekom Electronic Beats, 2017).

The third artist I want to discuss is a bit of a contrast to the two above. While still in the air-wired genre, Leonardo Ulian uses electronic components purely for their cosmetic value. A series of his works, all fittingly named *Technological mandala* with a number slapped on, is best described as electronic drapery, with patterns often symmetrically expanding from a point in the middle. This approach, relying only on the visual characteristics of the components, makes the circuits dysfunctional. It certainly has a more spiritual feel to it, relying on shapes, form and color rather than the intellectual beauty of complex systems we discussed earlier in the chapter.

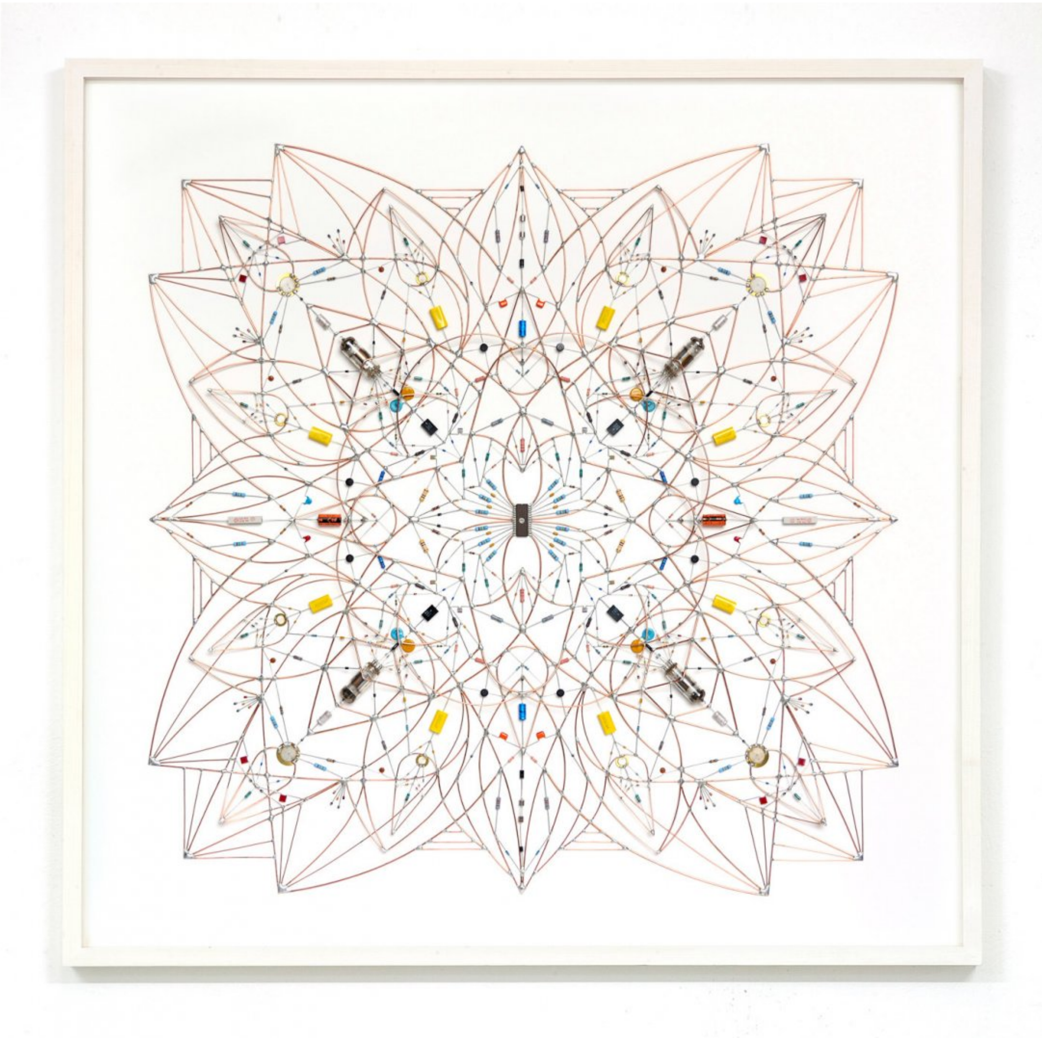

Figure 1: Technological mandala 92, by Leonardo Ulian (2016)

2.2.1 Hexagon #1

In this section I wish to analyze one of my own works, named *Hexagon #1* (2015), in order to describe my thoughts behind the choice of shape and size of a sculpture, and how it connects to the concept of Functionalism. We will see how the amount of modules determine the basic shape – i.e. how many sides or 'planes' required for the attachment of modules – and how each wire contributes not only to the functional aspect of the circuit, but also to the support of the structure.

Hexagon #1 is, as the name implies, a sculpture which design was derived from the hexagon. It uses five *integrated circuits* (ICs) (see fig. 2): an oscillator IC, a dual input AND logic gate (CD4081), a triple input NOR logic gate (74LS27), a divider (74LS92), and an audio amplifier (LM386). Five out of the six sides in the hexagon are used to mount the ICs, while the last is used as legs for the sculpture to stand on. The sculpture also consists of a relay, a transistor, two voltage regulators, a speaker, and various resistors and capacitors. But unlike the ICs, these components do not need to be directly connected to the power rails – which I will explain in a bit – meaning they can be placed quite arbitrarily within the sculpture, with weight and the amount of mechanical support required being the only consideration to take into account.

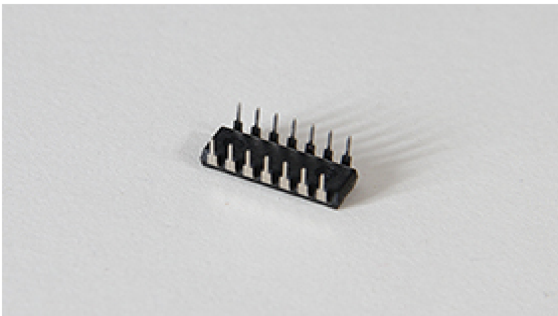

Figure 2: A 14 pin IC

From a technical perspective, the sculpture can be divided in half. As some might know, an electric circuit requires two poles in order to work, and current flows from one pole to the other. There is a negative/grounded (0 volts) part and a positive part, like in a battery. The edges of the hexagon are alternately positive and ground, giving the ICs easy access to both poles – or 'power rails' as they are called. For extra support, capacitors are used in between the rails, simultaneously working as power conditioners. Due to the triangular power rails, the balance of the initially symmetrical hexagon has been shifted and dissected into smaller parts (see fig. 3). The practical layout of the most basic needs for a circuit to function already lends itself well towards the final design: form follows function.

If you think of each IC as a module that is responsible for a certain action or process, you need to connect them in a meaningful way, like you would make a patch on a synthesizer or in musical programming software like Max/MSP: all other lines inside the sculpture are wires that are sending control or audio signals to relevant points in the circuit, contributing to the greater picture.

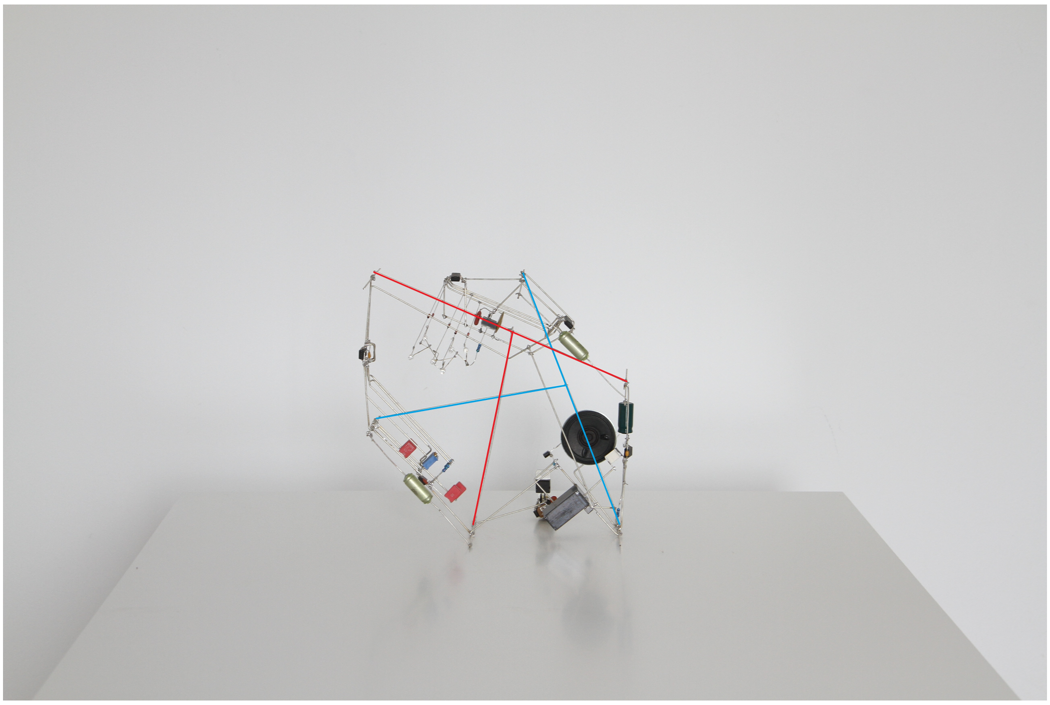

Figure 3: Power rails in Hexagon #1. Red lines indicate 12V, blue are ground

2.2.2 Cubic #2

Conceived in 2016, the design for this sculpture was inspired by the concept of 'Paper Architecture' – or rather, the idea of exporting a two-dimensional drawing into a three-dimensional space. Paper Architecture is a term used to describe the works of architects so improbable, imaginary, or downright unbuildable that they are limited to the two dimensions of paper. It can also consciously be used as a sort of meta-architecture – a commentary on the current state of style or visions of the future. The Constructivist Vladimir Tatlin's *Monument to the Third International* is perhaps the embodiment of Paper Architecture. Hopkins writes:

> *Designed between 1919 and 1920, Tatlin's Tower – a colossal, spiralling mass of steel – was intended to straddle St. Petersburg's River Neva and to reach 400 meters high. […] Fusing art, architecture and industrial engineering, it was intended to be both a functional structure and, through its scale and form, a symbol of the new socialist age. That Tatlin's Tower was never built was indicative not only of its unrealistic technological demands, but also the basic shortages of building materials following the Russian Revolution of 1917 and subsequent civil war when architects' work was largely confined to designs on paper* (Hopkins, 2014, p. 170).

