Sonic Artifacts:

by

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B.S. in Electrical Engineering
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Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning, in partial fulfillment of the requirements for the degree of
Master of Science
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Abstract

A Sonic Artifact is a physical object that represents and contains a musical album and allows for real time interaction with the listener. We restore the association of music with the physical artifact of its delivery, a design of the music merchandise of the future, now with the ability to interact with the music in real time. Rather than the audio experience being delivered as a file via a centralized music streaming platform or other method, the music will reside in an active environment associated with the artist. The musical experience has the potential to be unique upon each listen and the total composition and is dependent on the actions of the listener. If the listener chooses, they get to be a part of the composition.

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Table of Contents

1 Introduction

1.1 Purpose

Music and artistic expression in general are key applications of technology used to create perhaps some of the most potent media to communicate our ideas, intuitions, and nuanced interpretations of our human experience. Freedom of expression in music must be protected and the medium by which is it distributed needs to be further cultivated, all while staying free and open for all to both create and interpret its meaning. One goal of Sonic Artifacts is to help people continue to create and listen to their own choice of music. We propose that this involves keeping people actively engaged with both the listening and creative processes involved in sound and music creation. In the words of Talking Heads frontman, D. Byrne,

> It's a little strange, though, to realize that a large part of my identity is tied to something that is completely ephemeral. You can't touch music - it exists only at the moment it is being apprehended - and yet it can profoundly alter how we view the world and our place in it. Music can get us through difficult patches in our lives by changing not only how we feel about ourselves, but also how we feel about everything outside ourselves. It's powerful stuff. [1]

Indeed it is so powerful that we posit that music needs to continue its evolution in a manner which is financially equitable and intellectually stimulating for both artists and listeners. This thesis asks the question, what if we add thoughtful interactivity into the physical representation of music and tune these interactions to creatively correlate with what we hear? Will these aesthetic and functional musical extensions into the listeners space prove to be a valid delivery method and a richer palette for musicians? And equally as important, will the interactive experience serve as a heightened experience for listeners, who have thus been transformed into co-writers, or will our approach add clutter to a recorded medium that should remain ephemeral? Sonic Artifacts explores these questions.

1.2 Motivation

The music industry has been in flux since the introduction of streaming music platforms such as Apple Music, Pandora and Spotify. In the United States alone, physical album sales have

seen an overall decrease from 500.5 million sold in 2007 to 241.4 million in 2015 (Fig 1). Some revenue has transitioned from physical and online album sales such as iTunes to the streaming subscription market. As an example, my latest royalty statement from the performing rights organization Broadcast Music Incorporated or BMI (Fig 2), states that a track for which I own 20% of writers share was streamed by 168,851 people in one quarter of 2014, for which I was paid: $0.84. Payouts are similar from Spotify and Youtube in the same royalty statement. The creative commons style argument can be made that we reach more people and are getting more exposure which could translate into more people coming to our concerts but this assumes our band can afford to tour and contributes to the devaluation of recorded music. The given climate of the industry affords an opportunity to develop new methods to engage with and include fans using new technologies and paradigms. That is the mission of Sonic Artifacts.

