Hand Turned Synthesis: A One Chip Exploration of CMOS Electronics

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ABSTRACT
We discuss and give a concise overview of the historical practices and approaches to utilising budget-friendly electronic components as a foundation for constructing simple sound making circuits. Building on the work of Lunetta, Collins and Wilson we focus specifically on the use of a 40106 CMOS integrated circuit (IC). Our research goal is to provide a tool kit of circuits for common synthesis elements based around the use of a single 40106 IC that may be of use to those involved in sound installations and frugal instrument design as well as practitioners working within accessibility and workshop/pedagogical scenarios. The authors demonstrate the application of the tool kit in their own projects, such as a monophonic synthesizer as well as several hand cranked sculptures that are powered and 'played' by the interaction between the user and the hand crank. Overall, we gather a broad range of relevant information that is difficult to find in one place and provide a practical tool kit that is pitched at an introductory level and describe how this is incorporated into the design of interactive electronic instruments. We also attempt to highlight fundamental electronics and synthesis principles while embracing terminology common to both electronics and synthesizer communities.

Author Keywords
Synthesizer, Integrated Circuits, Lunetta, CMOS, DIY, Electronic Music, History, Sound Art, Installation, Accessibility, Low Cost, Sonic Devices, Community Music, Public Art, Ensemble

CCS Concepts
•Social and professional topics → *History of hardware;* •**Applied computing** → *Sound and music computing*; •Human-centred computing → Interaction design;

1. INTRODUCTION
This article presents designs of simple, yet novel, sound-making and processing circuits foregrounding low cost and accessible hardware synthesizer designs using a Complementary Metal Oxide Semiconductor (CMOS) integrated circuit (IC) or 'chip'. Simple CMOS circuits have long been used by the DIY synthesizer community and our main objective is to outline a robust synthesizer tool kit that brings together various approaches, with the goal of only using one CMOS chip. One of our designs, T.H.E.M, discussed in Section 4, foregrounds the idiosyncratic behaviours that CMOS technology exhibits when supplied a varying voltage supply.

Our goal is to discuss and explore the potential of simple hardware designs and their ability to be used in installation and performance situations by musicians without the need for assumed knowledge or a specific performance practice. Whilst CMOS based synthesizer designs can range from elaborate large-scale professional systems to portable and handmade devices, it is clear that devices such as Waisvisz's Cracklebox, BugBrand's Board Weevils, Bastl+Casper Electronics' Bit Ranger and even Buchla's Thunder offer novel and engaging interfaces that celebrate interactive performance. The connection between sound generating processes and musical interfaces can be observed across the range of these synthesizer designs, providing a rich and complex context for this project, without the need for interfacing with other devices or software, which can so often be the case for NIME's.

CMOS circuits have been celebrated and explored extensively in the maker and DIY electronics community. As such the breadth of information associated with simple synthesizer CMOS circuits can be, at times, overwhelming and confusing. The tool kit, presented in Section 3, aims to offer a clear usage of such circuits contextualised by established designs and approaches though a concise overview of historical approaches and practices related to CMOS music making circuits. In addition, we foreground synthesizer building blocks that can inspire musically creative outcomes yet are reliable and simple to build, and represent frequently used synthesis elements such as voltage-controlled oscillators (VCOs), voltage-controlled filters (VCFs), and voltage-controlled amplifiers (VCAs). Lastly, we demonstrate how they can be combined to create a basic monophonic subtractive synthesizer and are applied in work by the authors.

2. BACKGROUND
Over many decades a wide variety of electronic components have been used for sound synthesis, including the 4000-series chips, a CMOS logic family of integrated circuits. When these logic chips are utilised as simple circuits clocked at audio rates, they offer a wide range of audio synthesis possibilities. One of the most used chips is the 40106 Hex Schmitt Trigger, which is popular among circuit bending and DIY electronics enthusiasts and has been at the core of texts such as Nicolas Collins' book Handmade Electronic Music [5].

NIME'24, September 4–6, 2024, Utrecht, The Netherlands

2.1 The 40106

The 40106 is popular within the maker and DIY electronics community due to its affordance to be configured as an audio oscillator with just two additional components and a power source. This is achieved by adding a capacitor between ground and the input of the Schmitt trigger then creating a feedback loop with a resistor across the input and output of the same Schmitt trigger, as shown in Figure 1. This configuration creates a feedback loop in the circuit, connecting output to input, resulting in a rapid opening and closing of the output of the Schmitt trigger, in turn producing an oscillating waveform. The 40106-based circuit can be configured in various ways to produce different waveforms and to provide other useful applications beyond astable oscillation, as documented by Wilson [25], Williams [22], and Collins [5]. Given the six individual Schmitt triggers on the 40106, up to six independent waveforms can be generated at once. With an individual CD40106 chip costing well less than USD$1, this provides the basis for quite inexpensive and approachable sound synthesis.

In the work reported here, we continue a long tradition of using the 40106, combined with passive electronic components, to generate analogue signals.