The idea with *Cubic #2* was to design a multi-layered PCB and to recreate it in three-dimensional space as a part of a sculpture. More like a draft in the design process rather than a technical blueprint, I drew a rough layout of the placement of components and 'traces' (see fig. 4). Rather than mechanically fixing the components to a copper traced board, I made all the connections with tinned copper wires to make it seem like the circuit was 'hanging in the air' (see fig. 5). The "PCB" is instead fixed to a hollow symmetrical cubic shape, enclosed by bars resembling the flying buttresses used in Gothic architecture.

Cubic #2 was my first primitive attempt at creating a human-interactive sculpture. I am normally not so excited about interactivity – I much more prefer to let the sculptures live a life of their own (discussed in the next chapter) – so the interactive aspect of this sculpture is rather well hidden and withheld. Rather than inviting the audience to interact, the sensors are camouflaged as insignificant parts within the rest of the circuit. Not before a brave (or dimwitted) soul starts touching and waving their hands about, the sculpture will react with a new sound.

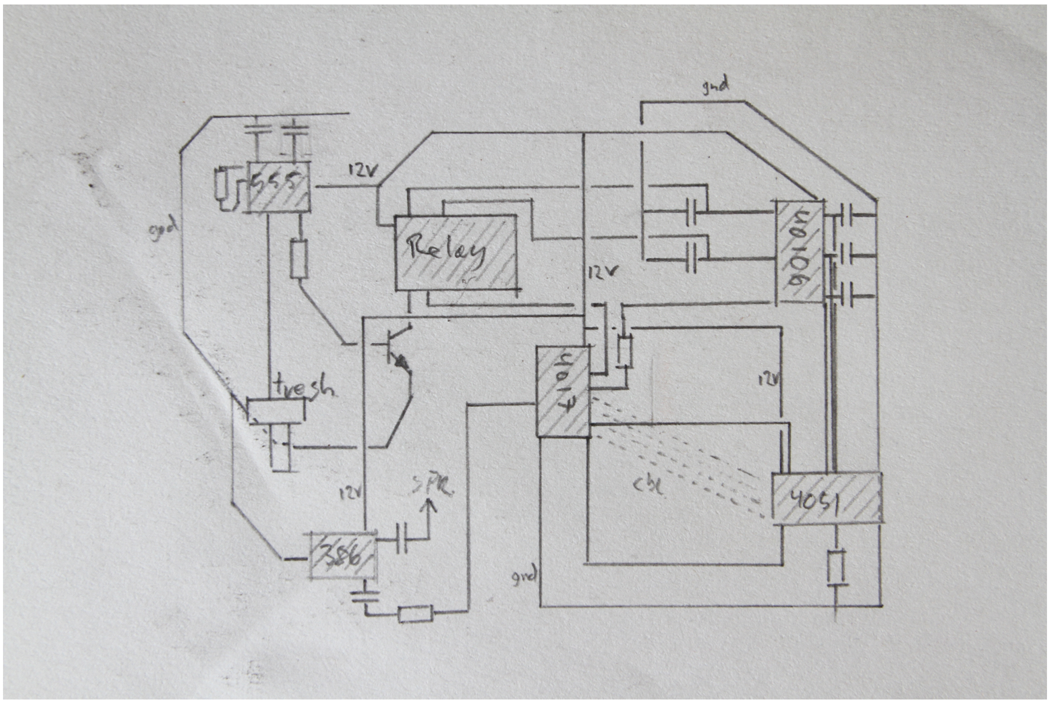

Figure 4: Cubic #2 PCB design on paper

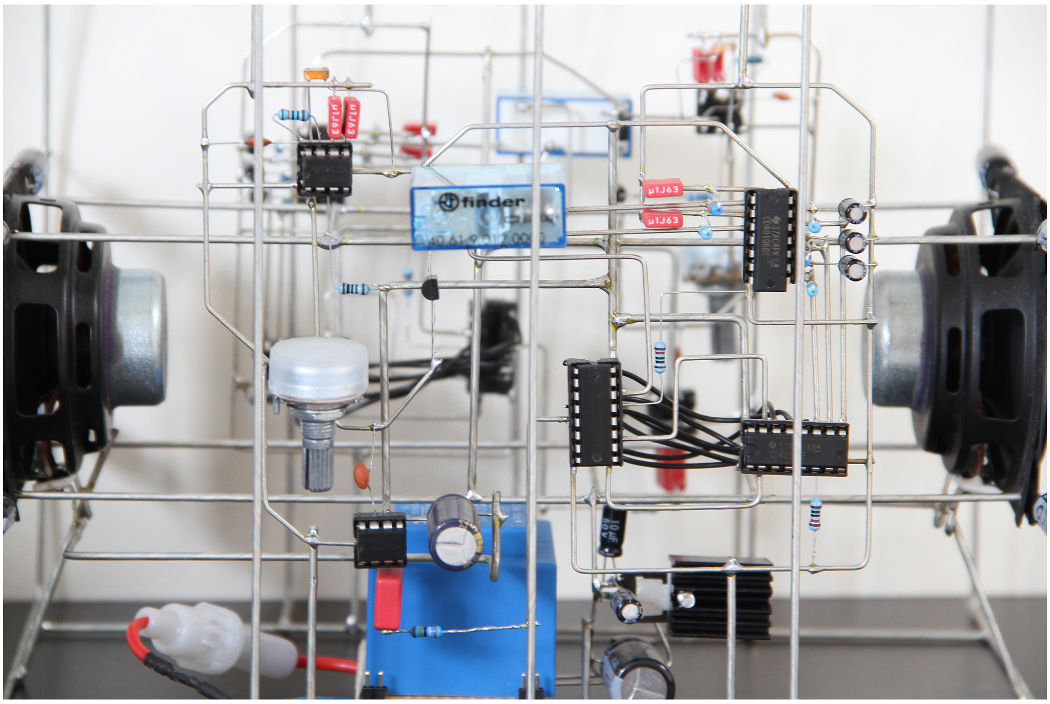

Figure 5: Cubic #2 after construction

2.2.3 Limitations

One particular issue with the freeform format is the limitation of complexity in the circuit. There are various reasons as to why a complex circuit wouldn't be as viable in a freeform format, and the first one is noise.

Although the circuit design of my sculptures have a lot in common with synthesizers, proper shielding and grounding are not on that list. The lengthy wires stretching from one part of the circuit to another are in fact antennas, introducing extraneous noises from the outer world into the circuit. This can be particularly critical if the wire in question is connected to a high-gain amplifier, as the noise will be amplified equally as the intended signal. Also the lack of separate grounds can be an issue. On a well designed printed circuit board, there will be separate grounds for the digital part and the analog part of a circuit due to the ripples and power surges caused by the digital circuitry, which will affect the performance of the analog part. In air-wired electronics, you won't always have the luxury of choosing exactly how you want your ground to be laid out because of other, more pressing matters that needs to be addressed – such as mechanical support. Building a precision circuit with a calibrated 1V/octave voltage controlled oscillator only to find that both the audio output and the control voltage input are corrupted due to noise would defeat the purpose of such a complex construction.

Secondly, modular synthesizers are instruments which inputs are designed to be able to receive a large range of signal varieties to accommodate for musical flexibility. Freeform sculptures do not have this flexibility; due to the lack of space for unneeded components, a module within the circuit is constructed to receive a specific type of signal, and that type only. This tailor-esque approach might not be a disadvantage at all, as it saves time and unnecessary cluttering of free space within the sculpture.

Third is weight. Some components require more mechanical support than others, and it might be necessary to add parts that do not promote the circuit's functionality in order to mitigate the burden or distribute the load across the sculpture. Weighty components, such as transformers, can be placed at the root of the sculpture to add stability, but in other cases it might be necessary to use large resistors or capacitors as a quick remedy.

Speaking of transformers, the fourth issue is power. In all modern apparatus, high voltage constituents of a product are hidden from the light of day in order to prevent people from frying their eyebrows. In freeform electronics, you can imagine the potential calamities of having 230 volts flowing around in a fragile steel wire construction in a room full of trigger-happy tactile enthusiasts (to digress: in one particular exhibition, a bloke figured it would be great fun to treat the steel wires as strings on a guitar, so he happily strummed his fingers across an entire sculpture, leaving it disfigured (at that moment I wished I had disregarded any forms of sensible advice from the European electrical directives during construction)). Naturally, the whole sculpture is not running directly on 230 volts; the most common voltage in my sculptures is 12 volts DC, hardly noticeable if touched. But the transformation between 230 volts and 12 volts has to happen somewhere, namely in the power supply, and I can see two options that are viable for use in my sculptures: 1.) buying/building an external power supply, and 2.), integrating the power supply in the sculpture in a safe way.

