# Introduction

## Introduction

The traditional route for both recorded and performed musical expression has been through playing a musical instrument. Through this simple but powerful interface, ideas can be explored by the skilled practitioner in a free flowing, intuitive manner. The ubiquity of high powered computers has led to a fundamental change to this process, however. Electronic music can now be produced entirely on a computer, enabling those without the background or training to produce music to a professional standard. The affordances of infinite editability and tweak-ability allows the novice producer to organically build compositions through a process of trial and error. The requirement to perform to a high standard is no longer necessary.

The primary tool of this new breed of electronic musician, is the Digital Audio Workstation (DAW), a powerful software application for composing, arranging and editing musical events and audio material, mixing tracks and applying audio effects. To control this power, the electronic musician must master the vast array of knobs, sliders, buttons and complex hierarchies of settings. This complexity poses some difficult Human Computer Interaction (HCI) challenges both for software developers and end users (Duignan, Noble and Biddle, 2010).

A common solution to this is to provide the user with real world metaphors in the presentation of the interface. In this way, the highly abstract process that takes place in digital systems can be grounded in a metaphorical language understandable to the user. An extremely dominant metaphor is that of the analog mixer and the hardware multi-track tape machine which have, since the mid-1990s, become a mainstay construct in the interfaces of commercial DAWs (Bell, Hein and Ratcliffe, 2015). The effectiveness of this metaphor is evident in the vast amount of music produced in this environments. There are some situations, however, where the metaphor can get in the way and lead to another new, separate layer of complexity that must, in turn, be managed by its users.

## Motivation

This leads to the central motivation behind the work on SonicSketch: that of exploring alternative metaphors that support the early stage of music production and fulfills the role traditionally filled by an instrument. In exploring these alternative metaphors, an attempt is made to regain some of what is lost when working directly with the computer. At the same time, the distinct advantages of working in a digital medium will be maintained.

The intention is not to suggest that analog studio metaphors can be replaced, or even that there is any reason that they should be. Instead, the intention is to augment these rich metaphors with other metaphors more suited to certain stages of the creative process. The need for such efforts is in some ways acknowledged by mainstream DAW manufacturers. For instance Ableton Live, a highly popular DAW application, has recently opened its application programming interface (API) to allow other programs to create compatible files (Ableton, 2017). This enables producers to work in diverse, idiosyncratic and perhaps less featured environments more suited to the capturing of ideas and creative flow. The option is open to then move freely to the more powerful fully featured environments offered by the DAW.

## Goals and Objectives

The overarching and primary goal of this project is to create a software application called SonicSketch that is specifically targeted at the early ideation part of the music production process. Building on a strong theoretical and technical foundation it will forego densely populated analog studio inspired DAW interface patterns and will instead focus on the metaphor of sketching. Users will draw various graphic symbols and lines on screen to produce sounds of different pitch, amplitude, and timbre which can be played back and altered in realtime.

The final artifact should be:

Beginner friendly

the user should not need any lengthy explanation or instructions on its use but should be able to dive in and start making sounds straight away.

User friendly

basic standard usability features should be added to reduce friction and allow users to engage more freely with the application.

Expert friendly

flexible enough to allow users to use it for longer periods of time without getting tiring of it.

These aspects will be assessed by using self-assessment as well as by testing with users. User testing will take the form of both interview and a standard usability test. To maximize availability and broaden the potential user base of testers, the application will be developed as a web application that will run in a modern browser without requiring the installation of any special software.

## Approach

The project is based upon and builds on SonicPainter, an application built by William Coleman for his Master's thesis. Similarly motivated by the overwhelming complexity of modern DAWs, the interface aims to be minimal and free of distraction. It presents a minimal canvas like space that allows the user to draw lines of various length, shape, and orientation resulting in sounds that vary in timing, duration, frequency, and timbre.

Building on this existing work is advantageous in several ways. It provides a more concrete foundation than starting off with a blank slate. Features and approaches can be assessed so that certain features that work well can be incorporated and improved. Equally pitfalls in the original work can be avoided. A summary of intended improvements are as follows:

* Increased discoverability of functions by adding user interface elements that enhance the "sketch" metaphor.
* Increased accessibility by making it available online.
* Improvements to usability such as allowing users to sketch in a freehand way more easily.
* Technical improvements to avoid crashes and unexpected application behaviour.
* Improve correlation between the visuals and the audio.

## Thesis structure

This thesis begins with a discussion of the current dominant tools and practices in use in music production today with a strong focus on the ideation phase. A historical perspective is then given on more idiosyncratic approaches to music creation systems. An emphasis is given to systems that utilize a more visual approach. This is followed by a discussion of more recent work that to some degree takes influence from these approaches. The theoretical and practical approach that was taken in the build out of the project is then given and is followed by a more detailed technical walkthrough of how the system was put together. An evaluation of the success of the project is then given both from the perspective of the creator and from users that tested it. Finally, the broader implications of the work are discussed in addition to some suggestions for future research and development.

# Background: Sonic Sketching as an Alternative Metaphor

## Introduction

This chapter begins with a discussion on the dominant metaphors present in the modern DAW and expands on the earlier introduction to the topic. A concrete example is given to illuminate the issues and limitations that these metaphors can impose on its users. This is followed up with a survey of legacy systems that take a graphical approach to their interface and can be conceptually framed with the metaphor of sketching.

## Dominant DAW metaphors

As has been asserted, analog studio metaphors of tape machines and hardware mixing desks dominate the UI approach to DAW interface design. Other prevalent metaphors often found in these interfaces are that of the *outboard effects units*, and the *piano roll* (Levin, 2000; Bell, Hein and Ratcliffe, 2015; Adenot, 2017; Ableton, 2017). A description of these now follows.

### Multi-track tape recorder

Multi track tape recording was introduced into the recording studios in the 1960s and is typified by the systems produced by Ampex and the Studer. These allowed producers to record multiple tracks of audio information which could be edited and using dubbing techniques mixed to taste. This unlocked significant creative possibilities and made albums like "Sgt Peppers Lonely Heart Club Band" possible. The underlying model of tracks typically manifests itself in DAWs as rectangular blocks stacked from top to bottom and running from left to right. Similar to editing tape, these can be spliced, cut, and pasted. Terms and techniques prevelant in DAWS like bouncing, overdubbing and markers (which were originally created using a physical pen), all have their roots in their analog precedents.