2.2 Early Approaches to CMOS Synthesis

In the 1970s Stanley Lunetta created CMOS-based sound sculptures, such as the Moozack Machine: "a sculpture that produces, mixes and processes electronic sound" built around digital logic circuits [1]. Lunetta's website details further circuits, dubbed Moozack Machines [12], which make use of 4000-series CMOS logic family IC's. These sculptures and circuits are an important starting point for our projects, considering that Lunetta's work, by design, thrived on a simple and inclusive approach, often using a wide variety of low-cost CMOS IC's to make sound. Lunetta's SOUND GUN is an example of such an approach, utilising CMOS IC's for sound generation coupled with a simple mercury tilt switch for gestural control [13], [28]. Howard Moscovitz said of Lunetta's practice:

"Stan taught us about the joy of the surplus electronics stores, and he was into building really simple digital circuits that clocked at audio rates. For example, you make simple oscillators using digital inverters with RC networks. If you uses [sic] NAND gates instead of inverters, you get some sort of neat modulation when you hook up another oscillator to one of the free gate inputs. Run the osc into a modulo-N converter and you can get different pitches based on the code you put on the four inputs." [16]

Moscovitz also mentions that those who were taught by Lunetta gave the name *Lunettas* to these simple circuits, which often used "one 'naked' IC, … hooked up to ban[a]na jacks so you can make patches" [16]. Online forums such as Modwiggler.com and electro-music.com are popular spaces for sharing Lunetta circuits and approaches, with electro-music.com featuring a dedicated subforum filled with lively discussions [29]. One notable example from this community is Tom Bugs (BugBrand), a forum member who presented schematics early on and went on to create his Board Weevils, that "stem from the same core circuit using CMOS 4000 chips to make simple squarewaves which are quasi-ringmodulated together" [30]. Bugbrand's Board Weevil's incorporate touch, photocells and power starving[1]. Lunetta's unique approach to CMOS synthesis may have been especially relevant in the 1970s when the cost of early hardware synthesizers was high and software-based alternatives were limited.

Collins echoes Stanley Lunetta's approach to making music with 4000 series chips, describing the 40106 IC as "The World's Simplest Circuit: Six Oscillators on a Chip, Guaranteed to Work" and presents circuits for obtaining triangle and square waves from the 40106 IC [5]. Collins takes a methodical approach to experimenting with a variety of CMOS chips and passive components to create volume and tone controls, Theremins, and cross-modulated oscillators. The book is often used as a guide by musicians new to DIY electronics.

In his book subtitled A Modern Approach to Old-School Sound Synthesis, Ray Wilson [25] offers a comprehensive overview and tutorial on DIY electronic sound synthesis. The book includes a variety of practical projects and detailed explanations of electronic theories. While the book delves into topics beyond the basic components emphasised by Lunetta or Collins – it utilises bipolar power supplies common in Eurorack synthesizers. Collins states that "one of the biggest problems for non-engineers making audio circuits was power supplies — they were difficult to build, and always seemed to contribute excessive hum and other noise" [32]. The 4000 series CMOS IC's accept a wide range of voltage and can be easily powered by a 9-volt battery. Whilst Wilson's book uses such power supplies, it has an excellent appendix focused on CMOS logic chips, covering the operation and potential applications of many of the 4000 series ICs, including the 40106, with circuits for generating common waveforms. Wilson's website, Music From Outer Space [26], is an invaluable resource for designs and education, often used within the DIY electronics community, featuring design such as The Weird Sound Generator (WSG) that utilises the 40106 as a noise instrument, incorporating cross modulation as a fundamental design.

2.3 A (Brief) Overview of the Variety of Approaches to CMOS Synthesis

Since the early discussion on forums about Lunettas, many other approaches to CMOS synthesis have been shared online, often in connection to modular synthesis practices. However, the breadth of information that emerges on a forum can be confusing. To consolidate resources, guides such as Introduction to the Lunetta-style CMOS Synths by Sergio Gonzalez [9] have been created. Additionally, Jon Dent provides a useful overview of CMOS chips and their uses in Lunetta-style circuits [10]. Casper Electronics (Peter Edwards) has contributed a series of tutorial videos, connected to the OMSynth [33], a circuit development tool, which explain how to make oscillators with the 40106 and other CMOS chips and a ISD1820 (Voice recorder). Edwards later released the BITRANGER with Bastl Instruments, based upon CMOS logic chips [34]. His archived website [35] is a useful resource for circuitbenders and DIY enthusiasts. Elliot Williams' Logic Noise series on Hackaday [22] contributes to the discussion around the 40106, building on Collins' approach by buffering the output of a 40106 with another CMOS chip, and configuring the 40106 to produce sawtooth and pulse waves along with discussion about cross-modulating oscillators. Williams' Logic Noise series eventually moves away from the 40106 to add more 4000 series CMOS chips and op-amps, but the discussion of an AR generator and a voltage-controlled oscillator are noteworthy for their frugality and utility [23]. It is no surprise that Williams' work has resulted in a CMOS synthesizer called The Klangorium, which ties together all the building blocks of the series [24].

Other approaches to this style of CMOS synthesizer abound, such as the Moduletta which demonstrates the almost endless creative utility of 4000 series; the 40106 is not used as an oscillator [36] [19]. Moritz Klein's YouTube channel [37] features a series of videos on building simple synthesizer modules from the ground up, for the popular Eurorack modular format. Klein has teamed up with Erica Synths to make each module available for purchase under the brand name *mki x*

[1] Tom Bugs notes that power-starving causes connected synthesis circuits to "inter-modulate in very strange ways, slightly tameable but with a life of their own. The range of sounds it helps to create out of the simple heart of these circuits is quite amazing."[31]

es.EDU. Each module is accompanied with detailed construction guides which give clear explanation of the function and purpose of CMOS chips, op-amps and discrete components (transistors, resistors, diodes, etc...) used in each module [38]. Whilst his approach is frugal at times, it is concerned with interfacing with Eurorack control voltage and input/output standards and, as such, his circuit designs quickly depart from single power supplies to using bipolar power (+-12v) making them more complex than the aspirations we have for simplicity and approachability in this article. Lastly, Peter Blasser (Ciat-Lonbarde) combines the spirit of Lunetta's CMOS instruments with a more complex, and slightly chaotic, approach by printing design layouts on paper into which components are paced and their legs soldered together to form a circuit [5].