There are two general types of power supplies. One is the traditional linear transformer-type of supply, where 230 volts AC gets transformed into a lower voltage AC, and then regulated to whichever DC voltage you are after. It produces clean and stable power, but the disadvantage is that the excess power is dissipated in heat, making it very inefficient. There is also a size and weight drawback due to the big transformer and the heatsinks attached to the regulators. The second type is the switching power supply, which switches the unregulated voltage on and off at extremely high speeds. These are the ones you have in your computer charger and whatnot. The advantages are efficiency (very little power dissipation), small size and weight. The big disadvantage, however, is that the switching action causes horrendous noise, both in the DC output and as electromagnetic interference (Horowitz & Hill, 2015). In my earlier sculptures, I used cheap external switching supplies, but quickly found out that, while it was a safe option, the sound was badly affected. Thus I decided that I would build by own linear supplies (which seem to be the standard in other non-digital audio electronics anyway) for the cleanest power possible. The size and weight were issues still, and could have been solved by hiding enclosed supplies in the vicinity of the sculptures, but I felt it was striding against my vision of the sculptures as separate and self-sufficient entities, so I decided to integrate the power supplies while hiding the exposed high voltage points with two close-proximity parallel insulating plates. However, this safety measure has an aesthetic snag I am yet to solve.

Chapter 3

Approaching synthesized sound

With the aesthetical and functional foundations and the issues that come with them explained, it's time to dig into the inner workings of the circuit. It is common to divide a circuit into multiple *modules* for it to be analyzed. A module is responsible for a specific task in the circuit, like generating or processing a signal. A filter, for example, receives any type of signal and processes it according to the construction of the filter, before it sends the signal on its way to the next module. The process within the filter can also be influenced by another module if sent the appropriate signal. This type of influencing signal is called *control voltage* (CV). The electronic signals being sent across the circuit are "conversations" between the modules, and the way they influence each other affects the resulting output of the entire circuit altogether.

To avoid confusion, definitions of the terms *analog* and *digital, continuous* and *discrete* are in order. Analog signals exist only in the "real world" domain. They are continuous – meaning there is no quantization; any measurement on an analog voltage curve will contain infinite decimals. Digital signals on the other hand consist only of binary data – 1s and 0s. They are discrete values. That is the case with any data transmission in our computers and phones, as computers need tangible numbers to operate with – not infinitesimal values that would literally take an eternity to handle. These are by all means insufficient explanations on the topic, as I happily omitted *analog-to-digital conversion* (ADC), *digital-to-analog conversion* (DAC), sample depth and sample rates – but it will do for the sake of this paper, and avoids leaving the less interested reader confused as a freshly released fart in a wicker chair.

There is more to musical synthesis than what I will explain in this chapter; due to the ragtag nature of the sound generating methods used in my sculptures, I will not be discussing more sophisticated techniques, at least not in great detail. The circuits in my sculptures are inspired by the CMOS (read: digital) style synthesizers of the late Stanley Lunetta – a pioneer in the field of bending and abusing digital electronics to build synthesizers and sound sculptures – and hardly requires any form of analog precision.

To properly translate electronic signals to musical terms, we need to divide them into two categories: control signals and audio signals. Audio signals are all signals meant to be perceived by the human ear. Control signals encompass all signals meant to structure or control processes that are not meant to directly be heard unless reflected through an audio signal. That being said, control signals can also function as audio signals and vice versa.

3.1 Control signals

There are various types of control signals. Some of them contain musical information, like rhythm, pitch or articulation, while others are constituents of signals that are yet to be processed, like data signals being fed to a logic gate. The principles I will explain in this section are digital electronics fundamentals repurposed for musical use, common both in my sculptures and in synthesizers.

3.1.1 The master clock

The first control signal, the master clock, is the conductor (an orchestra conductor, to avoid confusion with the other version of this homonym that is more relevant to the field of electronics) of all things digital. It is what sets the speed and makes sure the different modules in a circuit stay in sync. A circuit can have multiple clocks, as a clock basically is an oscillator performing synchronization or pacing duties. But the master clock is (by my definition) the clock in charge of the major processes; it's the pulse of the circuit. A clock signal is produced by an oscillator. An oscillator can be anything that produces a periodic waveform – like a square wave or a sine wave – with relative stability. It's essential to each and every digital device, from your calculator to your smart phone. As Horowitz & Hill (2015, p. 425) states: *"A device without an oscillator* *either doesn't do anything or expects to be driven by something else (which probably contains an oscillator)"*. In musical electronics, however, the master clock is similar to tempo. In a synthesizer, the clock signal can be used to synchronize parallel rhythmical processes – often built from subdivisions of the same signal – or drive sequencers. It is also more flexible as a musical tool. The frequency can be changed, or the periodicity of the waveform altered – for example by putting your square wave clock's duty-cycle to 66% to get a swing feel.

3.1.2 Logic gates

The second part on the topic of control signals is the logic gate. A logic gate is a device that, based on two or more binary inputs, outputs a single stream of digital data. Essential in any computer, there are several different types that perform specific logical operations, namely AND, NAND, OR, NOR, and XOR (even the single-input INVERT and BUFFER gates are sometimes counted among this group). Logic gates can be cascaded and used in very complex decision-making processes, but can also be used singularly in simple binary switches or in waveform generation. The gate types prefixed with an N are simply inverted versions of their non-prefixed namesakes, and can thus be considered as simple cascaded gates (Horowitz & Hill, 2015, pp. 703-716). It is common (even Ludwig Wittgenstein (1921/2001, p. 38) did it) to notate logic operations with *truth tables* (see table 1). They provide a clear overview of what you can expect at the output of a gate at any combination of inputs.

For musical purposes, the logic gate is an absolute beast. While it can produce non-periodic audio signals, creating rhythmical control signals is where it really shines. Due to the variety of parameters that can be changed – the amount of inputs, the characteristics of the input data, the variant of logic gate used, and the combinations of variants – the output material is extremely flexible. Endless streams or short loops of rhythmical data can be used to drive sequencers, envelope generators, voltage controlled amplifiers (VCAs), motors and drum machines.

My favorite logic gate is the *Majority gate*, a combination of the AND and OR gate types. It needs three or more inputs in order to work, and the output goes HIGH (or to the binary state '1') if two or more of the inputs are HIGH, otherwise it stays LOW (the binary state '0') (see table 1). If the inputs are different subdivisions of the master clock, say /3, /4 and /5, the output is an extremely musical slowly repeating pattern with unexpected syncopations.

Input A	Input B	Input C	Output
0	0	0	0
1	0	0	0
0	1	0	0
0	0	1	0
1	1	0	1
0	1	1	1
1	1	1	1

Table 1: Truth table of the Majority gate

3.1.3 Envelopes

An *envelope generator* can produce two, four, or more blocks in a one-shot waveform used to control the pitch, articulation or volume of an audio signal. If a four-stage envelope is used, the blocks are *attack* (the rising time), *decay* (the length of the tail after the initial attack), *sustain* (the target voltage of the decay), and *release* (the duration of the note fading to silence). Another common variant is the two-stage envelope, where only the *attack* and *release* are utilized. If used to control a filter and a voltage controlled amplifier, it is comparable to the bow-hand of a violinist.

The envelope generator is often triggered by an oscillator or a gate signal produced by logic gates or sequencers, but it can also be activated by a button or a keyboard (see fig. 6). If the triggering signal is periodic and at a suitable frequency, the envelope generator can also be used as a waveform generator in the audio domain.

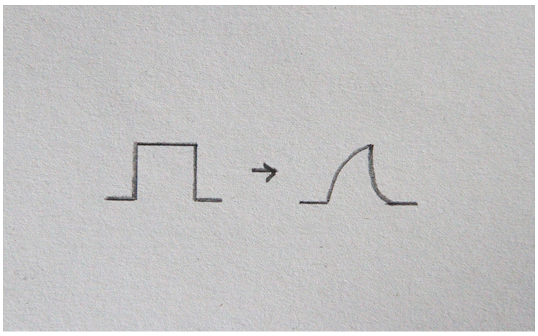

Figure 6: Two-stage envelope: transforming a gate signal into an envelope

3.2 Audio signals

This section covers signals from oscillators and noise sources inhabiting the frequency range of the human ear. These signals are not limited to the sounds directly produced by their respective generators. They can be molded through a variety of processes, for example by filtering and modulation. The filter, albeit not technically a sound source, goes under this section because of its timbre-shaping ability.

3.2.1 Oscillators

What an oscillator really only does is making its output voltage swing between two points periodically. How the voltage gets from one point to the other depends on the style of oscillator, with the simplest being the relaxation oscillator, which is based on the charging and discharging of a capacitor. For musical purposes, the most common oscillators normally produce one, more, or all of the four basic waveforms: sine, triangle, square and sawtooth – all named after their characteristic waveshapes created by the order and amplitude of their harmonic content. They are the building blocks of musical synthesis, and if properly set up for it, they can be combined, modulated, cross-modulated and filtered in order to create more complex sounds.

3.2.2 Noise

Noise, while not as easily defined as oscillators, is non-periodic and comes in a large variety of forms. Denis Smalley divides it into two big categories; granular noise and saturate noise:

> *Extrinsically we associate granular noise with sea, water textures, wind, static interference, granular friction between rubbed and scraped materials (e.g. stone), unvoiced vocal consonants, and certain types of breathing and fluid congestion. […] The second definition is not distinct from the first, and is concerned with density – a saturated spectral state which cannot be resolved into intervallic or relative pitch. Saturate noise can be looked upon*

as another aspect of some of the sources mentioned above (e.g. sea), but can also come about through spectral compression, where an area of spectral space is closely packed such that pitch awareness is impossible (Smalley, 1997).