### Multi channel mixing desk

The multi channel mixing desk metaphor is present in the large majority of DAWs and is normally represented in a similar fashion to the sliders (or faders) found in hardware mixing desks (fig:mixing-desk). The mixing desk enabled the producer to control the relative amplitude of a finite amount of channels in addition to performing tasks such as panning to balance the signal in a stereo field. The slim vertical sliders found on most systems were codified in the 1960's by Bill Putnam and were created with ergonomics in mind (ref???). This layout allowed the producer to manipulate multiple channels of audio simultaneously in a practice known variously as "riding the faders" and "playing the mixer". Despite the fact that the digital variants of these are largely controlled by a mouse that only affords the manipulation of a single fader at a time, they are still, largely speaking, presented in this fashion on screen.

### Outboard effects unit

Outboard effects are hardware units used in studios to add audio effects to one or more channels on the mixing desk. The standard configuration of most studios allows for two different ways of applying these effects, by using insert effects and send effects. Insert effects are typically used when it only needs to affect a single channel, for instance, a chorus effect applied to an electric guitar. Send effects allow the producer to send a certain amount of the signal from a channel to specialised channels to perform processing on the signal in parallel with the original signal. It is typically used to apply effects that affect multiple channels of audio such as reverb effects. The introduction of Virtual Studio Technology (VST), by Steinberg, was responsible for bringing the outboard effects metaphor to a whole new height. This allowed third party developers to create virtual effects and instruments, and let producers expand their virtual studio beyond the built in effects. The visual interfaces increasingly paid homage to their hardware influences, emulating not only functionality but also the visual look (see figure fig:hardware-effects). (Levin, 2000) describes this as skeuomorphism, a design pattern where visual objects not only mimic real world objects in functionality but also incorporate unneeded visual features. The purpose of this is not only decorative but also educational, and gives connotational cues on how it should be used.

### The piano roll

The piano roll is a primary metaphor found in almost all mainstream DAWS and is typically used to represent MIDI musical note information. MIDI, which stands for Musical Instrument Digital Interface is a standard protocol developed in the 1980s to allow control instructions to be sent between devices. It provided a standard language to for instance tell a synthesizer to play a particular note at a precise time and duration. These instructions could be collected into a MIDI file to, in effect, create a playable digital score. It is slightly distinct from the previously discussed examples in that it originates from a much earlier time period, the player pianos of the 1920s. The original piano rolls were operated by feeding a roll of paper with holes punched to indicate the precise timing that an attached piano should strike its notes. This provides an apt and suitable description for the MIDI musical data it normally represents. Similar to a player piano, no audible results are possible without an attached piano, and in the case of MIDI, an attached sound generating synthesizer device.

## A compositional example

Rather than discussing the issues that can arise from the metaphors in the abstract, let us consider a compositional idea and how we might achieve this in a DAW. The idea is broken into the following compositional "recipe":

1. Two notes of the same timbre are played together about an octave apart for a duration of 2 seconds.
2. The first note glissandos to the frequency of the second note and vice versa.
3. The first note starts with a small amount of vibrato that quickly dissipates.
4. The second note starts with no vibrato but adds a small amount as the note nears completion.
5. When these two notes end, the same pattern is repeated except this time with different timbres and frequencies.
6. This is repeated 3 more times with different timbres and frequencies to complete this ten-second piece.

While this may seem like a contrived example this, in fact, constitutes a compositional technique called Klangfarbenmelodie that involves splitting a melodic line between instruments or timbres to create a timbre melody. The glissandos and altering of vibrato intensity add further complexity and better illustrate some of the weaknesses inherent in DAW metaphors.

### Realization in a DAW

To achieve this in a DAW we have a few different options but a possible solution would be as follows:

1. Working with the multitrack tape metaphor we can create ten separate tracks to house two different versions of each timbre. A vibrato plugin effect should be added to each of these by using a send or an insert effect. Two different tracks are needed for each of the timbres due to the fact that the two notes are played at the same time and both have different frequency and effect trajectories. If on the other hand, they had the same effect modulations or were played at different times, no additional tracks would be needed.
2. Working with the piano roll metaphor, create a single note in each of these tracks setting each one to the desired fundamental frequency.
3. Now edit the pitch bend automation lane by clicking into the relevant dialog
4. Similarly, open the relevant dialog to edit the intensity of the vibrato effect
5. Repeat this for each of the notes in the composition.

At this point, we may have achieved what we set out to do. However, we now may want to tweak each of these elements to taste and perhaps add more material. An explosion in track count and overall complexity is inevitable. This can lead to a serious slowdown in workflow, a loss of flow and cognitive overload. A common technique to combat this complexity overload is to bounce the tracks and then continue working on these simpler artifacts (Duignan???). This, of course, negates a key advantage to working in a digital environment, the fine-grained ability to freely change, tweak and undo. Locating each note in separate tracks leads to an unnatural separation of what is, in fact, closely related compositional material. This requires awkward context switching and excessive navigation through the system to focus on different details.

There are of course other tools in the DAW that may achieve this task more easily. For instance, a sampler may allow us to use different timbres on the same track and may work better in this case. We now have the extra task of exporting each of these samples in preparation for our composition work. Some other options present in many DAWS include aggregate instruments, multi-timbral instruments, and perhaps some midi routing options. Another option is to use an alternative, more flexible, environment such as an audio programming language. Some brief consideration of this will now be given.

### Realisation in code

The piece could be realised in quite a straightforward manner in an audio programming language such as *Csound*. Central to *Csound* is the concept of the *unit generator* (or ugen), an abstraction to define both sound generators and processors. These can be patched together in a simple textual coding language to form instruments. A score is then specified, again in code, to define note onsets, durations in addition to other arbitrary parameters defined in the instruments. Each of the required timbres could have been represented as separate csound instruments, with each one configured with the desired timbre in addition to the vibrato effect. *Function tables* could be used to control the movement of the pitch glissando and the varying vibrato intensity. A function table is a list of numbers in Csound that can be read from, at various speeds, to supply control data to parameters (amongst other uses). A number of routines are available in Csound to generate commonly used list types. In this case, a line segment generator would be most applicable and would be used to generate a shape such as shown in fig:gen05. The Csound score would refer to each of the defined instruments with each note amounting to a single line of code, making the entire score a total of five lines. Demonstration code is provided in the appendix.