3. BUILDING A SYNTHESIZER WITH A 40106: A TOOL KIT

In the sections that follow we discuss a range of circuit schematics and outline our approach to creating building blocks towards a tool kit for a simple electronic synthesizer based on the CMOS 40106 integrated circuit and other components, contextualised by existing CMOS synthesis practices. For anyone unfamiliar with circuit schematics, Sparkfun have a useful overview [18].

The varying approaches to CMOS synthesise outlined in Section 2.3 often incorporate multiple 4000 series chips and Operational Amplifiers (Op Amps). This is in contrast to our approach in this article, which foregrounds the use of a single 40106 chip for analogue synthesis. In the third edition of Handmade Electronic Music, Collins discusses the Op Amp stating that “We built our first oscillator ... with just four parts … [t]o make the same with an op amp would double that count, square your changes of wiring error and make it 10 times more likely you’d walk away from the book then and there.” [5].

Echoing Collins' approach, we misuse a 40106, which is inherently a digital chip, for various analogue tasks, however to aid simplicity and approachability we avoid including any further IC’s. Whilst this contrast’s Lunetta’s approach of using multiple CMOS chips, we still emphasise the economy of the materials used, and Collin’s approachability and simplicity, instead employing transistors for voltage buffering and vactrols (opto-isolator see Section 3.1.2) for voltage control of circuit elements. Lastly, we strive for a sustainable and material minimisation in our designs acknowledging the ongoing discussions around sustainability in the design and building of new musical tools within the DIY and music making communities (e.g. [14], [21]). Our circuits strive to achieve utility whilst economy and ease of use is at the forefront of their design.

The schematics and design files of the circuits presented in this article are available on the authors’ GitHub [27].

3.1 40106 Waveshapes

The 40106 easily produces square and triangle waves, depending on where the output to the circuit is connected. Oscillation frequency, and thus pitch range (when oscillating at audio rates) is set by the values of the resistor and capacitor as shown in Figure 2. When the supply voltage is varied, this also affects the oscillation frequency.

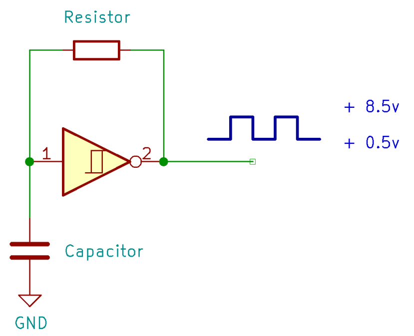

Figure 1. Schmitt trigger oscillation using a resistor and capacitor when powered at 9 volts.

Oscillators are a fundamental element in an electronic synthesis system, frequently being used as Voltage Controlled Oscillators (VCO), Low Frequency Oscillators (LFO), or as a modulation source. Commonly they are found as discrete modules within a synthesizer system interconnected either by patching or hardwiring. Electronic oscillators are often complex in design and usually involve multiple components and require a stable voltage supply. Conversely using a 40106 allows us to create 4 discrete waveforms with a handful of components.

Figure 2 displays a schematic of a circuit using a 40106 and passive components that generate various waveforms which can be visualised by an LED[2]. A feedback resistor creates oscillation in the Schmitt trigger by connecting its output to its input. The feedback resistor sets the oscillation frequency, and its range is determined by a capacitor. The left image generates square or triangle waves, the right image generates saw or pulse waves by adding a diode.

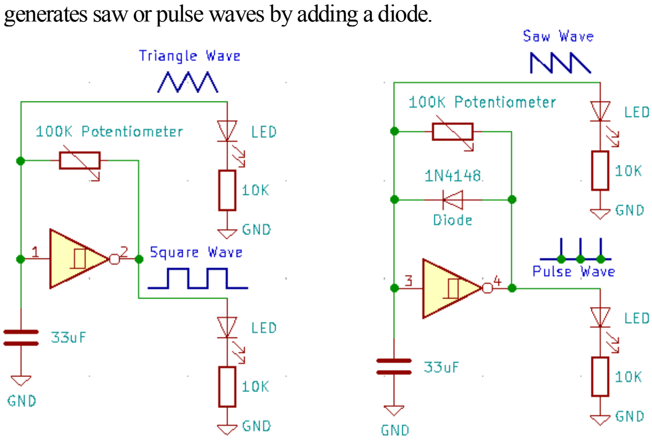

Figure 2. LEDs driven by low frequency square, triangle, sawtooth, and pulse waveshapes.

When varying the input voltage, the 40106 exhibits interesting behaviours. A higher voltage will result in a lower rate of oscillation. This is because each Schmitt trigger is a dual comparator that can detect an input signal relative to upper and lower threshold values. The output retains its value until the input changes sufficiently to cross a threshold and trigger a change to the opposite state (high or low). This dual threshold action is called hysteresis implying that it can hold its historical state. Typically, the hysteresis thresholds of a 40106 Schmitt trigger range across 1/3 of the supply voltage, making it versatile and useful as an impromptu gate [25]. As voltage increases, so do the upper and lower thresholds, and they decrease as voltage increases. Since oscillation is determined by the charging and discharging of a capacitor, at a lower voltage it takes less time for the charging and

[2] A 9-volt battery can be used when testing these circuits. The 40106. Pin 14 is connected to +, pin 7 is connected to -

discharging cycle to take place due to the constrained upper and lower thresholds; this cycle takes longer at higher voltages due to the expanded thresholds; this is contrary to the notion that higher voltage results in faster oscillations/speed e.g. a motor. Our circuits are designed to work at 9V, but other voltages between 5V – 12V are acceptable.