The exact definition is not really important, but it comes to show that there are many ways to create noise. In electronics, noise can be used both as an audio signal and as a control signal, in digital and analog ways. For audio, you have the obvious analog noise generator that outputs a signal approximated to white noise. Some of them are slow enough to be used directly as control voltage, but any noise signal can be sampled and used as a random step sequencer for the same purpose. Digital noise is more interesting though. As with the logic gates, the output signal can be so fast that it is perceived as a granular texture, even though it's just a non-periodic square wave. At suitable frequencies, the resulting 'wave' sits in and about the liminal space between perceivable pitch and clicks and noises. This method was used for the sounds in *Cubic #2*.

The "trueness" of digital noise is questionable. Paul Berg (2014) mentioned in his class *Programming and Music* that even in computers, the "random" bit sequences are created from a specific number – like the time and date of when the random number generator was initialized, or the amount of seconds the computer has been running. In other words, most digital randomness are pseudorandom bit sequences (PRBSs). From the book *The art of electronics* on pseudorandom bit sequences and noise generation:

It turns out to be remarkably easy to generate sequences of bits (or words) that have good randomness properties, i.e., a sequence that has the same sort of probability and correlation properties as an ideal coin-flipping machine. Because these sequences are generated by standard deterministic logic elements (shift registers, to be exact), the bit sequences generated are in fact predictable and repeatable, although any portion of such a sequence looks for all the world just like a random string of 0s and 1s (Horowitz & Hill, 2015).

Besides their noisy audio qualities, these pseudorandom bit sequences can be used to generate unpredictable rhythmical patterns.

3.2.3 Filters

Filters have a wide variety of usages in electronics. By definition they reject unwanted harmonic content or noise from a signal. In non-musical contexts, they are used to block direct-current (DC), demodulate modulated signals (e.g. in radio receivers), condition power supplies, and to anti-alias quantized signals to name a few. All filters can be built using the two basic forms of filters: low-pass and high-pass. Low-pass filters attenuates content above the chosen cutoff frequency, and high-pass filters attenuates the content below. Combined they can create band-pass filters, notch filters and comb filters. The slope of the filter (i.e. the amount of attenuation at any given point above or below the cutoff frequency) is measured in decibels per octave (dB/oct). Simple passive filters with a 3dB/oct slope can be made with a simple resistor and capacitor network, but the active filters used for instance in musical synthesis are more sophisticated, tailored to have steeper slopes and adjustable cutoff frequencies and resonance. In fact, the resonating character of a filter can be so strong that it is pushed into self-oscillation, resulting in a near-perfect sine wave depending on the sharpness of the q-point (the bandwidth of the resonating area with respect to the cutoff frequency).

3.3 Circuit design

The typical components in musical synthesis explained above are of no use unless they are combined. As mentioned in the introduction to this chapter, the modules need to communicate in order for the circuit to work. In this section I wish to present two hypothetical circuits in a non-technical format to illustrate not only a standard approach to patching together musical building blocks, but also the possibilities of exploiting digital circuitry in sound generation. While these examples are tested on my synthesizer, there should be no reason for them not to work under other circumstances, for instance in a sound sculpture.

3.3.1 Majority gate as an audio signal

In this example I tried to find that spot between audible pitch and noise to create a relatively random, yet repetitive audio signal. Few modules are used, yet even fewer could have been used to achieve a similar result. The master clock has to be well up in the audio range because its frequency is divided into three different subdivisions in the clock divider, namely /3, /5, and /7. Subdivision might be the wrong term here, because what is actually going on is that the clock divider counts each “tick” of the clock and sends that tick to the respective output. The /3 output needs three ticks from the master clock before it goes HIGH, and the /5 needs five ticks, etc. The output of the Majority gate goes to the input of a 12 dB per octave low-pass filter before it is sent to the amplifier.

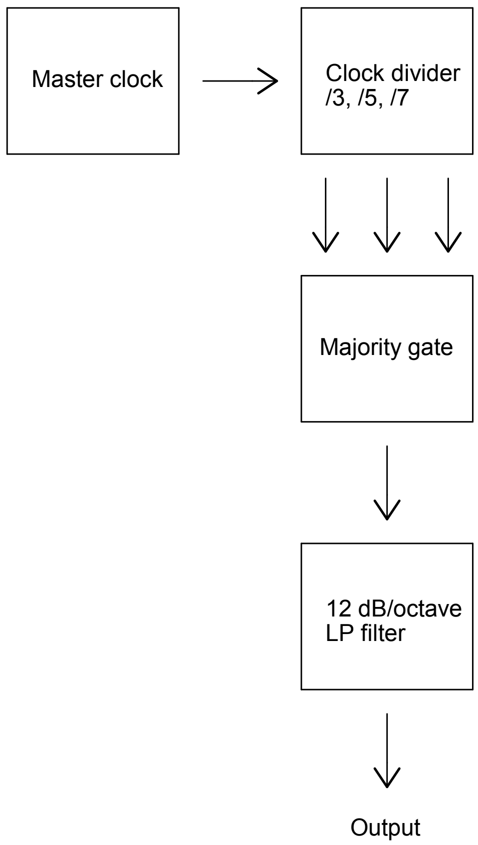

Figure 7: A Majority gate being used as an audio signal

3.3.2 Using envelopes as control signals

Building from the previous example, we can instead of using the logic gate as an audio signal, use it to trigger an envelope generator that will help us control more parameters. We are still using the master clock as a basis for all that is happening, but another square wave oscillator is added as a sound source. The output of the Majority gate is triggering a four-stage envelope generator (ADSR), which in turn is controlling both the cutoff frequency of the filter and the volume of the amplifier. The result is a repetitive pattern of water-like sounds due to the high resonance of the filter.

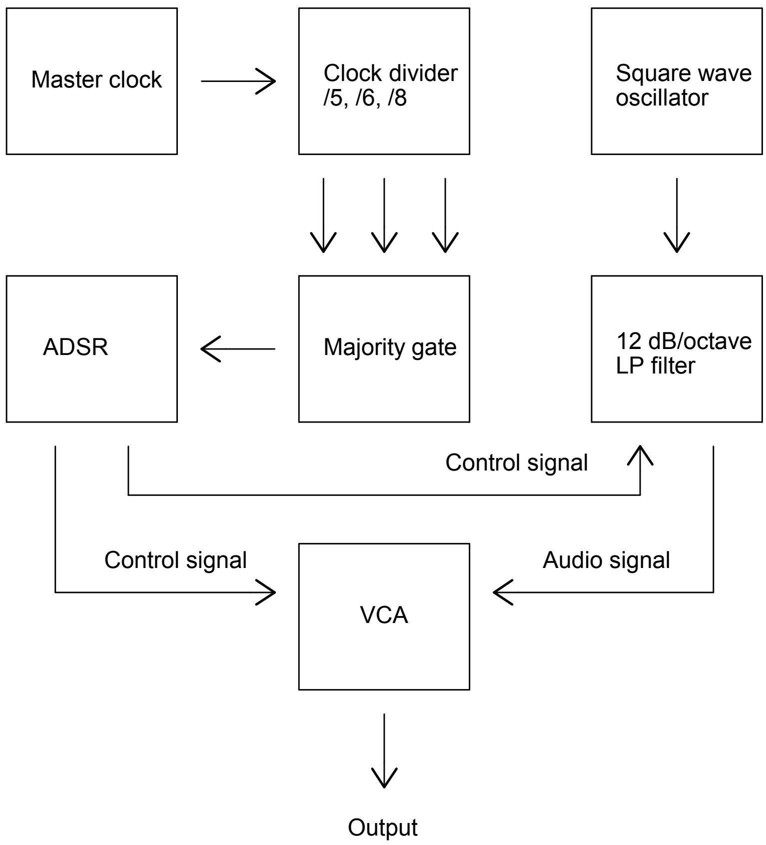

Figure 8: Using envelopes to control parameters

Chapter 4

Composing with sound sculptures

The danger of electronics, from a musical perspective, is that the vision you set out with might not coincide with the result. The possibility of ending up with an over-glorified fart machine at the end of a long and vigorous battle against the currents is very much present. In this chapter I wish to discuss, if not strategies, at least things to keep in mind to avoid such fatal circumstances. Before I start, it's important to clarify the goal of the compositional aspect of my sound sculptures. It is not to create a piece of music that is linear in time. Rather, the aim is to create a timeless sound-world that expands on the inner workings of the electric ecosystem, and if nothing else, is in fashion with the electronic aesthetics of the sculptures. A sound sculpture is *" […] an ongoing piece that continues from its point of conception until it is either deactivated or destroyed"* (Lunetta, n.d.). It differs from David Tudor's "performative ecosystem" (e.g. *Rainforest IV*) because the audience in most cases are not required to interact (if interaction is available) in order for the piece to have any meaning. But interaction might still be a viable way to invite the audience to explore and understand the workings of a circuit.