Depending on the experience of the reader, this may or may not seem like a better approach than using the DAW owing to the following central issue. It is not beginner friendly and a reasonable amount of prior experience and/or training is required. Perhaps a bigger criticism that could be made, however, is that it can lead to an analytical rather than a creative way of thinking. In "Thinking Slow, Acting Fast", Daniel Daniel Kahneman contrasts these two ways of thinking which he terms *System 1* and *System 2*. System 1 is instinctive, fast, emotional and is a mode of thinking that may not register consciously. System 2 is slow, logical, analytical and registers prominently in active consciousness. Routine tasks such as walking, opening doors etc only use system 1 thinking. These can be completed while exerting minimal cognitive effort (all the while calculating the complex motor sensory actions that must take place). Complex analytical tasks such as programming require system 2 thinking. Approaching creative tasks such as music making in this way where instinct and emotion are often crucial can slow down or stop the process. Perhaps it is best summed by John Cage: "Don't try to create and analyse at the same time. They're different processes" (Popova, 2012).

## Sketching as an alternative metaphor

While audio programming languages are an abstraction over more complex underlying computational processes, they largely speaking offer a model that is closer to these processes than the more abstracted DAW interfaces. As we have discussed, though what is gained in flexibility can be lost in intuitiveness and ease of interaction. Rather than discarding these higher level metaphors, perhaps a better approach would be to explore alternate metaphors.

A rather promising but nonmainstream approach is that of sonic sketching. This has a long and illustrious historical precedent reaching back well before the, now more prevalent, studio metaphors. As is pointed out by Levin (2002), the exploration of synchrony between audio and visuals is a practice going back centuries and was variously termed "ocular music, visual music, color music, or music for the eyes" (Levin, 2000). The twentieth-century technique of the optical soundtrack, however, brought these ideas to a new level of sophistication. The technique, which involved placing marks via photography or direct manipulation to specify audio properties, was explored by such luminaries as Oskar Fischinger, Norman McLaren and Daphne Oram. Oram's particular take on the technique will now be discussed.

### Oramics

A primary motivating factor behind Daphne Oram's development of the Oramics machine was to bring more human-like qualities to the sounds generated by electronic means. The machine worked by playing back multiple lanes of film tape in unison, defining a monophonic series of notes as well as control signals to shape their timbre, pitch and amplitude. She details the thought process behind this in her hugely insightful and broad ranging journal style book, "An Individual Note" (**???**).

The aspects of the sound that she wishes to control are volume, duration, timbre, pitch, vibrato, and reverb. In order to do this, she describes a simple musical notation language based on the freehand drawing of lines combined with discrete symbols. The lines, which she describes as the analog control, are used to define volume envelopes. Interestingly, the default and preferred method for the parameters she wishes to control is the continuous line rather than discrete note symbols. For instance, she avoids the use of a static velocity per note and instead only specifies the use of a control envelope to change amplitude.

The discrete symbols, which she categorizes as digital control, are used to define individual pitches and are termed neumes. She highlights that notes should not remain static and, thusly, an analog control of each note is also specified. Similarly to amplitude and vibrato, timbre is also defined by the freehand drawing of lines and is something that with practice the "inner ear" can develop an intuition as the sonic results of different line shapes. It is Oram's belief that the hand drawn nature of the lines make the results slightly inaccurate and to some extent unpredictable. Herein, however, lies the possibility of bringing more humanity to the cold and precise machines generating the electronic signal.

### UPIC

The UPIC ("Unité polyagogique informatique du CEMAMU") was a graphic sound synthesis system that was designed by Iannis Xenakis and arose from his graphic approach to composition. His earliest work, "Metastasis", was conceived using a graphic approach to describe trajectories and sound masses (figure fig:xenakis-metastatis). This approach has been attributed to his background in architecture, having worked in the studio of Le Corbusier. The UPIC was first conceived of in the seventies with the realisation of the first version in 1975 and its first public showcase in 1977. The work "Mycanae Alpha", composed in 1978 was the first work to use the system and was a "nine-minute 38-second composition of dense and intense textures, of phase-shifting waveforms rich in harmonics that cascade, flutter, crash, and scream like sirens in a vast cosmological territory" (**???**).

This early version worked by drawing on a large digitizing graphics tablet which was interpreted by a high-powered computer (for that period) and converted into audio signals. The graphic approach to sound specification worked on a synthesis level by allowing the composer to draw and audition waveforms. Larger structures could be drawn in by switching to a "score" page and drawing lines, or "arcs" as they were denoted, on a pitch-time canvas. The final version of the application ran on personal computers and allowed for real-time interaction with a 64 oscillator synthesizer. At this stage, the input means had changed to a computer mouse but nevertheless retained the graphic approach of interaction.

A primary goal of the UPIC project was that of pedagogy. Xenakis reasoned that the universality of sketching meant that it could provide an excellent teaching tool for a wide audience, even for young children (figure fig:xenakis-children). Another goal of the system was to encourage composer autonomy. At the time of its conception in the seventies, the technical barrier to entry into electronic music creation was very high and interfaces to help with this were rare or non-existent. Though the UPIC is not available to the general public currently, it has inspired a number of other systems that are available.

### A Golan Levin's AVES

Golan Levin created the interactive audio-visual system, AVES, a series of audio visual installations in the late nineties and represented a landmark in the field of visual music. It is an attempt to move away from the diagrammatic approach to musical interfaces and to present an interface that is painterly in approach. Taking strong influence from visual artists such as Paul Klee, he presents a system that maps user input from a graphics tablet and mouse to visuals and audio. The intention is to create a strong visual correlation between these two modalities. A variety of approaches are taken to achieve this, all of them involving an algorithmic approach to a certain degree. For instance, in the piece "Aurora", he maps visuals of vast quantities of particles to a granulated sound synth sound source. He didn't take the approach of an exact mapping of visual particles to audio particles, however, and instead used a statistical control approach to approximate the correlation in between the visual and aural. (Levin, 2000)

For Levin, the digital pen input in combination with it's infinite variability represents an ideal instrument for creative expression in his digital temporal audio visual paintings. (???) The reason he gives for this is, similar to a musical instrument such as a violin, the pen is instantly knowable in that a child can pick it up and start creating marks but infinitely masterable through practice and hard work, and ultimately a vehicle for creative expression after a certain amount of mastery. A set of criteria that he and John Maeda arrived at to evaluate the success of their experiments was: is it instantly knowable, how long did you use it, how much of your personality can be expressed through it and, finally, with practice is it possible to improve using it.

Levin's work is largely realtime and transitory in nature with gestures giving rise to visual and audio reactions that rise, fall and dissipate. A description that he uses of some of work is that of creating ripples in a pond. Therefore his work is very much geared towards an instrument like experience and is not concerned with the recording or visualization of a score or timeline of musical events as would be the function of compositional tools such as DAWs. Indeed it is a conscious design decision to avoid such representations. Many of the principles and ideas of his work can, however, be applied in the context of a composition tool.