3.1.1 Using a transistor as a buffer to maintain integrity of triangle and saw waveshapes

The schematic shown in Figure 3 is suitable for generating audio signals. A transistor is used to maintain the integrity of triangle and sawtooth waveforms. The transistor is configured as an emitter follower allowing it to drive greater loads than the 40106 alone. This goes beyond Collins' suggestion of using a single capacitor [5]. The signals obtained from the input of the Schmitt trigger (triangle and sawtooth) are at a lower level, so a voltage divider is inserted after the signals from the output side (square and pulse) to reduce their level so both sides match.

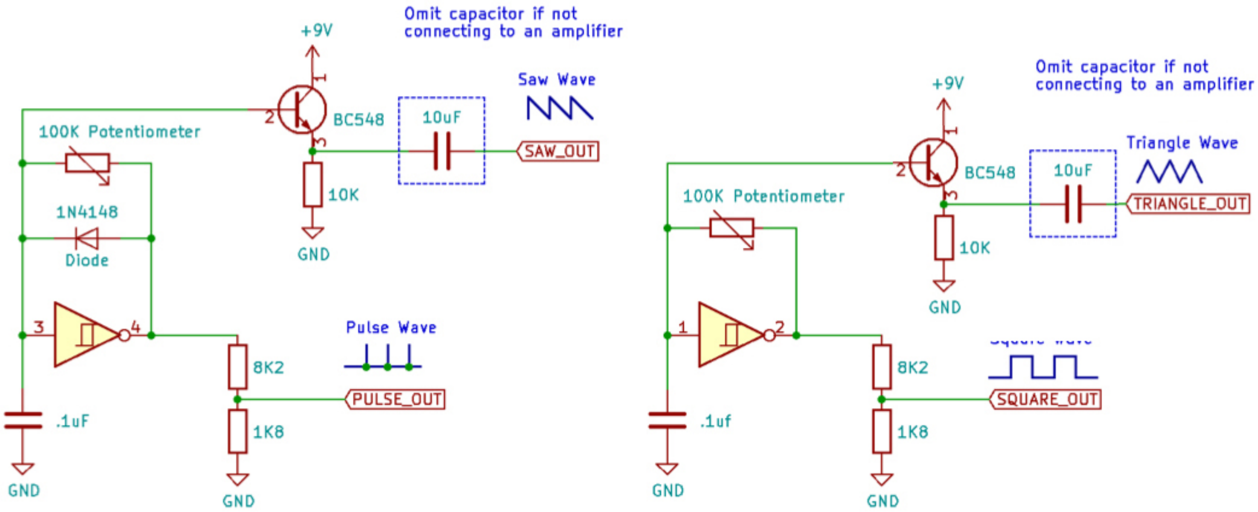

Figure 3. Audio rate square, pulse, and buffered triangle and pulse wave (with voltage divider for level control).

3.1.2 Vactrols to control resistance with light level

A vactrol is a common name for an opto-isolator, it transfers electrical signals between two isolated circuits by using light. We use them for applying voltage control using resistors, such as potentiometers. A vactrol can be made from an LED and the LDR put in close proximity and shielded from external light. The LED brightness varies the LDR's resistance. Collins [5] provides an overview of making and using vactrols.

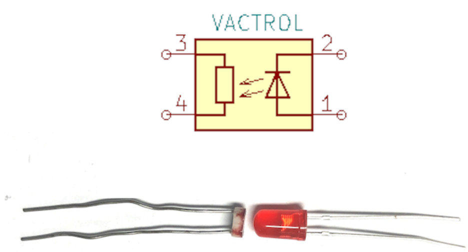

Figure 4. A vactrol consists of a single or more LED/s and LDR encased to exclude external light.

3.2 Synthesis Building Blocks

This section introduces electrical circuits that act as modules for various synthesis functions, including: VCO, VCF, AR, VCA, and an Audio Amplifier. The modules for the building blocks of the frugal synthesizer. Each module can be combined, or elaborated upon, to provide different utilities if desired.

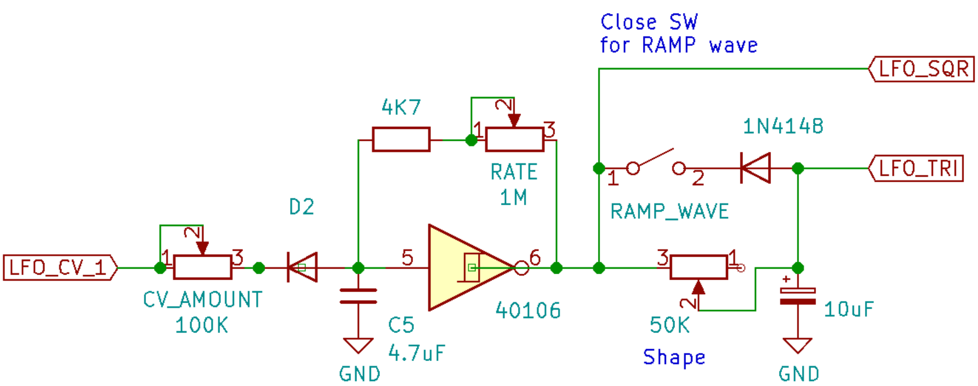

Figure 5. Low Frequency Oscillator circuit (LFO).