Composing with sound sculptures is an exploratory process. You start with an idea of a circuit, and an expectation of how that circuit is going to work. Whether it lives up to expectations or not is irrelevant, as you by exploring and expanding on the initial circuit start to unfold the near limitless potential of processes the electronic world has to offer. The creative part is not necessarily about sculpting the sonic qualities of the circuit as much as it is about *sonifying* the processes of an ecosystem. It is similar to algorithmic composition in the sense that you create a system and restrict the amount of possibilities and variations to a set of parameters. The downside is that you, as the creator of the system, could fail miserably in your assessment of musical quality and transparency of the processes in the system. Peter Edwards' (2014) phrasing of this problem is too good to pass up:

> *The strength and potential risk of this method is that actions derived from a set of initial circumstances don't always go as intended. This is exciting because it can lead us to unexpected discoveries, and it is also dangerous because the results can end up far outside of the musician's or anyone else's definition of interesting music. In the latter case, the value must instead be derived from the concept behind the experience* [the experience of exploring a circuit's possibilities, ed.]. *In order for this to work, an audience must know what that concept is and agree it is worthwhile. Utilization of obscure or novel functions of the system may be enough to satisfy the musician but not the audience who likely knows very little about these functions or the system itself. This can lead to music that is conceptually impenetrable as well as sonically unsatisfying. It can also lead to very clever music that inspires us to reconsider the value of sound once it is given an appropriately stimulating context.*

The problem of transparency was the first thing I set out to solve when I started making sound sculptures. The ubiquitousness of printed circuit boards in daily appliances have lead us to take their functions for granted, and it's not before a circuit's constituents are separated or modularized that we start to question its internal workings. I originally planned to lay out my circuits as a road map, where the audience could follow the electric current, so to speak, and get a visual representation of the processes within. However, due to the relative complexity of a circuit required to create sufficiently interesting sounds, the intended visual transparency in such a road map solution would pass most people by. Instead of relying on an exact visualization of the system, it would be easier to guide the audience through audio, and use lights to emphasize the sounds. Thus, the idea of my early sculptures was to create a simple random pattern that, while controlling the entrances of simple sound events, would be visualized with *light-emitting diodes* (LEDs). The circuits used for the two first sculptures, *Hexagon #1* and *Hexagon #2* were electronic dices that would generate six different miniature "mosaïques" randomly at sporadic intervals, with the change of image marked by bursts of noise. The sounds and the visual image were, however, not a "1-to-1 ratio", as the noise would always have the same quality regardless of what LED pattern was shown.

4.1 Strategies

4.1.1 Sonification

In search of a better visual representation of the audio, I decided to try to use *exactly* the same signals that were used to control the LEDs as the audio itself. The resulting sculpture, *Cubic #1*, was configured in such a way that I could tap the control signals going to the LEDs straight to a pair of amplifiers. This could be regarded as a simple form of *sonification*.

> *"Sonification is the use of non-speech audio to convey information. More specifically, sonification is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation"* (Kramer et al., 1999, p. 3).

Although it's an all-encompassing definition of any audio that helps us analyze, monitor or perceive data, its usage in arts could transcend the role of merely being an auditory tool. The sonified data could of course still be used analytically to help an audience understand the system in a piece of art, but the aesthetic characteristics of the sounds produced could also directly be used as an essential part of the piece itself (Gruska, 2013).

Cubic #1 had a 8x8 LED matrix driven by 16 square wave oscillators tuned closely together. As the oscillators slowly drifted in and out of phase, the patterns on the LED matrix would visualize the same ebb and flow that characterized the control signals. The oscillators were panned in the stereo field of the speakers in such a way that they followed the visual patterns on the matrix as they swept over the display. As stated above, the oscillators were also directly connected to the amplifiers so that the speakers would produce loud clicking noises for every transient of each square wave. Due to the byproduct of power supply noise produced by the digital circuitry – as mentioned in an earlier chapter – the sounds produced were entirely unexpected. Guttural screams and crackling noises was introduced to the amplifier, either by power supply ripples or electromagnetic interference. In any case, the product was a sonification not only of the control signals themselves, but also the side effects of the entire construction.

It might be valuable to mention that the artists working specifically with sonification often will deal with "real world objects". In my case with *Cubic #1*, the entire piece is created with the process of sonification in mind, contrary to an already existing object that unintentionally became the victim of being sonified. In my context, the word 'sonification' could arguably be exchanged with 'algorithmic', but the surprising, or rather unexpected nature of the musical results I've gotten over the years are way beyond those of an algorithmic composition. In almost all cases, this unexpectedness would be the result of a 'poor' construction leading to interesting outcomes, as was the case with *Cubic #1*. It is almost like an improvisational layer on top of the 'algorithm' that you can choose to embrace or discard. In *Composition #11* (mentioned in the next section) there is a faint rhythmical figure that can be heard under the sine waves – which did not appear during prototyping – and to this day I have no idea what the cause of this is, giving me no other choice than to embrace it.

4.1.2 Interaction

Interaction can be used to let an interactor have control over parts or the entirety of an process. It can be more or less transparent depending on the parameter being interacted with, and the nature of the interactor and the interactee. A typical interactee would be a sensor, for example a proximity or light sensor. The interactor can be a human or any natural or unnatural element that has an influence on the sensor's data input – like temperature would be an influence on a temperature sensor. The advantages of interaction are that they invite the audience to engage with the sculpture, while possibly educating the interactor about the process of the circuit. The disadvantage is that the result of the interaction can be predictable, or take away from the perception of the sculptures as independent entities (in chapter 2 we saw Walter Giers de-emphasize interaction once he discovered ways to involve aleatoricism in his work, in order to give his work 'a life of its own'). In any case, it allows the interactor to compose "his own" music while interacting, which might lead to interesting results.

Also mentioned in chapter 2, Peter Vogel says interaction is only a byproduct of involving a sculpture in the temporal domain. I can only deduct that he sees interaction as the most viable strategy to compose nonlinear music. I personally avoid interaction because of the aforementioned disadvantages, but also because it, if not done properly, can give the sculptures a toy-like quality. That being said, I did implement interaction in a few sculptures, most recently *Composition #11*, a De Stijl-inspired work with two proximity sensor-controlled sine waves that could be tuned by a very small margin by the interactor, thus creating a variable beating-effect. Here, the whole sculpture was tailored to appeal for interaction and individual composition, with clearly advertised sensors at the center of the construction.

Interaction doesn't have to be by the way of sensors reading external forces. As we will see in the next chapter, other agents, for example another sculpture, can influence a circuit in a more direct manner. This way of interacting is closer to the ways of an ecosystem, where everything works in tandem.

4.1.3 Performative

As a crossover between an instrument and an interactive sculpture, Peter Vogel's *Sound wall* requires human input to work. He calls it a *materialized score*; it is a piece that is unfinished, and requires the interactor to finish it (Martin, 2013). In short, it is a sculpture that contains pre-composed parts, and the interactor triggers them by casting his shadow over the light-sensors. This sort of interaction is more likened to how you play an instrument, in contrast to the type of interaction that changes certain variables in an ongoing process. It puts the performer rather than the electrical process in focus, and the sculpture turns into an inanimate tool rather than a self-sufficient entity. That the *Sound wall* is performative gets emphasized by the size of the piece; it is four or five meters in width and hung on a wall. The space between the sensors makes it so that the performer has to move around in order to interact, thus creating a sort of a choreographic-to-sonic interaction – perhaps exemplifying the graphical notations of dance that Vogel wanted his paintings to become, albeit in a more open manner.

In the compositional prototyping phase of my own *es*-series of sculptures (discussed in the next chapter), I was testing the network communication system I had integrated by controlling the sculptures from my computer, using the musical programming environment *SuperCollider*. There I could write routines (small scores) to automate the processes of the sculptures exactly how I wanted, but I could also directly perform them myself. In this context, the whole idea of the independent ecosystem that I set out to create in the first place would be rendered obsolete. Simply using a computer for all aspects, including sound generation, would be more efficient, but also defeat the notion of self-sufficiency.

4.2 Sound aesthetics

I've always been interested in polyrhythms, rhythmical counterpoints and streams of permutative patterns. While these topics quickly could get very theoretical or mathematical, I prefer a more intuitive approach. In the context of sound sculptures, I consider sound mostly as an agent by which the rhythmical characteristics of a process are represented – meaning that the sound characteristic itself is not as important as long as the sonification of a process is perceptible. This idea is partly caused by the limited sound reproduction capabilities of my sculptures; the speakers need to be small and light, where the inability to produce a high range of frequencies is an unfortunate side-effect. Yet, this deglorified notion of sound suits the ideals of my inner Functionalist.

Most of my earlier pieces (i.e. paper music) contain some sort of rhythmic duality where there is a repeating 'reference' pulse along with another rhythmical layer phasing in and out in respect to the reference. This approach has carried over to my sound sculptures. As explained in chapter 3, logic gates are excellent sources of streams of repeating rhythmical material if given the proper input signals. Depending on the input and type of logic gate, you can get both quantized and non-quantized syncopations over the reference rhythm, which results in highly interesting patterns that one would find hard to repeat from memory. Perhaps it is this rhythmical intricacy that I find the most fascinating within all of music. When you listen to a long, unpredictable looping pattern in conjunction with a pulse, or reference, it is almost as if you are listening to the pattern from different angles. You observe how a certain syncopation behaves between two pulses, and how that behavior changes as it shifts in time with regard to the reference. Another 'fancy trick' is to change the tempo of the reference pulse in the middle of a loop, by for instance adding a dot or making it a tuplet, creating an unstable foundation for the rhythmical counterpoint and leaving the listener mildly confused. This technique is used sublimely by Jo Kondo in his piece *Walk* (1976) for piano and flute. I would also like to add the album *Catch 33* by Meshuggah as an example. The whole album consists of sequencing sections of repeating irregular rhythmical loops, yet the drums stay in 4/4 at all times, making it hard to tell whether the drums or the loop is the anchoring reference.