### William Coleman's sonicPainter

SonicPainter by William Coleman is a novel musical sequencer that seeks to address some of the shortcomings of traditional approaches to music sequencing found in commercial DAWs (Coleman, 2015). The focus of the line and node based interface (see figure) is to bring timbral shaping to the fore rather than being hidden away in miscellaneous automation lanes. The design takes influence from legacy musical systems, in particular, UPIC and incorporates ideas from visual music and embodied cognition.

Similarly to traditional sequencers, the x axis represents time and the y-axis, pitch. Note information is input via keyboard and mouse. A click starts a note and can be followed with additional clicks to continue to shape it. It can be ended by clicking a keyboard shortcut. By drawing notes as lines in this manner, the unfolding of the note can be explicitly represented visually. Other timbral aspects such as vibrato are represented by further visual manipulation of the line. For instance, an overlaid sine wave line indicates the timing and amplitude of the vibrato. In addition, the system allows for freehand input of notes. Coleman recommends that the system could be improved by adding multi-touch input, allowing for other synthesis techniques, time/pitch grid quantization, and further visual timbre feedback representations.

## Conclusion

The dominant metaphors present in DAWs, which are by and large analog studio influenced were discussed including details on their origins and their reincarnation in digital form. A short compositional example was given and the process to realise this in a DAW was described. The piano roll, multi-track mixer, and outboard effects metaphors were shown to be a poor fit for this particular compositional idea and resulted in an excessive amount of tracks and, therefore, complexity. A simpler solution was described in the csound audio programming environment. The lower level abstractions provided here allowed for a more succinct and simpler implementation of the piece. Some potential pitfalls to this approach were given. This includes a steep learning curve for novice users and a potential bias towards an analytical rather than a creative mode of thinking. Rather than abandoning the high-level metaphors present in DAWs it was posited that another approach could be to explore other metaphors more suited to certain compositional ideas. To this end, the metaphor of sketching as an interface to audio systems was explored by tracing it's early roots in the optical soundtracks of Oram to the realtime synth sketching of Xenakis's UPIC through to the contemporary approaches of Golan Levin's AVES system and William Coleman's SonicPainter.

# My approach

## Introduction

The following chapter opens with an appraisal of currently available graphical synthesis systems that were discussed in the previous chapter to more clearly define the niche that SonicSketch seeks to fill. Some theory behind the development is then given including HCI considerations, the Musical Interface Technology Design Space and research into cross modal perception. The practical approach is then given which delves into the more technical aspects of the project build out including a discussion on the Web Audio Api, *tone.js*, *paper.js*, *ClojureScript* and *react.js*.

## Appraisal of options

## Approach - theory

### HCI considerations

1. The natural user interface

* NUI is an evolution of the concept of the graphic user interface and refers to an approach to human computer interaction beyond that of the traditional keyboard and mouse or what has been termed the WIMP model. It encompasses a set of guidelines and best practices which are set out most comprehensively by Wigdor (2014). Some of the basic tenets of NUI are as follows:
  + Harness existing skills when possible without necessarily mimicing the real world tool or instrument (Wigdor and Wixon, 2011, p. 13).
  + Be friendly and learnable by beginners but allow for mastery given enough practice (a sentiment shared by Levin, above) (Wigdor and Wixon, 2011, p. 13).
  + Immediate feedback for all interactions should take place, most usually but not limited to, visual feedback. (Wigdor and Wixon, 2011, p. 87)
* Furthermore, the interface should take advantage of the particular affordances offered by the input method. (Wigdor and Wixon, 2011, p. 115) An apt example of this is the early introduction of digital pens for windows laptops where the pen wasn't suited to the WIMP interface and failed to receive widespread usage. In this case, the interface forces the user to carry out awkward gestures for the medium, including double clicking and right clicking, failing to take advantage of the stroke gesture much more suited to it.
* The system CrossY, referenced in Wigdor (2014), uses a cross gesture stroke to interact with buttons, menus, and widgets, as well as the painting functionality (**???**). The CrossY gesture system enables the user to, for instance, select brush size and colour in one stroke by dragging the pen from right to left across an icon and validating selection by dragging past the left or bottom selected leaf icon. This is illustrated clearly in the left-most diagram of the provided figure (fig. 3).

### The Musical Interface Technology Design Space (MITDS)

### Cross modal perception

## Approach - practice

### Delivery on Web Browser

### Modern web browser as a delivery platform

### Benefits of using tone.js Mann (2015)

### Paper.js for the graphics system

### FM synthesis

### Live coding workflow

1. [Introduction]
2. React.js framework

* react is a web framework built by facebook that aids the developer in updating the dom (document object model), a process that is required when the state of teh applciation changes. this was a role traditionally carrried out on the server and served to users as a static page. this all changed however with the rise of single page applications (spa) around the 2???s. the value proposition of the spa is increased interactivity and responsives to user input, allowing the look and contents of the page to update dynamically as the user interacst with the system. to aid in the construction of these spa's a number of frameworks to help the process were introduced by the open source community. some popular early examples include *backbone.js* and *angular.js*. a technique that saw some popularity was a system called two way binding which created two way link between the current state in the model and the visual appearance of the view. this however has a number of issues including some serious performance issues, in addition to some conceptual problems (???ref). react offers a simpler one way bidning ssytem using what is termed the virtual dom. in this model a special virtual version of the dom is constructed and when the model changes is updated. the parts of the dom that require changing can thusly be pinpointed and the real dom can be efficiently updated. this system has proven to be particulalrly beneficial when paired with functional programming techniques, a style of programming that emphasizes the use of pure functions as the primary building block of programs. in the case of working with the dom, it can lead to not only an increase in efficiency in the rendering of the applications but also a simplification of the programming model. a number of projects have emerged that attempt to bring this benefits of the react model beyond the realm of the dom including writing console prgorams (???ref), writing web audio applications (???ref) and even arduino projects (???ref).