3.2.1 *Voltage controlled oscillators*

A variety of methods are available to achieve voltage control of the oscillators. The schematic in Figure 6 uses a vactrol, however, a diode [2] or a transistor [3, 16] can be used.

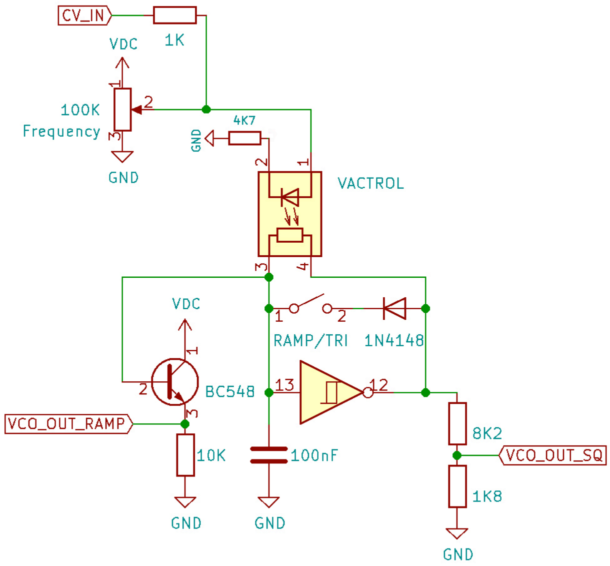

Figure 6. A voltage-controlled oscillator circuit (VCO).

3.2.2 *Low frequency oscillators*

LFOs resemble VCOs but have slower frequency ranges. They are commonly used to modulate other modules, e.g., adding vibrato to VCO pitch. The circuit shown in **Error! Reference source not found.** outputs square and triangle/sawtooth waves, which can produce different modulation effects. The triangle waveshape is governed by a potentiometer (shape) which also acts as a quasi-level control and gives more musical possibilities for modulation. The waveshape becomes more like a sawtooth (ramp) wave when the RAMP_WAVE switch is closed.

3.2.3 *Low pass filters*

Filters are used to change tone colour by excluding some parts of the frequency range. The filter shown in Figure 7 consists of a capacitor and resistor and can be made active through the inclusion of a transistor detailed by Don Lancaster [11]. The same method is commonly employed by Doepfer and shows the possibility of control by vactrols [7]. Another possibility for a single transistor VC filter design is the PAIA 2720 DIY Synthesizer [17]. The design in Figure 7 allows a double vactrol (two LDR's and one LED) to control the cut-off frequency of the filter. By using the vactrol we can make this voltage controlled.

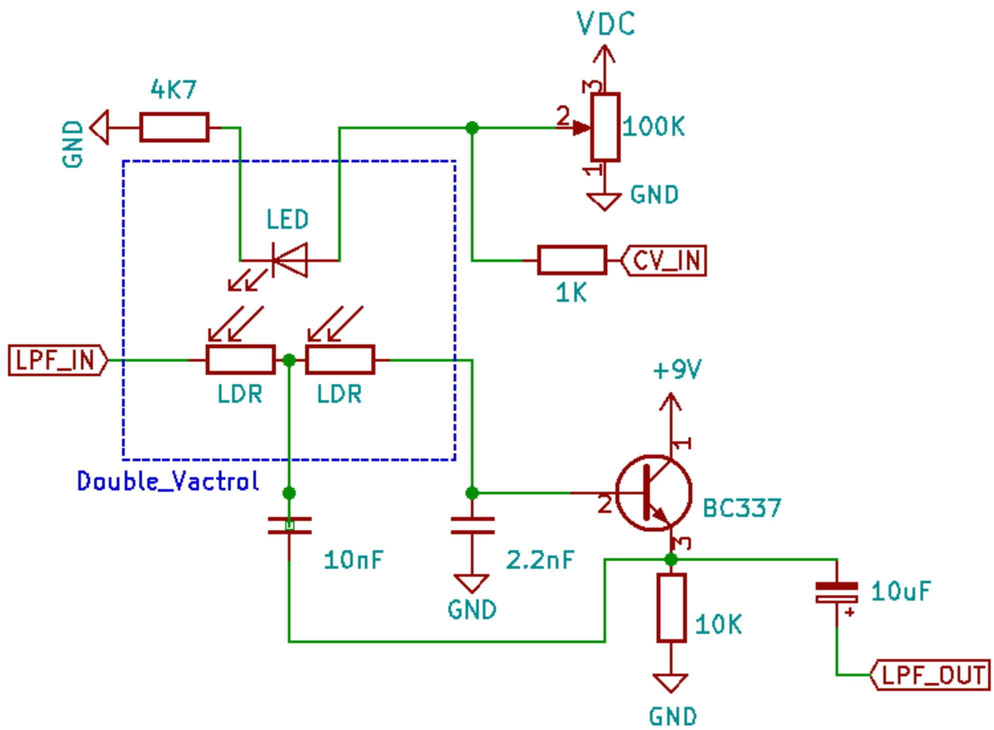

Figure 7. Low Pass Filter circuit (LPF).