Harmony is often a result either of vigorous tuning of oscillators or byproducts of certain processes in the circuit (an example is given in the next chapter). Creating an equal-tempered environment would generally not be the most rewarding thing to do due to the issues discussed earlier in this paper, so the choice of pitches normally stems from halves, doubles or other ratios of a frequency. This does, however, result in an open tuning which suits the nonlinearity of the sound world. The word *harmony* itself is probably not the best to describe what pitches are intended for in my sculptures. If you think of the sound output of a sculpture as a data signal which equals the result of a process that is being communicated, I regard pitches more as diacritics that add 'emotional' content to that data signal. The data signal stays the same no matter what, but the context which the listener perceives it in is changing, giving the data signal dynamic weight. You could say the data signal is rhythm, with pitches resembling 'accents' which excite the rhythm.

Chapter 5

The es-series of sculptures

This chapter is about my most recent work, the *es*-series. It is a group of sculptures capable of communicating wirelessly over Wi-Fi using the *open sound control* (OSC) protocol in order to "compose" in real time. The idea of the series is to expand on the idea of the circuit as an ecosystem; while the sculptures contain modules that are conversing and influencing each other on their own, they require input from other sculptures in order to function. Each sculpture is only a part of the bigger picture, and thus becoming modules themselves. The auditory composition is a sort of non-narrative, or non-directional, speech, where new "sentences" and phrasings are invented for each utterance, yet the conversation never moves forward. The spatial disposition of the sculptures made possible by the wireless communication adds to the contrapuntal quality of the conversation.

I would have liked to talk about the design of each sculpture in the series, but it is hardly interesting. Two of the designs were made in *SketchUp*, a *computer-aided design* (CAD) program for architects. They utilize the concept of parabolic hyperboloids seen in Le Corbusier and Xenakis' Philips pavilion at the 1958 World's Fair, albeit in a simpler manner to accommodate for electronics. The last of the sculptures were inspired by Antoine Pevsner and Naum Gabo's Constructivist works, and was ad-libbed due to running out of materials (in true Constructivist fashion).

Code and schematics can be found in Appendix A, while the sculptures themselves can be seen in fig. 9.

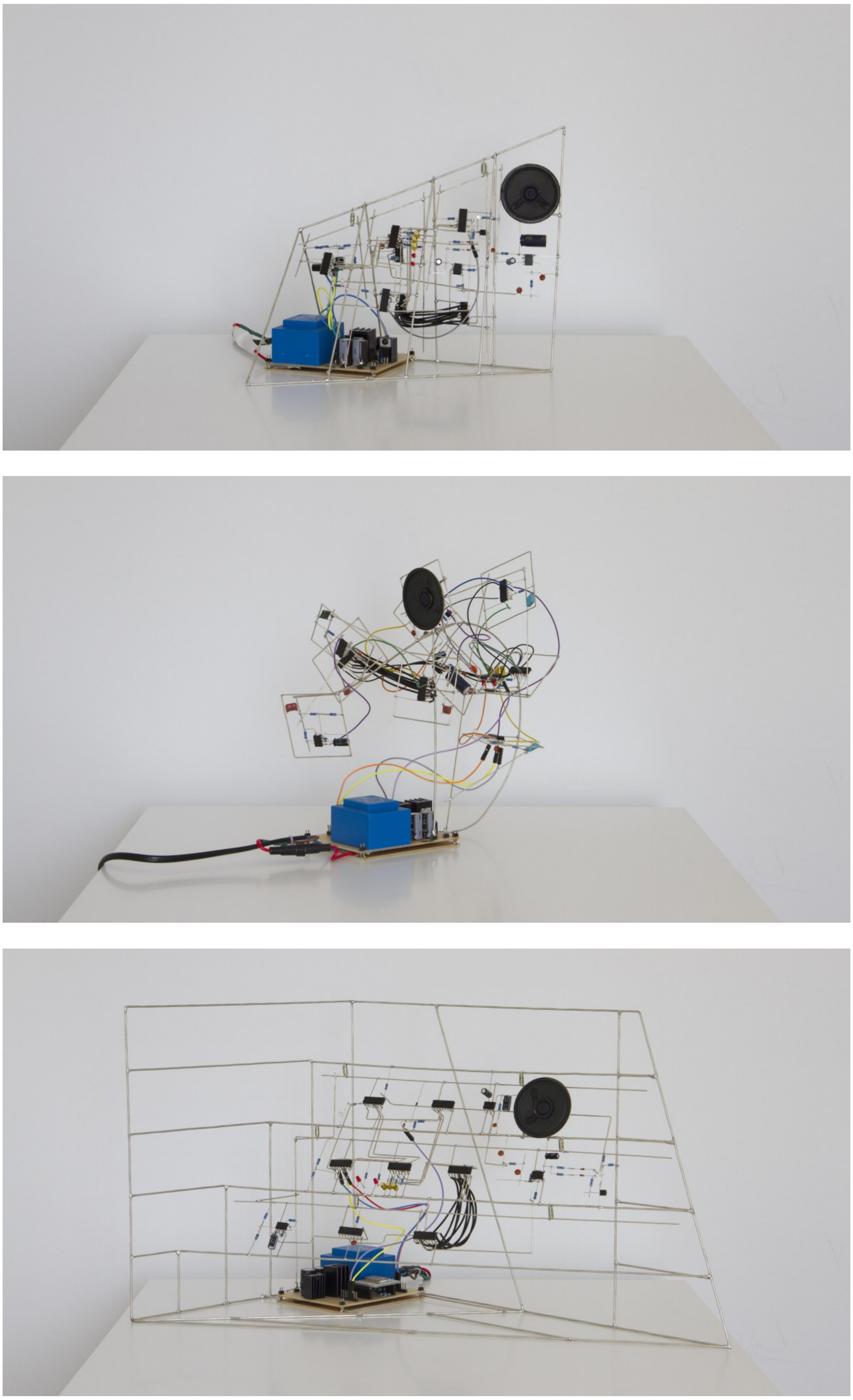

Figure 9: The sculptures in the es-series

5.1 ESP8266 as a means to communicate

For the wireless communication aspect of these sculptures, I used the ESP8266, a microcontroller made by Chinese company Espressif Systems. ESP8266 is in many ways similar to the famous Arduino (for what it's worth, you can even program it using the Arduino *integrated development environment* (IDE)), but it is smaller and cheaper, and more importantly, it has native support for Wi-Fi. First being produced in 2014, it is a comparatively new addition to the ever growing *Internet of Things* (IoT) bunch – a collective term for the interconnectivity of devices over networks – and I have been able to observe the growth of both community and documentation of this chip (I'm particularly happy about the growth of the latter, as all the early manuals were in Chinese).

Without getting too technical – a microcontroller is a small computer that can be programmed by the user. It allows us to customize certain processes like control functions or sensoring, depending on what input or output you program it to receive or send. Typically, a microcontroller has a number of *general purpose inputs/outputs* (GPIOs), and perhaps an ADC, that allows you to connect it to external components. The charm about the ESP8266 is as mentioned the integrated Wi-Fi that – unlike other boards, like Arduino, where you would have to use a Wi-Fi extension shield – requires no extra add-ons in order to function. To communicate over Wi-Fi, you need a *wireless access point* (AP), which is the hub of communications, to which each device (*station)* is connected. The ESP8266 can function both as a station and as an AP (Kolban, 2016).

5.1.1 Configuration

In the *es*-series, the three sculptures acts as stations, while an external router acts as the access point. The protocol used to communicate is OSC, which allows us to send data across the network. A typical OSC message will contain an address, a typetag (defining the type of data being sent), and an argument (the data itself), however the typetag is not required (Wright, 2002). Since I was programming the ESP8266s in the Arduino IDE, a simple message would look like in the following example; whenever a GPIO is in a HIGH state, a message called */message* will send the integer *1* to a network address (IP address and port):

```
if (input == HIGH) {
    OSCMessage msg("/message");
    msg.add(1);
    Udp.beginPacket(IPaddress, port);
    msg.send(Udp);
    Udp.endPacket();
    msg.empty();
}
```

In my setup, each sculpture generates a data signal through a logic operation that is being sent to the other respective sculptures' ESP8266s, changing an assigned GPIO's binary state. The assigned GPIOs are controlling the opening and closing of analog switches in the circuits, thus changing the recipient sculptures' behaviors. In this case, the signal flowing through the analog switches controls the entry of sound events in each particular sculpture, and thus the other two sculptures – being in control of the opening and closing of the switch – have a say in the phrasing of the sound. Due to the signal routing in the circuit, the sculptures will never enter at the same time, which results in a conversation-like behavior. The master clock, which controls the duration of each collective phrase and the silences between them, needs only to be programmed in one of the ESP8266s and sent, in the same fashion as described above, to the other sculptures.

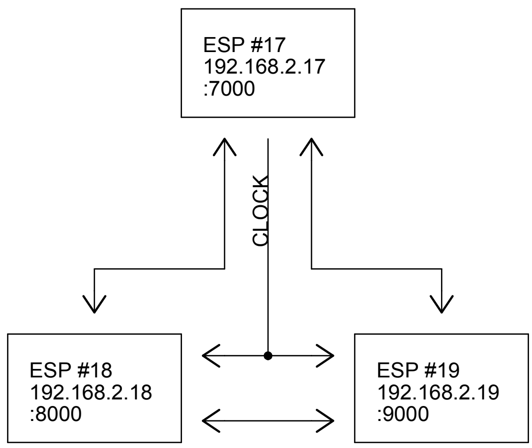

Figure 10: The signal flow between sculptures. All communications are administered by an access point (not shown).