1. Clojurescript
2. Managing state with re-frame

## Conclusion

# Execution

## Introduction

The following chapter gives an outline of the process that was undertaken to build out the final application. A description of early prototype work is given to give context to the construction of the final working prototype version. This is followed by a description of the technical architecture of the system as well as an outline of the sometimes tricky setup process of getting the live reload system working (as described in the previous chapter). Some detailed discussion of the the core functionality of the system is then given. The core of the system primarily consists of timeline events, which visually manifest themselves as strokes on the canvas and aurally as fm syntesized frequency modulated sounds. As will be discussed an important aspect of any well constructed software system is a good degree of seperation of concerns, a characteristic espoused to and evident in the resulting code. To this end, the code that brings the central functionality to life can conceptually divided into a data or entity layer, a business logic or use case layer and an output layer which in this case consists of the visual output into a html canvas element and the audio output through the web audio api. In this sense the architecture conforms to the principles of the Clean Architecture as presented by Bob Martin (Martin, 2012). (**???**\_clean\_2012)

## Early prototype work

### Melodypainter

Melodypainter is an early protoype built out in Max MSP that allows users to draw freehand lines, which are converted into break point function data and used to generate a melodic profiles using Bach for Max MSP. Bach is a suite of composition tools that allow for a number of computer aided composition techniques (CAC) and provides similar functionality to IRCAM's Open Music system. These melodic profiles are then filtered to only includes notes from a pentatonic scale, to give reasonably pleasing aural results. Some notable flaws in the system include the following. It is limited to strictly western tonal music styles. It has no allowance for rhythm and plays only eight notes giving results a noticeably bland and predictable quality. The freeform nature of sketched input however was quite a pleasing means of inputting the control information.

### Sonicshaper [0/1]

A separate application was created in Processing which allowed users to draw shapes, using either mouse or ideally, pen input and have a sound that is associated with each shape played back. As the sound of each shape plays back, it is lit up using animation, creating a strong connection between the shape and it's resulting sound. The application uses the "gesture variation follower" system (Caramiaux *et al.*, 2015), which while promising in principle, didn't have a high rate of accuracy in recognizing the shapes.

### TODO Web version of William Coleman's SonicPainter [0/1]

A potential starting point that was considered was using the code from William's SonicPainter and porting it to the web platform. This process proved to be quite straightforward. The processing code could more or less be embedded in a webpage as is using "processing.js", a web version of the Processing library that enables users to run processing sketches in the Web Browser. Some notable changes that had to be made were removing the OSC functionality as this is not technically possible to use in a browser. In addition, some other pieces of code had to be commented out and tweaked. As it's not possible to run Max MSP patches in the browser, the audio system was re-implemented using Tone.js. As SonicPainter uses simple FM synthesis, a very close approximation to the original version could be created. In the end, it was decided not to build on this codebase however as there were some issues with functionality and usability that would be difficult to resolve in an inherited codebase. A fundamental issue was that transitions between certain states would cause crashes or unpredicatable behaviour. An example of this is when a user attempts to use the vibrato tool while in the process of creating a note. Instead of either finishing the note and starting the vibrato tool or disallowing the behaviour, the program would crash. This is a common problem in software development and is evidence even in commercial products. To alleviate such issues in the new codebase a more disciplined approach would be taken to managing transitions between states. The process of porting the code did however give a more in depth incite into Coleman's implementation incuding the pitfalls mentioned above. In addition, the basic visual look and conceptual functionality would form the basis of the workings of SonicSketch.

## Actual implementation

### Setting up the architecture

1. Clojurescript and javascript npm modules

* Despite the fact that clojurescript has existed for six years(???), some areas of the development process are still difficult, particularly when building out a more complex real world application. It should be noted that a good deal of work is being carried out to make this a smoother experience and thusly these pains are likely to become less of an issue in the near future (???ref). It should also be noted that building applicatons using plain javascript is not a trivial process and in all likelyhood will include a build process using a system like webpack or browserify. A primary issue that had to be resolved to allow the application to be built out was the incorporation of javascript npm modules. NPM is the module system used by node.js originally for more server oriented technologies but increasingly for rich clientside applications. For a purely javascript application, it would be a matter of simply adding the desired libraries as dependencies. However, with the use of clojurescript some extra steps needed to be carried out. In addition to adding the dependencies, a javascript file was created that imported these into a "deps" object. This deps object could then be referred to in clojurescript using the standard interop syntax js/deps.myDependency. At the time of development an alpha feature that allowed npm dependencies to be declared as part of the project.clj file was experimented with but was not used in due to difficulties getting it to work. While the project setup was not as elegant or succint as might be wished, it did provide a stable base to build on and a means to harness the rich resource that is the NPM ecosystem and use such tools as Paper.js and React.js.

1. Paper.js and react.js (paper.js bindings)

* As has been outlined in the previous chapter, a declarative coding style would be employed to enable a live coding workflow and to avoid a building a codebase that is increasingly difficult to understand. In other words the code should as much as possible describe the "what" of the functionality rather than the "how". These qualities emerge quite naturally when using the *React.js* architecture. Paper.js however runs in the context of a canvas element and thusly it is not possible to directly use *React.js* with it. This shortcoming has been addressed in projects such as *three.js react bindings* and *pixi.js react bindings* which allow the use of react's declaritive programming style for 3d and 2d scenegraph oriented systems that run in the html canvas element. These solutions both work by creating dummy empty dom elements and hook into the *React.js* lifecycle events to the real work of updating the scenegraph. In many ways the scene graph structure of projects like these and indeed Paper.js exhibit a high resemblance to DOM structures and APIs making React a good fit for them. A similar approach to the above mentioned libraries approach was taken to integrate paper.js for use in SonicSketch and worked reasonably well but required quite a bit of setup. During the development of the project, a more suitable solution emerged from the open source community at an opportune time. This used the next version of *React.js* which has better support for render targets that are not the DOM and has the distinct advantage of not requiring the creation of redundant DOM nodes. The library was far from comprehensive and thusly a custom version of the library was used that included some custom functionality required for SonicSketch.

1. Tone.js and react.js

* In some ways audio output can be thought of in a similar way to the visual output of the app and thusly can be treated in similar way by *React.js*. It can use the declarative data oriented system of react to configure the particular settings and connections in the audio graph and hook in to its lifecycle events to instanciate the various audio generating and processing web audio nodes. This addresses a notable (by design) ommission in Tone.js which does not allow the code to query the state of the audio graph once it has been setup. It is down to the userland code to keep track of this and manage it accordingly. The value proposal offered by introducing react.js into this part of the system is that it maintains the simple relationship between state and generated output. Conceptually the flow of change is:
  1. The state updates
  2. The react wrapper objects update their properties accordingly
  3. The lifecycle events are triggered which takes care of altering, adding and removing web audio nodes (thus altering the audio being output)
* The design of this part of the application is influenced by *react music*, a system that uses *React.js* with tuna.js, a web audio library similar to tone.js (???ref).