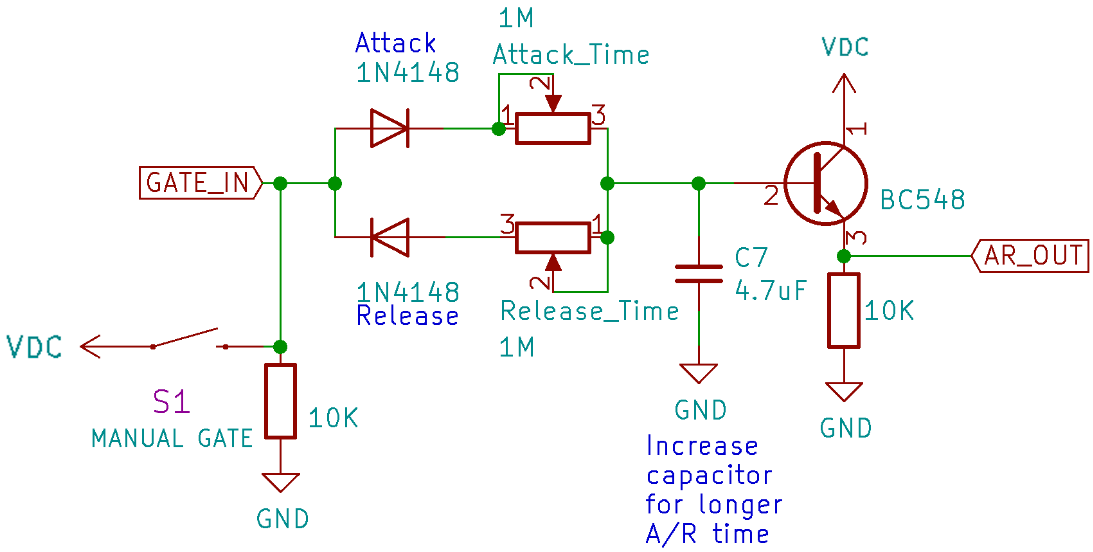

Figure 8. Attack-Release envelope generator (ENV).

3.2.4 Attack-Release envelope generator

Figure 8 is a classic Attack-Release envelope generator. These are useful for controlling a sound's amplitude or pitch contour. A gate signal or button is used to generate a voltage envelope that can be fed to a VCO, VCF or VCA. This design is quite common. Erica Synths and Klein [8] and Wilson [25] explain its function. The overall attack-release duration can be changed by modifying the capacitor value.

3.2.5 Voltage controlled amplifier

The VCA adjusts the level of a signal, it is a simple circuit utilising a vactrol and a resistor to form a voltage divider. Collins details the construction and use of these [5]. The capacitor removes any DC offset present in the signal.

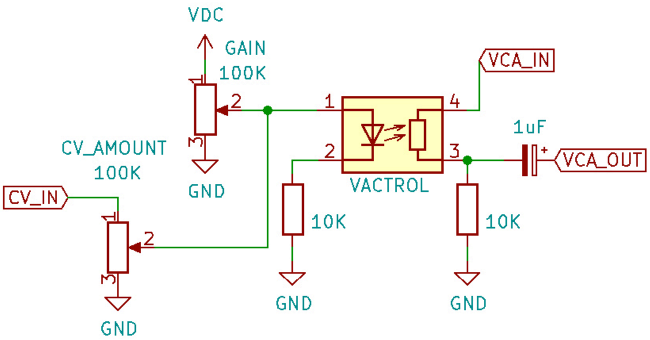

Figure 9. VCA circuit.

3.2.6 Output amplifier

The output amplifier uses the widely available LM386 chip. It shares its power (VDC & GND) with the other modules. If a varying voltage is supplied, then the amplifier will vary its volume in relation the voltage level supplied.

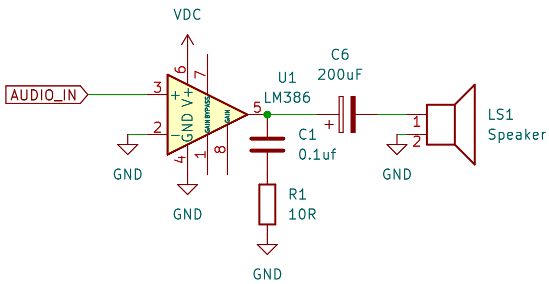

Figure 10. LM386 Amplifier circuit.

3.3 Combining Building Blocks: Building a Synthesizer

Having outlined our synthesis tool kit above, we turn our attention to a simple monophonic subtractive synthesizer. We have designed these building blocks, so they connect one to another in (almost) any combination. There are many creative ways of connecting modules to form a synthesis architecture. This flexibility is the basis for the popularity of Eurorack modular synthesizers. Our modules are less flexible, due to their simplicity, but their somewhat idiosyncratic nature can also lead to interesting results.

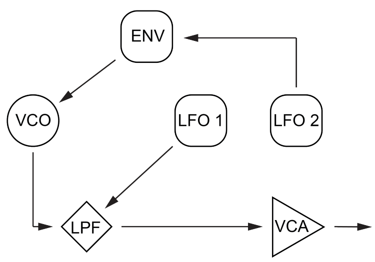

Figure 11. Synthesis Modules, Configuration and Connection.

Figure 11 details the creative use of six building blocks to create a monophonic subtractive synthesizer consisting of a VCO, two LFO's, VCF, VCA and an ENV building block, but patched in a creative way. Each 'module' is able to patched to one another with a 3.5mm connector. The layout is such due to the constraints of designing for a single sided PCB board, which was hand etched, drilled and populated by the authors. It is noted that a revised layout would be less idiosyncratic and follow more standard synthesizer layout conventions.