5.2 Sound

The sound, or composition, of the *es*-series is meant to emphasize the metaphorical and non-metaphorical conversational aspect of the sculptures, with the non-metaphorical of course being network transmissions, and the metaphorical being how the sculptures take the roles of participants in a conversation during the auditory and visual representation of said transmissions. However, the conversational metaphor is not required to be understood in order for the audience to get something out of the piece. The rhythmical counterpoint, choice of pitches and how they change over time should provide sufficiently tangible information for a listener to stay interested for at least a couple of minutes.

The generation of sound itself is divided into two parts: a continuous stream of audio and an amplitude controller. The continuous stream of audio, produced by a voltage controlled arpeggiator, is sent to an amplifier which "volume knob" is controlled by an envelope generator triggered by incoming data (see fig. 11). This incoming data is produced by two square wave oscillators and a NOR logic gate, further gated by a switch controlled by the two other sculptures and the master clock, causing data to reach the envelope generator only when the master clock is HIGH and when none of the other sculptures are playing.

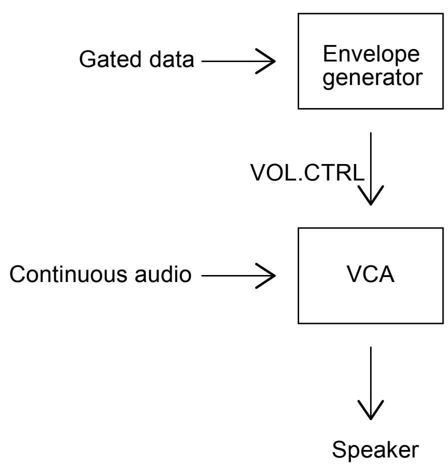

Figure 11: Volume control in the es-series

The voltage controlled arpeggiator consists of a *low frequency oscillator* (LFO), a *voltage controlled oscillator* (VCO) producing square waves, a sequencer and a multiplexer which data inputs are connected to three closely tuned square wave oscillators. A multiplexer is a digital switch with multiple inputs, or channels, and one output. Which channel being routed to the output is data input dependent. One would think that the sound output is produced by the square wave VCO, which is how it would work in synthesizers, but it is actually the interplay between the sequencer and the multiplexer that produces the final waveform. The VCO is merely a clock signal with variable speed controlled by the LFO. The sequencer sequences, or counts, the clock signal to eight different channels in the multiplexer, which chooses which channel to route to its output based on the incoming data signal from the three square wave oscillators. The output of the multiplexer is sent to the reset of the sequencer, thus creating a brief periodicity monitored by the first output of the sequencer until the data input of the multiplexer changes its state. In other words, the arpeggiations are created by the periodicity of the resetting of the sequencer, and the duration of each note – or the rate of change, rather – in the arpeggio is determined by the state of the data inputs of the multiplexer. It is a brilliant example of how digital circuitry can be exploited in a musical way. A simple illustration of the process can be seen in fig. 12.

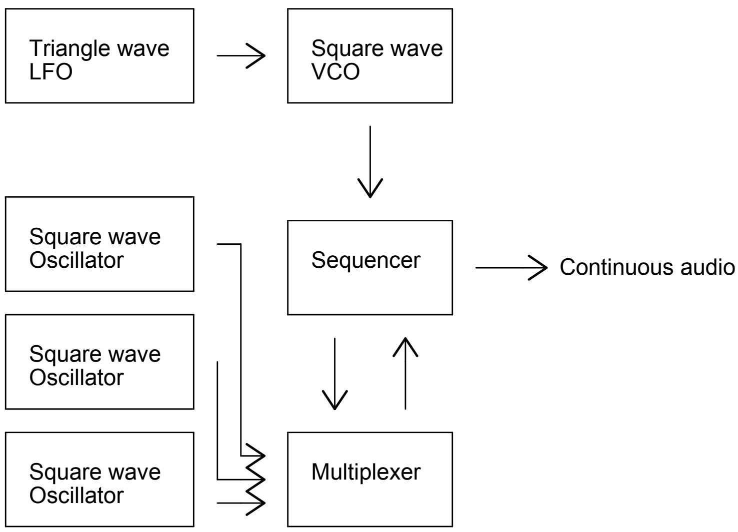

Figure 12: Sound generation in the es-series

As for the choice of harmony; there is no way around a set of inverse Pythagorean pitches derived from divisions of the incoming clock signal, so 1/2, 1/3, 1/4, 1/5 and so on. So if the clock signal is 500 Hz, the frequencies of the set of pitches will be 500, 250, ≈ 166.67, 125, 100, ≈ 83.33, ≈ 71.42, and 62.5. Even when the pitch of the clock signal is slowly fluctuating because of the control voltage it is receiving from the triangle wave oscillator, the ratios between the pitches stay the same. Because all three sculptures contain the same circuit and are tuned approximately to each other, they collectively slide in and out of tune. I found that using *Composition #11* (the sculpture with the user-adjustable sine waves) in conjunction with the *es*-series was quite effective, not only because of the stark contrast in sound, but also because the sine waves functioned as a harmonic anchor to the arpeggios in constant flux.

5.3 Expansions and possibilities

I can imagine many ways to expand on using microcontrollers with Wi-Fi capabilities to communicate between sets of sculptures. With interaction, one idea would be to have a sculpture vicariously react to the information received by a different sculpture to obscure the influence the interactor has on the process, thus preventing predictability, while keeping the appearance of an independent ecosystem. It would also be possible to place different sculptures in different rooms, where the sculptures act as 'telephones' and let people interact with each other by abstract means. The imagination is really the limit when it comes to what can be achieved with the continuous growth of IoT technology.

Chapter 6

Conclusion

In this thesis, we have seen that the process of building electronic sound sculptures is bilateral; there are visual and auditory parts that need to be addressed. The visual design and sound are not necessarily amplifying each others' characters, but they are intertwined in functionality and contribute to the greater whole of the sculpture. We have established strategies for composing with nonlinear material through sonification and interaction, while still catering to the musical senses through harmony and rhythm. We have also seen that the greatest challenge of composing in a nonlinear medium is to intellectually involve the audience in exploration, both visually and auditorily, through listening, analysis or interaction. The pinnacle work of my Master studies, the *es*-series, was an attempt at answering, to one degree or another, these points. Whether successful or not, it has opened the door for many opportunities to be investigated further.

Bibliography

Berg, P. (2014). Class on Programming and Music, n.d., The Hague, the Netherlands

Edwards, P. (2014). *Collaborating with circuits: Music, invention and electricity.* Master's thesis, Institute of Sonology. Retrieved from http://www.sonology.org/docs/2014MII%20Edwards%20Peter.pdf

Gruska, J. (2013. *Streams & Currents.* Bachelor's thesis, Institute of Sonology. Retrieved from http://194.171.57.139/sonology/NL/thesis-pdf/jonas_gruska_thesis.pdf

Herbert, R.L. (Ed., 1964). *Modern Artists on Art: Ten Unabridged Essays*. Englewood Cliffs, NJ: Prentice-Hall, Inc.

Hopkins, O. (2014). *Architectural Styles.* London: Laurence King Publishing.

Horowitz, P. & Hill, W. (2015). *The Art of Electronics* (3rd ed.). Cambridge: Cambridge University Press.

Illies, C & Ray, N. (2016). An Aesthetic Deontology: Accessable Beauty as a Fundamental Obligation of Architecture. *Architecture Philosophy*, 2(1), (pp. 63-82). Retrieved from http://ojs.library.okstate.edu/osu/index.php/jispa/issue/view/550

Kolban, N. (2016). *Kolban's book on ESP32 & ESP8266.* Retrieved from https://leanpub.com/ESP8266_ESP32

Kramer, G., Walker, B., Bonebright, T., Cook, P., Flowers, J., Miner, N., Neuhoff, J. (1999). *Sonification Report: Status of the Field and Research Agenda.* Retrieved from http://sonify.psych.gatech.edu/publications/pdfs/1999-NSF-Report.pdf

Lunetta, S. (n.d.). *Moosack machines.* Retrieved from http://moosack.net/stang/me.html

Maloney, D. (2016, May 4). *Getting ugly, dead bugs, and going to Manhattan.* Retrieved, April 12, 2017, from https://hackaday.com/2016/05/04/getting-ugly-dead-bugs-and-going-to-manhattan/

Martin, J. (2013, February 17). *Peter Vogel – The Sound of Shadows* [video file]. Retrieved from https://vimeo.com/59829961

Pugin, A.W.N. (1841). *The true principles of pointed or Christian Architecture* [Open Library version]. Retrieved from https://openlibrary.org/works/OL2495561W/The_true_principles_of_pointed_or_Christian_architecture

Smalley, D. (1997). Spectromorphology: explaining sound-shapes. *Organised Sound*, 2(2), (pp. 107-126).

Telekom Electronic Beats. (2017, February 7). *Walter Giers – Electronic art* [video file]. Retrieved from https://www.youtube.com/watch?v=3-zyXnc2Xls

Ulian, L. (2016). Technological mandala 92 [Online image]. Retrieved, April 29, 2017, from http://www.leonardoulian.com/works/technological-mandala-92-model-everything/

Wittgenstein, L. (2001). *Tractatus Logico-Philosophicus.* New York: Routledge. (Original work published in 1921)

Wright, M. (2002). The Open Sound Control 1.0 Specification. Retrieved from http://opensoundcontrol.org/spec-1_0

Appendix A

Code and schematics for the *es*-series.