1. Reagent and react.js paper.js bindings

* The final piece of the jigsaw in the underlying technology stack is the integration of react with clojurescript via the *Reagent* library. The core syntax of this system is simple clojurescript vectors similar to the following:
* [:div   
   "Hello " [:span {:style {:font-weight bold}}  
  world]]
* This would result in the following html output:
* <div>Hello <span style="font-weight: bold">world</span></div>
* As can be seen the vectors begin with a keyword that corresponds to the tagname of the html. Additionally, instead of using html tag keywords, function calls can be made to generate html to allow for code reuse and logic. It was unclear how the paper.js bindings would work within this system due to the fact that it required a different version of react and uses non standard tag names for elements that can be drawn on screen such as "circle" and "rectangle". This however turned out to be much more straightforward than expected and the provided paper.js primitives could by simply using the relevant paper.js keywords. Complex scenegraphs could be constructed by using the following succint clojurescript syntax to describe the playback indicator:
* [:Group {:position [position 0]  
   :pivot [0 0]  
   :opacity 0.75}  
   [:Rectangle {:pivot [0 0]  
   :size [1 height]  
   :fill-color "#ffffff"}]  
   [:Path {:segments [[-5 0] [5 0] [0 7] [-5 0]]  
   :fill-color "#ffffff"}]]
* As can probably be inferred from the code the position and height are properties that are passed into the hiccup and trigger updates to the visual display when they change: in the case of position, when the playback position changes and in the case of the height, when the user resizes the browser window. The path element describes the triangle that is places at the top of the screen.
* The current state of the art in live code reloading in the browser is still not as comprehensive or as easy to setup as might be wished. Once it has been configured it is difficult to return to the compile and run workflow, and is in most cases a worthwhile investment of time. With these underlying elements in place the process of creating the core functionality application could begin and will now be described.

### Core functionality - timeline events (or notes)

At the core of the application is the creation of timeline events which unfold in a looped fashion. These events are created based on the input of the user with a mouse or mouse like input device. On the production of a valid input gesture, the screen is updated immediately with a visual display of this content. The details of this gesture is stored in memory and the event that will eventually create the sound is registered with tone.js. Much of the events that occur in the system are captured in a main "View" component which houses the central html canvas element. To aid in organising the large amount of functionality associated with the component, higher order components are used to separate this out into logical groupings. A higher order component is a component that wraps a normal component to add functionality to it and accepts the same properties as the component it wraps (???ref-react). In this case the most logical grouping is by tool and so there are higher order components setup for each of the tools: draw, vibrato, delete, move, resize and probability.