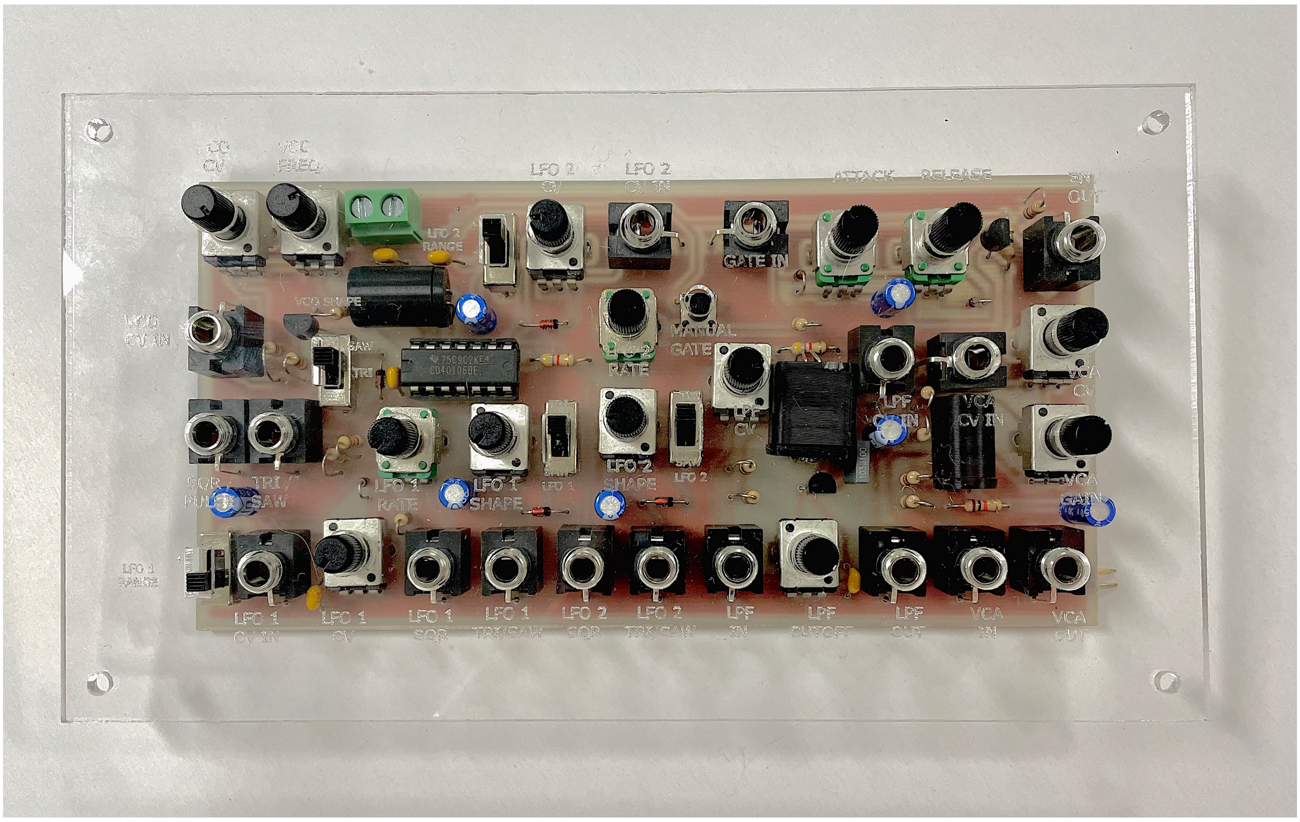

Figure 12. Monophonic Subtractive Synth with 3.5mm connectors for patching.

4. USING THE TOOL KIT WITH A HAND CRANKED POWER SOURCE AND POWER SUPPLY

The 4000 series CMOS ICs display idiosyncratic behaviours when varying the power supply voltage. These behaviours can be exploited; power starving is a common technique that exploits this and is used extensively by Tom Bug's in his Board Weevils. Hand cranking a dynamo produces a voltage output that is often unstable, since its rotation, when operated by a person, is not at a constant speed. Products such as hand cranked portable torches often exhibit this relationship through a changing of light output that is relational to the hand cranking speed or pattern.

The Handmade Electric Machines (T.H.E.M.) [6] is an interactive public art installation project developed by the authors in 2023 with a specific focus on using the 40106 Hex Schmidt Trigger, configured as an audio oscillator. T.H.E.M. features six different sound and light-making instruments in three human-sized enclosures, all based on a gestural interface of hand cranks and a dynamo as a power source, that can be played together or separately. Each instrument incorporates 40106 synthesis designs based upon those presented in Section 3, but configured in differing ways so each instrument has a unique sonic character. T.H.E.M. was presented as part of Curiocity Festival and the World Science Festival Brisbane, where 24,000 public interactions occurred over 12 days (according to Southbank Corporation data), the outdoor installation withstood the temperature and humidity extremes that are common in Queensland, Australia, and even survived being 'fed' several ice-creams.

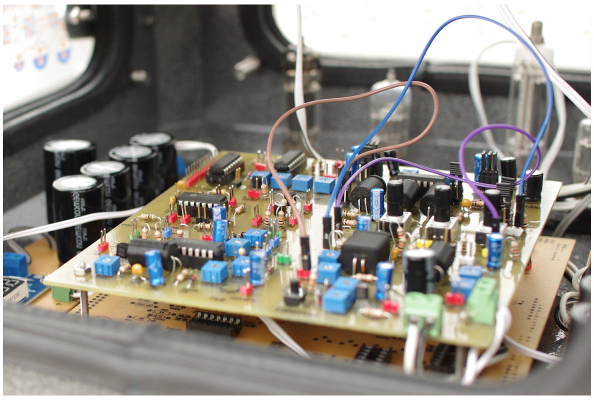

Figure 13. Inside T.H.E.M.