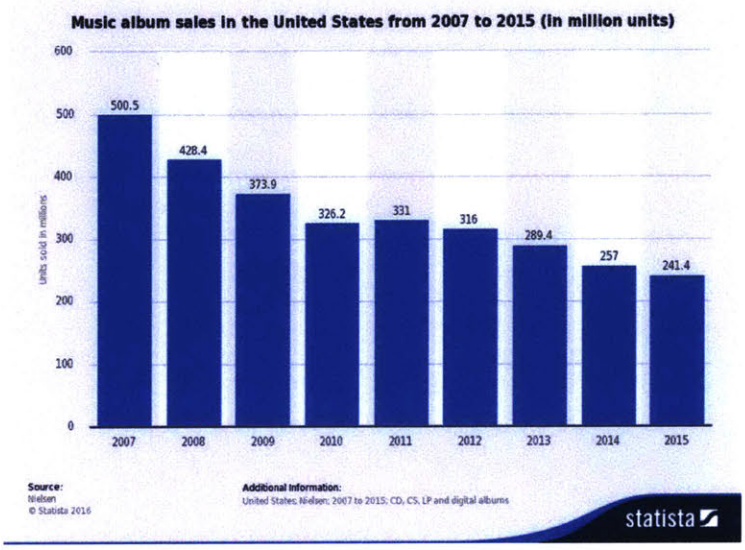


Fig 1. Physical Album Sales in the US

PANDORA 2014								
BOAT TRIP	013764369	FF	168,851	2014	20.00%	$0.83	$0.00	$0.83
DEEP WAR	013764374	FF	7,554	2014	20.00%	$0.04	$0.00	$0.04
DESERT GOD	011360812	FF	3,028	2014	20.00%	$0.01	$0.00	$0.01
LANE	016639859	FF	6,462	2014	20.00%	$0.04	$0.00	$0.04
LORD	010264135	FF	11,033	2014	25.00%	$0.06	$0.00	$0.06
OPEN EYES	011360813	FF	7,322	2014	20.00%	$0.05	$0.00	$0.05
SHE REX	013764386	FF	4,451	2014	20.00%	$0.02	$0.00	$0.02
SIOUXSIE BLAQQ	013764367	FF	4,071	2014	20.00%	$0.02	$0.00	$0.02
WILD MACHINES	011357903	FF	19,364	2014	20.00%	$0.09	$0.00	$0.09
WORDS	017235632	FF	4,340	2014	20.00%	$0.03	$0.00	$0.03
YELLOW END	013764373	FF	4,435	2014	20.00%	$0.02	$0.00	$0.02
PANDORA 2014 Total								**$1.21**

Fig 2. A portion of my earnings royalty statement from Pandora

According to Marshall McLuhan, the initial development of the phonograph for reproduction of audio was met with resistance from the existing musicians of the 1870's. For example, John Philip Sousa argued that, "The phonograph is an extension and amplification of the voice that may well have diminished individual vocal activity, much as the car had reduced pedestrian activity." [2] By recording speech patterns people would inevitably conform to the recorded

speech patterns and lose individuality. The invention of recorded music as opposed to just recorded speech poses a similar issue. Instead of going to hear music, an experience which is equally as much about the space it inhabits and the vibe of the audience themselves, music was broadcast using a portable medium. The experience shifted from an event to an individual listening. This isn't necessarily bad, but as anyone knows who goes to a concert, there is something special about hearing the music a listener enjoys, being played by live musicians. It's the flaws that are endearing; the changes invoked both by the space and the mood of the listeners. Walter Murch the sound editor and film director states: "Music was the main poetic metaphor for that which could not be preserved. One could argue that this evanescence helps focus our attention. They claim that we listen more closely when we know we only have one chance, one fleeting opportunity to grasp something, and as a result, our enjoyment is deepened." [3]

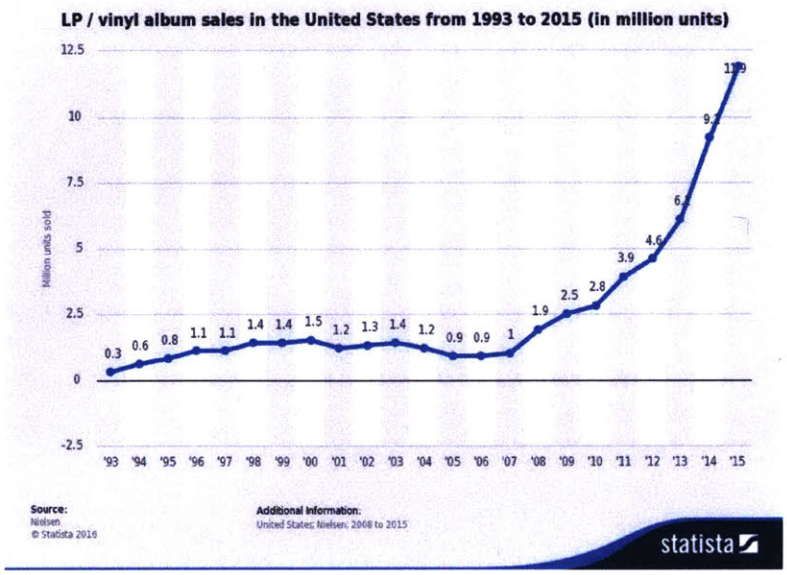


Fig 3. Growing LP Sales in the USA

Sonic Artifacts supposes a step back towards this spirit of inclusion in the musical experience while also adding interactivity. Individuals or groups of people interact with a piece of hardware. There is evidence that people still like to purchase physical musical merchandise. For example, Long Play record or LP sales in the US has been growing. In 2015, vinyl LP sales reached 11.92 million, up 37% from the year before. A survey was conducted polling musicians on their receptiveness to a Sonic Artifact with results found in section 5.

1.3 Contribution

Sonic Artifacts do not involve vinyl or cassette tapes directly, but rather explores the use of their width and length form factor. The project is inspired by culturally relevant form factors such as cassette tapes and compact disc cases, things that listeners can engage with, and then put back on the shelf with their collection (or if they don't collect LP's keep on their coffee table). Sonic Artifacts is about giving people a way to acquire art in support of the music they care about in a new technologically interesting way. Music is generally distributed as a static file, typically a .WAV or .mp3, or as an online stream. But music no longer needs to be limited to these medium of fixed content. Sensors on the physical album afford for the listener to become more involved with the music by influencing the music itself in real time. Music is delivered to an external object and this object receives information from a parallel data track in the audio. It is a new way to think about the broadcasting and distribution of music.