1. Add timeline event

* This is the default tool that is activated when the user opens the application and enables the user to add timeline events by drawing them onto the screen. It is added to the system when the "draw" tool is activated and a mouse drag operation is carried out from left to right within the bounds of the canvas element. The event is captured in the main canvas view and is initiated when the user left clicks the mouse triggering the following function:
* (defn pointer-down [{:keys [temp-obj active-preset]} evt]  
   (let [pointer-point (.. evt -point)  
   group (js/paper.Group. (clj->js {:position   
   [(.. pointer-point -x) (.. pointer-point -y)]  
   :applyMatrix false  
   :pivot [0 0]}))  
   circle (js/paper.Shape.Circle. (clj->js {:fillColor "#ffffff"  
   :radius 5}))  
   path (js/paper.Path. (clj->js {:strokeColor "#ffffff"  
   :strokeWidth 2  
   :fullySelected true  
   :segments [[0 0]]}))]  
   (.. group (addChildren #js [circle path]))  
   (reset! temp-obj {:path path  
   :circle circle  
   :group group  
   :loc pointer-point})))
* This function receives a hashmap with a reference to a *ClojureScript* atom which can is reset! to contain a temporary visualisation of the newly created note. This function uses a heavy amount of javascript interop to directly instanciate paper.js objects and add them to a shared group.
* As the user continues to move the cursor further points are added to the path created in the pointer-down function. Some constraints however are placed on the creation of the path and only points that are past the last previous from left to right are added. If the users backtracks it lead to a deletion of points, providing an intuitive undo like behaviour and implementing a recipricol HCI interaction pattern recommended by NUI principles.
* (defn pointer-move [{:keys [temp-obj active-preset]} evt]  
   (when-let [{:keys [path group] :as temp-obj} @temp-obj]  
   (let [pointer-point (.. evt -point)  
   rel-pos (.. group (globalToLocal pointer-point))]  
   ;; Only add positive points relative to first  
   ;; Remove points greater than pointer-points  
   (when-let [last-seg (.. path getLastSegment)]  
   (let [first-seg (.. path getFirstSegment)  
   first-point (-> first-seg .-point)  
   last-point (-> last-seg .-point)  
   pointer-x (.-x rel-pos)  
   amp-env (-> active-preset :envelope)  
   stage-width (.. evt -tool -view -viewSize -width)  
   max-width (if (= (-> amp-env :sustain) 0)  
   (let [time (+ (-> amp-env :attack)  
   (-> amp-env :decay)  
   (-> amp-env :release))]  
   (-> time  
   ;; Seconds to beats  
   (\* (/ js/Tone.Transport.bpm.value 60))  
   (time->euclidian stage-width)))  
   nil)]  
   (when (or  
   (nil? max-width)  
   (< pointer-x (+ (.-x first-point) max-width)))  
   (-> path (.add rel-pos))  
   (let [greater-segs (filter  
   #(> (-> % .-point .-x) pointer-x)  
   (.-segments path))]  
   ;; Remove greater points  
   (doseq [seg greater-segs]  
   (.removeSegment path (.-index seg))))))))))
* Completion of a note occurs when the user releases the button and triggers the pointer-up function:
* (defn pointer-up [{:keys [temp-obj active-preset stage-size]} evt]  
   (let [{:keys [path circle group loc] :as temp-obj} @temp-obj]  
   (.simplify path 10)  
   ;; Send the actual note  
   (dispatch [:note-add (-> (path->note path loc stage-size)  
   (assoc ,,, :preset active-preset)  
   ;; Use the color from the active preset  
   (assoc ,,, :color (:color active-preset)))] )  
   ;; Remove temp stuff  
   (.remove path)  
   (.remove group)  
   (.remove circle))  
   ;; Unset temp obj  
   (reset! temp-obj nil))
* This function simplifies the path by calling the paper.js simplify method on the path object and dramatically reduces the amount of data captured while preserving the basic characteristic of the user's stroke (???ref-simplify-fn). Most importantly it calls the *re-frame* dispatch function to add the note to the app database. A path->note function is used to convert the stroke from the domain of euclidean space on the visual space of the canvas to the domain of time-pitch space for use with the audio synthesis system. The path->note function can be seen below:
* (defn path->note [path first-point stage-size]  
   "Main entry point to this namespace"  
   (let [path-width (.. path -bounds -width)  
   width (:width stage-size)  
   height (:height stage-size)]  
   {:freq (domain/euclidean->freq (.. first-point -y) height)  
   :onset (domain/euclidean->time (.. first-point -x) width)  
   :duration (domain/euclidean->time path-width width)  
   :velocity 0.5  
   :enabled true  
   :probability 1.0  
   :color @(col/as-css (get colors (rand-int 100)))  
   :height (.. path -bounds -height)  
   :width (.. path -bounds -width)  
   :envelopes {:frequency {:raw (paper-path->vec path [width height])  
   :sampled (paper-path->sample path stage-size)}  
   :vibrato (reduce (fn [a b] (assoc a b [b 0])) (sorted-map) (range 11))}}))
* The domain of time-pitch is used to store the notes in memory and makes it possible to maintain a relative relationship between the screen size and the drawn notes.
* The dispatched note event is handled by a *re-frame* reg-event-db handler which describes the alteration that is required to be made to the database. It also uses a series of interceptors, to perform validation of the database and to remove some of the boilerplate from the event handler functions. Interceptors are similar conceptually to middleware and is the place where all of the side effects arising from an event are actioned. Moving application side effects to this placed ensures that they are isolated and means that the majority of the program can be kept as pure logic improving to make it easier to test, debug and reason about. As can be seen the handler function is very simple:
* (reg-event-db  
   :note-add  
   note-interceptors  
   (fn [notes [note-info]]  
   (let [id (allocate-next-id notes)  
   note (assoc note-info :id id)]  
   (if (>= (:duration note) 0.001)  
   (assoc notes id note)  
   notes))))
* This does a simple check to make sure that note has a minimum duration and if so alters the notes vector to include the new vector which will instruct *re-frame* to update it's internal atom with this new state.
* The structure of the note hashmap is defined using *clojure.spec*, a core library to perform data validation and a tool that may be used similarly to types in strongly typed languages. The note specs are defined as follows:
* (s/def ::id int?)  
  (s/def ::freq float?)  
  (s/def ::onset float?)  
  (s/def ::duration float?)  
  (s/def ::velocity float?)  
  (s/def ::color string?)  
  (s/def ::note (s/keys :req-un [::id ::freq ::onset ::duration]  
   :opt-un [::velocity]))
* Although note specified here, notes also have an envelopes key that stores frequency and vibrato envelopes. For example:
* {:frequency {:raw [{:point [-0.01 99.7] :handle-in [0 100] :handle-out [0 99.8]} ...  
   {:point [2.8 98.02] :handle-in [-0.10 100.4], :handle-out [0 100]}]  
   :sampled [-0.36991368680641185 ... -2.172026174596564]}  
   :vibrato {0 [0 0], ... 10 [10 0]}}
* The update in state spins *re-frame*'s subscription system into action and any views that are subscribed to the changed application state are now re-rendered. The graphics-notes view for instance is subscribed to :notes, :graphics-stage-width, :graphics-stage-height: and :mode:
* (defn graphics-notes []  
   (let [notes (subscribe [:notes])  
   width (subscribe [:graphics-stage-width])  
   height (subscribe [:graphics-stage-height])  
   ....]  
   ;; playback-time @(subscribe [:playback-time])  
   (into [:Group]  
   (map (fn [note]  
   ^{:key (:id note)} [graphics-note\* ...]) @notes))))
* When a note is added this render function will run which will call the [graphics-note\*] component for each of the notes, and update the visual display of the screen to show the new note. A similar process happens in the audio system except, in this case, new web audio nodes are created, timeline events are queued up at the correct time and audio envelopes are setup that traces the curve of the drawn lines. (Adenot, 2017)
* (defn fm-synth [{:keys [out] :as props} & children]  
   "FM synth"  
   ;; The new synth is instanciated using js interop  
   (let [synth (js/Tone.FMSynth. (clj->js (dissoc props :out)))]  
   (reagent/create-class  
   {:component-did-mount  
   (fn []  
   ;; The synth is connected to it's output (which is passed  
   ;; in as a property to the component)  
   (.. synth (connect out)))  
   :reagent-render  
   (fn [props & children]  
   ;; The render function renders a dummy span dom element and  
   ;; renders it's children and passing it's synth as the out  
   ;; for these components.  
   (into [:span]  
   (map (fn [child]  
   (assoc-in child [1 :out] synth))  
   children)))  
   :component-will-unmount  
   (fn []  
   ;; Here we dispose of the synth  
   ;; This will happen when the parent note is removed or when  
   ;; a live code reload happens  
   (.. synth dispose))})))
* The above shows the fm-synth which sits at the heart of the audio generating part of the system. Potential parent components of this would be audio effects or the master bus. It's child components are comprised of note events and envelopes that drive frequency changes over the course of the note playback. The composition of events, envelopes, synths, effects and channels is shown in truncated form:
* ;; Parent component is the project and  
  ;; has settings such as tempo  
  [project {:project :settings}  
   [master-bus {}  
   ;; Master volume is set here  
   [volume {:volume :settings}  
   ;; Adds a simple reverb effect  
   [reverb-effect {}  
   [  
   ;; First note  
   ;; Each note has a vibrato effect  
   [vibrato-effect {}  
   ;; Envelope to control vibrato depth  
   [timeline-evt evt  
   [envelope {:param "depth"  
   :env vib-env}]]  
   ;; The fm synth that generates the signal  
   [fm-synth (get-in evt [:preset])  
   ;; Timeline event that takes care of queuing  
   ;; it's child components  
   [timeline-evt evt  
   ;; In this case a note  
   [note {:note :settings}]  
   ;; And a frequency envelope  
   [envelope {:param "frequency"  
   :state state  
   :env freq-env}]]]]  
   ;; Second note  
   [vibrato-effect {}  
   ;; ...  
   ]  
   ;; ...  
   ]]]]]