All three sculptures are essentially using the same schematic, apart from one resistor in the oscillator section, which vary between each sculpture by about 20kΩ. The code for each of the three ESP8266s vary by their respective IP addresses, and the master clock generator is only required in one of the programs.

A.1 Code

```
#include <ESP8266WiFi.h>
#include <WiFiUdp.h>
#include <OSCMessage.h>le
#include <OSCData.h>

const char* ssid = "SSID";
const char* pass = "password";

WiFiUDP Udp;

//static IP current device
const IPAddress ip(192,168,2,17);
const IPAddress gateway(192,168,2,1);
const IPAddress subnet(255,255,255,0);

//receiving port
const unsigned int localPort = 7000;

//send-to 18
const IPAddress sendIP18(192,168,2,18);
const unsigned int sendPort18 = 8000;
```

```
//send-to 19
const IPAddress sendIP19(192,168,2,19);
const unsigned int sendPort19 = 9000;


OSCErrorCode error;
unsigned int ledState4 = LOW;
unsigned int ledState5 = LOW;
unsigned int ledState14 = LOW;
unsigned int ledState16 = LOW;
int p = 0;
int c = 0;
int d = 0;
int e = 0;
unsigned long previousMillis = 0;
unsigned long interval = 2000;


void setup() {
  Serial.begin(115200);
  delay(10);
  WiFi.mode(WIFI_STA);
  WiFi.config(ip, gateway, subnet);

  pinMode(4, INPUT); //logic data input
  pinMode(5, OUTPUT); //18 output
  pinMode(14, OUTPUT); //19 output
  pinMode(16, OUTPUT); //master clock

//WiFi connecting
  Serial.println();
  Serial.println();
  Serial.print("Connecting to ");
  Serial.println(ssid);
  WiFi.begin(ssid, pass);

  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }
  Serial.println("");

  Serial.println("WiFi connected");
  Serial.println("IP address: ");
  Serial.println(WiFi.localIP());
```

```
  Serial.println("Starting UDP");
  Udp.begin(localPort);
  Serial.print("Local port: ");
  Serial.println(Udp.localPort());
}

//receive 18 at pin5
void pin5(OSCMessage &msg) {
  ledState5 = msg.getInt(0);
  digitalWrite(5, ledState5);
}

//receive 19 at pin14
void pin14(OSCMessage &msg) {
  ledState14 = msg.getInt(0);
  digitalWrite(14, ledState14);
}

//master clock at pin16
void pin16() {
  unsigned long currentMillis = millis();


  if (currentMillis - previousMillis >= interval) {
    previousMillis = currentMillis;

    if (ledState16 == LOW) {
      ledState16 = HIGH;
      interval = random(1500,4000);
    } else {
      ledState16 = LOW;
      interval = random(2000,10000);
    }

    //clock output
    digitalWrite(16, ledState16);
  }
}

void loop() {
  //receiving OSC messages at pin5 and pin14
  //////////////////////////////////////////
  OSCMessage message;
  int size = Udp.parsePacket();

  if (size > 0) {
```

```
  while (size--) {
    message.fill(Udp.read());
  }
  if (!message.hasError()) {
    message.dispatch("/logic18", pin5);
    message.dispatch("/logic19", pin14);
  }
}

//sending OSC messages
//////////////////////
ledState4 = digitalRead(4);

//sending input logic data to 18
if ((ledState4 == HIGH)&&(p==1)) {
  OSCMessage msg("/logic17");
  msg.add(1);
  Udp.beginPacket(sendIP18, sendPort18);
  msg.send(Udp);
  Udp.endPacket();
  msg.empty();
  p = 0;
} if ((ledState4 == LOW)&&(p==0)) {
  OSCMessage msg("/logic17");
  msg.add(0);
  Udp.beginPacket(sendIP18, sendPort18);
  msg.send(Udp);
  Udp.endPacket();
  msg.empty();
  p = 1;
}


//sending 17 input logic data to 19
if ((ledState4 == HIGH)&&(d==1)) {
  OSCMessage msg("/logic17");
  msg.add(1);
  Udp.beginPacket(sendIP19, sendPort19);
  msg.send(Udp);
  Udp.endPacket();
  msg.empty();
  d = 0;
} if ((ledState4 == LOW)&&(d==0)) {
  OSCMessage msg("/logic17");
  msg.add(0);
  Udp.beginPacket(sendIP19, sendPort19);
```

```
    msg.send(Udp);
    Udp.endPacket();
    msg.empty();
    d = 1;
  }

  //sending clock to 18
  pin16();

  if ((ledState16 == HIGH)&&(c==1)) {
    OSCMessage msg("/clock");
    msg.add(1);
    Udp.beginPacket(sendIP18, sendPort18);
    msg.send(Udp);
    Udp.endPacket();
    msg.empty();
    c = 0;
  } if ((ledState16 == LOW)&&(c==0)) {
    OSCMessage msg("/clock");
    msg.add(0);
    Udp.beginPacket(sendIP18, sendPort18);
    msg.send(Udp);
    Udp.endPacket();
    msg.empty();
    c = 1;
  }

  //sending clock to 19
  if ((ledState16 == HIGH)&&(e==1)) {
    OSCMessage msg("/clock");
    msg.add(1);
    Udp.beginPacket(sendIP19, sendPort19);
    msg.send(Udp);
    Udp.endPacket();
    msg.empty();
    e = 0;
  } if ((ledState16 == LOW)&&(e==0)) {
    OSCMessage msg("/clock");
    msg.add(0);
    Udp.beginPacket(sendIP19, sendPort19);
    msg.send(Udp);
    Udp.endPacket();
    msg.empty();
    e = 1;
  }
}
```

A.2 Schematics

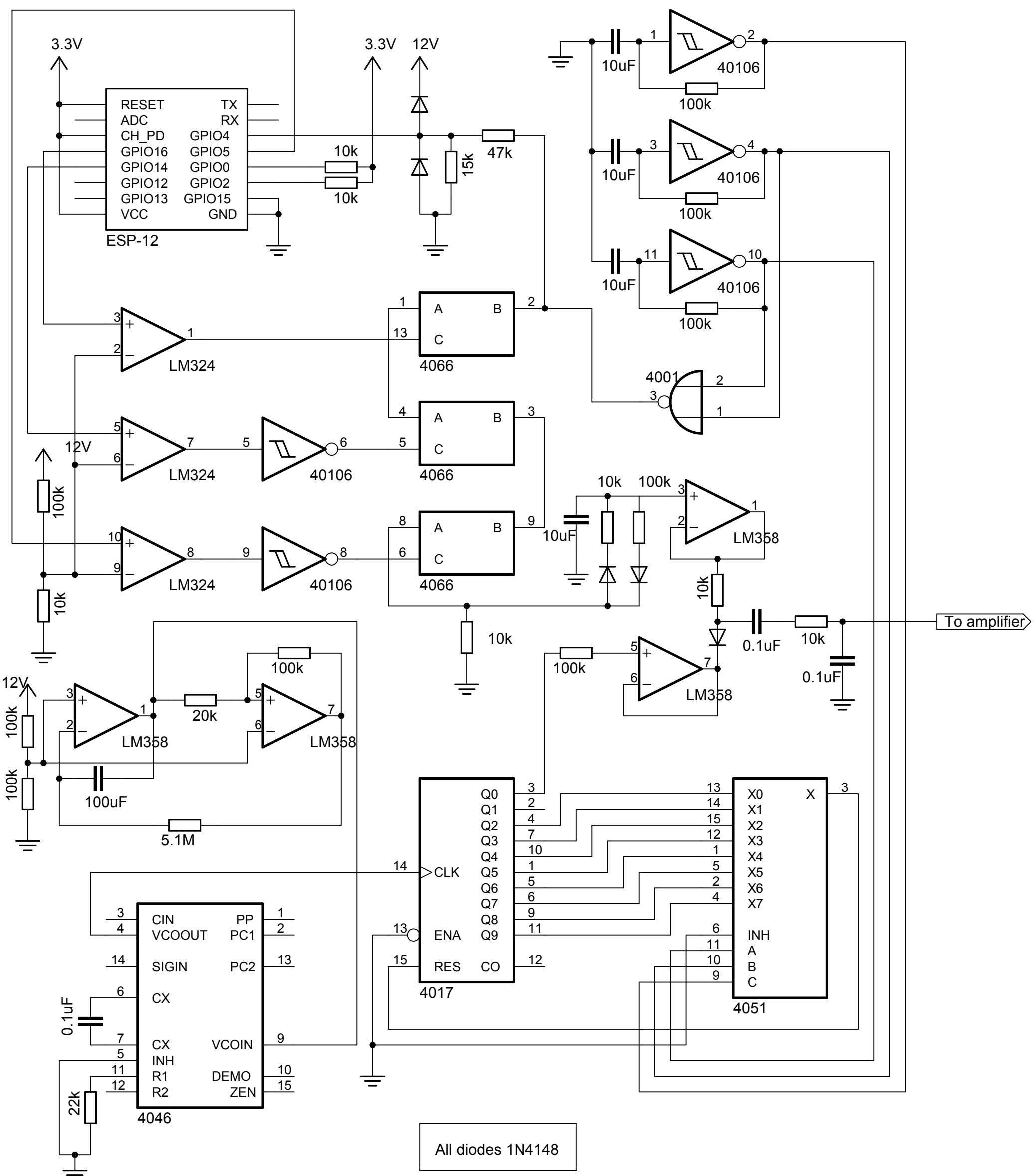

Figure 13: Schematics for the es-series