T.H.E.M. builds on the long history of hand cranked musical instruments, including mechanical ones like the hurdy-gurdy, music boxes, street organs, and Italian Futurist Luigi Russolo's Intonarumori noise machines. Hand cranking has played a role in contemporary interfaces such as the Wintergartan marble machine [15], the Humming Box [4] and the Generator Organ [39].

The T.H.E.M. project aimed to explore the production of electronic sound and light in a highly physical manner. The 40106 is a key component in the project, chosen for its reliability including the ability to withstand harsh weather conditions often experienced in sub-tropical environments. As the devices are hand-powered, they aim to reinforce the personal connection with electricity production at a time when societal methods of energy generation are in transition. The use of a hand crank for gestural interaction is effective because of the immediate nature of the audio feedback. The installation is designed for participants of all ages and abilities, with devices arranged at various heights. The visual aesthetic is inspired by early 20th century electrical enclosures that arose from the imaginations of Nikola Tesla and Raymond Lowey.

Figure 14. Public interactions with T.H.E.M. ***(Credit: World Science Festival, Brisbane).***

Our experience with projects using the 40106 combined with information shared by the community through publications and projects come together in the design of synthesis building blocks in the form of electronic circuits for the construction of frugal synthesizers. Alongside T.H.E.M we also ran 8 sold out workshops called Make a Circuit SING! An Introduction to Handmade Electronic Music", for 96 participants with varying skill levels and ranging from children to adults. Two public performances with professional musicians, alongside T.H.E.M. took place as part of the exhibition.

A portable version of T.H.E.M was also developed. Figure 15 shows this portable hand cranked patchable mono synth that utilises the building blocks and circuit design, discussed in Section 3.3. It is a portable version of one of the voices in T.H.E.M; its patchable interface is shown in Figure 12. Since many of the patches involve oscillation and voltage sources, which vary over time, the varying of voltage creates interesting patterns and pitch variations in relation to the pattern and speed of crank rotation.

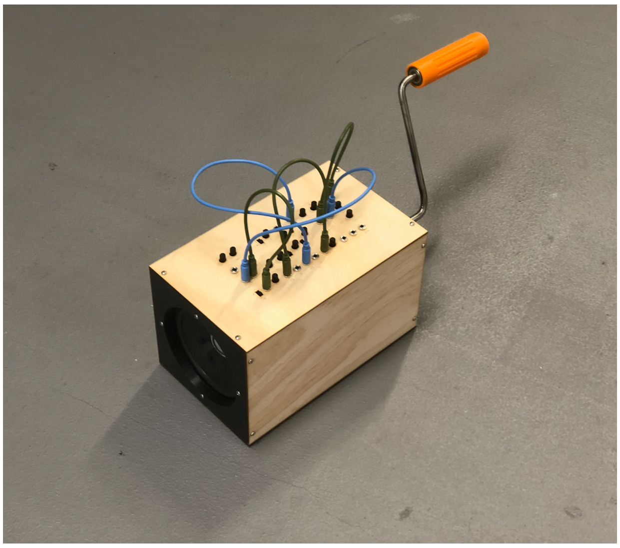

Figure 15. Portable and patchable monophonic subtractive synth that is played and powered by a hand crank.

5. CONCLUSION

This paper discusses and contributes to the long history of CMOS-based sound making. We highlight and draw extensively on the work of Lunetta, Collins, Wilson, Edwards, Williams, Klien and others, positioned by our own experience making installations, musical devices and facilitating pedagogical/workshop outputs focused on CMOS circuitry.

We have presented a series of building blocks that use a single chip: the CMOS 40106 integrated circuit. The building blocks consist of electrical circuits comprising passive components such as capacitors, resistors, transistors and diodes, that act as modules for various synthesis functions, including: VCO, VCF, AR, VCA, and Amplification. These modules can be combined into a wide range of synthesis architectures, from the conventional to experimental. Most modules include voltage control of one or more parameters via a vactrol or a diode, which facilitates interconnectivity and cross modulation possibilities. We extend the possibilities of control by utilising a hand-cranked gestural interface that allows the user to power and play these circuits.

Although some discussion has been quite technical and hardware-focused, our artistic research argument has been to position expressive, low-cost and entry level electronic devices alongside the cultural and artistic outputs that thrive in the DIY electronic music and NIME community. By avoiding microcontrollers and other programmable (PIC) chips (i.e., no computer is involved), we hope to have also suggested artistic, cultural, and social potentials by highlighting pedagogical scenarios, outdoor public artworks, and portable musical instruments. Rather than delving too deeply into electrical operation, our focus has been to gather and illuminate historical practices that still have much to offer. We also introduce a high-level tool kit for frugal CMOS synthesis that is intended to be of use to those who are either new to electronic music or perhaps already familiar with digital and modular synthesis but are interested in novel interface design and developing low cost and accessible instruments/devices. We have enjoyed working within the limits of CMOS IC architectures and their interaction with hand-cracked power management and have found this to be a creatively productive experience overall. We hope to have underscored the potential of such approaches to CMOS synthesis and highlighted the sonic affordances of low-cost electronic devices and their potential in installation, performance and workshop/pedagogical contexts.

6. ACKNOWLEDGEMENTS

We acknowledge the support from various Griffith University elements; The Queensland Conservatorium, Creative Arts Research Institute, Queensland College of Art, and the Interactive Media Lab.

7. ETHICAL STANDARDS

This paper is written as part of Timothy Tate's PhD studies at the Queensland Conservatorium, Griffith University. John R. Ferguson and Andrew R. Brown are Timothy's PhD supervisors. PhD funding is being received from the Australian Government Research Training Program Scholarship.

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