1. Editing notes

* Once created, a number of editing operations can be performed on the notes. Apart from the **delete** action all of these operations involve first selecting the note on the **mouse down** event, carrying out the editing of the note and completing the action with the mouse up event. The particular tool can be activated by clicking the icon the right-hand side of the screen (see ). Clicking one of these dispatches the :change-mode event and changes the **app-db** to the specified mode as well as setting the application to state :pending. Flowing from this change are a number of changes:
  1. The relevant paper.js tool is activated which will route further mouse events to the appropriate dispatch handlers. For instance, when the :resize mode is selected, **mouse move** events will be handled by :resize-tool-pointer-move.
  2. It updates the visual look of the cursor to remind the user which of mode they are in.
  3. A visual indicator is shown around the icon of the selected mode
* The overall effect of this is an activation of a number of different modes, each of which will now be discussed.
* In the case of deleting notes, the event is simply raised in the **click** event of the note, which takes care of dispatching the :note-delete event.
* This is handled by a very simple handler, (dissoc notes note-id) that instructs *re-frame* to remove the note in question from the database. Similar to the process that occurs when a note is added, the visual display is now updated to no longer show the note. In addition, the signal generator, effects, envelopes and events associated with the note are removed from the audio component tree with *React.js*'s lifecycle events taking care to clean up any synth's and effects by calling their dispose methods.
* Moving notes and resizing notes work very similarly and both follow the most basic pattern described above of selection, manipulation, and completion. The note selection event is raised from the note's **mouse down** event handler, dispatching the :note-select event with the **note-id**. This updates the **app-db** to set the :active-note-id: to the received id, sets the app state to  
  =:active, sets the note state to be :active and resets previously active notes to state, :normal. This state update changes the visual display of the active note to be highlighted by slightly lightening the colour of the note's surrounding glow. More importantly, the note now becomes the active item on which further user interactions are performed on. In the case of the **move** tool the stored onset and pitch properties of the note are altered to reflect the position of the user's mouse. This, in turn, updates the visual display of the note and causes the audio system to re-queue the note events to the new onset and pitch values. The **resize** tool, on the other hand, changes the size of the starting node of the note and alters the velocity accordingly. The altered size is calculated from the coordinates of the **mouse down** event and is clamped to a maximum size that corresponds to the maximum velocity of the note.
* The slightly more esoteric **probability** tool works in a very similar fashion to the **resize** tools and again creates adjustments that work relative to **mouse down** coordinates. The visual effect that this creates, however, is a dulling of the saturation of the note. Its effect is to add an element of randomness and depending on how saturated the note is, it will cause the note to randomly skip. The code for this is below: #=INCLUDE: "ch5-code.org::probability-queueing" If the probability is set to 1.0 (which is the default) or fully saturated the note will play on every loop. If however, it is below this it will skip in a random but probabilistic fashion, adding a small amount of stochasticism to playback.
* The vibrato tool is the most complex in its implementation and involves a small popup UI element that allows the user to draw in a vibrato envelope which is visually reflected in the note lines as an overlaid sinewave. After selection occurs, in the usual way, **mouse move** events dispatch to the :vibrato-continue handler which updates a vibrato modulation parameter in the note, a single float value that represents the current real-time vibrato value. This modulation parameter is passed back to the view through properties where triggers a :component-did-update function call. It is here that a dispatch is made to the :vibrato-envelope-point to create the envelope point. The reason for the back and forth between the view and the event handlers is to allow the event handlers to manage the state changes but deal with the specifics of the geometry of the vibrato overlay in the view. It is probably best illustrated in the provided figure ().
* A visual overlay is shown to the user when a vibrato action is started, that shows a 10 point envelope, whose points are all set to 0.0 by default. The user can then drag at varying heights at various horizontal points on the axis and create the time-varying vibrato envelope. This envelope is visualised (and remains visible after the vibrato operation has completed) with a sinewave that tracks the curve of the frequency envelope and varies its amplitude depending on the strength of the vibrato at that particular point. The code to achieve this is below:

### Secondary functionality

Aside from the core functionality of note creation and editing, a number of other use cases had to be catered for to make the application useable. This included transport controls, to allow the user to start and stop playback; some simple animation to show which notes are being played and to tighten the link between the visuals and the audio; undo and redo functionality; a fullscreen toggle to maximise the immersiveness; as well as the ability to save and load sketches. While not central to the concept, standard usability features such as undo/redo would be a noticeable omission that would decrease beginner friendliness. Some of these extra features were made more straightforward than would normally be the case due to the architecture of placing the state in a single place, the *re-frame* **app db**.

Both the transport and the fullscreen mechanism consisted of a simple finite state machine (FSM) that who's transitions are caused by user actions. The transport state machine responds to both the button click and **spacebar** keypresses to toggle its state between playing and stopped and based on this, triggering playback in *tone.js*. The fullscreen FSM transitions occur not only when the user clicks the fullscreen button but also when the browser fullscreen status changes. This keeps the UI in a correct and consistent state at all times, regardless of how the state is reached.

Undo/redo and save/load functionality was relatively straightforward to implement for the reasons mentioned above (centrally located state) as well as the ease of serialising *ClojureScript* data. Adding undo/redo was as easy as adding an additional dependency and adding it as an interceptor to any events that needed to be undoable such as adding or deleting notes.

The particular parts of the app state that needed to be restored were also configured and included the notes collection and the tempo. Both of these elements were saved and restored by the save/restore functionality which worked by serialising this data as a string and restoring with a single function call to *ClojureScript*'s reader/read-string.

As outlined in the previous chapter, *SonicSketch* an influence of the design of the user experience is the *Music Animation Machine* which visualises music so that even nonmusicians can relate the visuals to the music unlike following a CMN score. To achieve this, the :note subscription is itself subscribed to :playback-beat a reactive value that is kept up to date via the use of events that fire on every animation frame. The subscription checks if the playback head is within the notes range and if so sets its :playing property to true and updates :playback-time to reflect the position of the playback head in the note. Similar to any other changes in state, the note views react to this and update their visual look accordingly which due to the quickly changing nature of the value leads to an animation.

## Conclusion

This chapter outlined the development process that took place to bring SonicSketch to life. The early prototype work was detailed, including the porting of SonicPainter to the web, all work that contributed conceptually to the final artifact. The setup of the technical architecture to enable a live code reloading workflow was outlined. An in depth description of the primary functionality that enables users to draw and edit notes on the screen was given, followed by a more brief look at secondary functionality such as undo, saving and note animation.

# Evaluation

## Introduction

## Initial pilot test

## Exhibition

As you can see in the figure , the majority of activity is in the upper regions of the frequency spectrum and concentrated at the beginning and the middle of the screen.

## Performance issues

## Conclusion

# Conclusion and further work

## Summary of work completed

## Broader implications of development

## Future work

### Performance improvements

### Broaden visual language

### Allow for larger structures

### 3D spaces, VR, spatial audio

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