Sonic Artifacts is both a hardware interface and software platform that music artists utilize to create novel interactions with their listeners through specific hardware instances. Having a physical dynamic interaction with the music focuses the attention of the listener through direct engagement in the real world. Rather than the audio experience being delivered as a static file via a centralized music streaming platform or other method, the music will reside in an active environment. The artifact gives the artist a channel for direct communication of their art in new ways while allowing the listener to achieve a new level of interactivity.

One goal of Sonic Artifacts is to associate value with recorded music again. Right now streaming music is practically free for consumers and artists get paid around $.007 per play [4]. A major tenant of the Sonic Artifact approach promotes creativity away from listeners' phones and computers, thus creating a more focused and meaningful sonic experience, enjoying the music while actively engaging with it, all while creating something that is physical, aesthetically meaningful, and maintains value. The Sonic Artifacts approach is novel in that it couples the access and manipulation of individual stems otherwise known as instrument tracks in a given song with physical controls aesthetically embedded in hardware that is unique to each album. This experience is different than that of an app or a website.

2 Background

2.1 Albums as Art

The graphic artist Alex Steinweiss developed the entire graphical language of album art design. It was his idea to pitch to Columbia Records that they could replace the existing paper sleeves used to distribute vinyl records with colorful art that would prove to increase sales dramatically. [5]

Original record album art did not exist before Steinweiss pioneered the field. At first 78 rpm records were packaged in albums of three or four disks sheathed in separate, paper sleeves that were bound between pasteboard covers. Dedicated record shops were also rare and albums were often relegated to nooks in appliance stores, usually next to the record players. Record store displays were often the only marketing device for the records. In 1940 the first illustrated record was created by Steinweiss, a record called the Roger & Hart collection, seen below [6].

Fig 4. The First Illustrated Album Art Cover, 1940

Sales rose dramatically due to the cover, and a new genre of illustration was born. From 1938 to around 1945, Steinweiss designed all the covers for Columbia Records. During this period, he developed the entire graphic language of album design. Steinweiss is also credited with the introduction of the first LP or long play art. Here is a photo of him working in his studio:

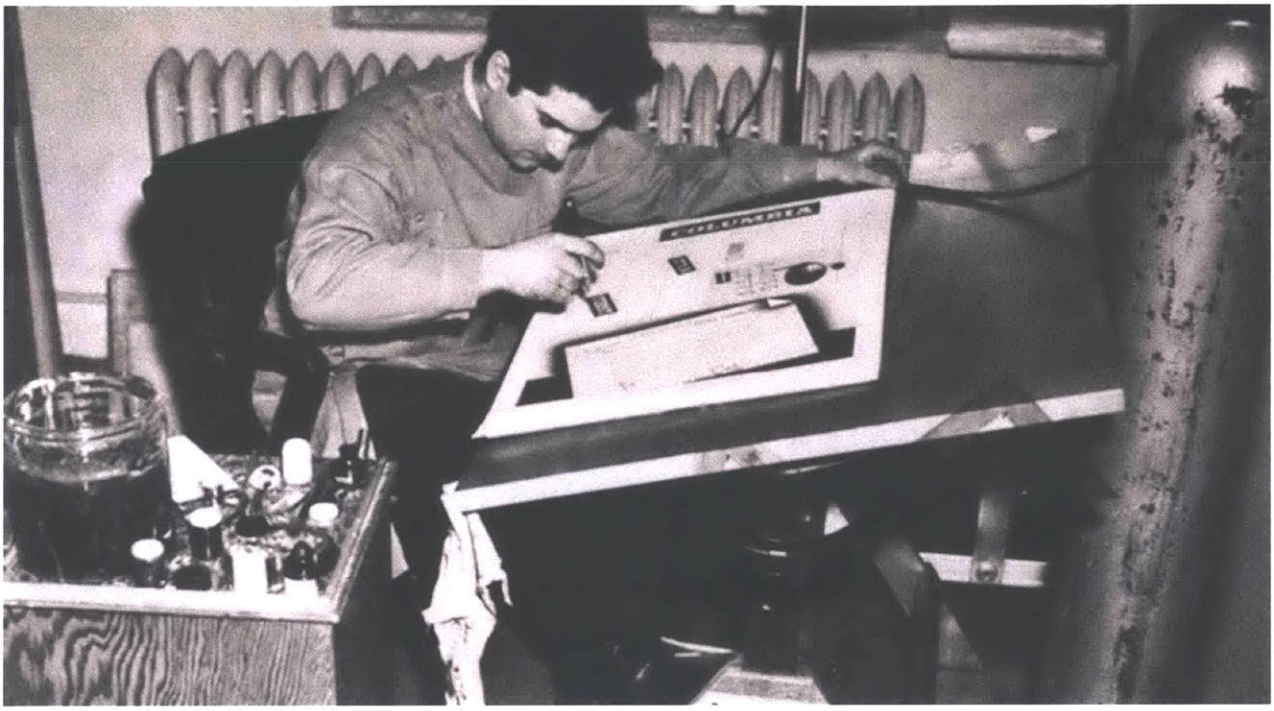


Fig 5. Alex Steinweiss in his studio

Steinweiss laid the foundation for album art, which is now inextricably linked to records themselves. They give identity to the product, much like a book jacket. Although the art originated on the vinyl record, the trend continued on the cassette as well as the compact disc and ultimately as thumbnails for the digital representation of music [7]. Sonic Artifacts honors and augments this tradition, keeping the link between art, design and music which all work in concert to add value to the next generation of physical representations of music.

2.2 Generative and Reactive Music

As with any art form, the medium of music evolves over time. A relatively modern pioneer that pushed music in new direction was the American composer John Cage. Perhaps most known for his infamous composition, 4'33, in which an entire orchestra sits quietly, Cage was also a trailblazer in the field of generative music. While made popular more recently by Brian Eno [8], Generative music is a term to describe music that is ever-different and changing, and that is created by a system. Sonic Artifacts draws from his ideas.

Cage developed systems of music based on algorithms, probability and something that Cage called indeterminacy. He describes this new phase of his musical thought: "more essential than composing by means of chance operations, it seems to me now, is composing in such a way that what one does is indeterminate of its performance. In such a case one can just work directly, for nothing one does gives rise to anything that is preconceived." [9] While chance introduces outside forces into a composition, it does not allow for direct user improvisation. Later in Cage's career he did incorporate improvisation through the use of selected objects such as cacti and seashells.

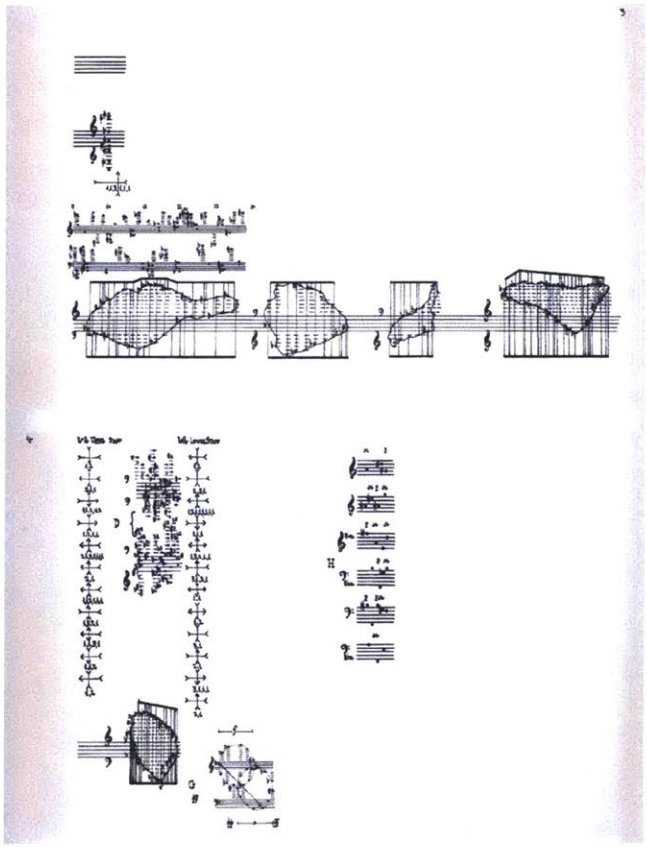


Fig 6. John Cage Notation of a Composition

Another contributor to the field is Karlheinz Stockhausen. A musical theoretician who created guidelines for musicians to follow and didn't tell the musicians what to play. Like Cage, his work involved elements of chance. Stockhausen is known for his work in electronic music, aleatory or controlled in serial composition, and musical spatialization. Sonic artifacts also draws from some of his ideas. Stockhausen is quoted as saying in 1971:

> I want to build a new tradition, an aural tradition, transmitted via the ears. I feel a duty to perform my music , and I have played all over the world. Then there are my recordings. I consider a record I make as important as the score. Many of them contain music which is not determinate. So the records are models for musicians. The musicians can refer to these recordings and learn from them, and develop their own new approaches to creating sound worlds.
>
> This new aural tradition which I have started means that our musical knowledge will come to be based more and more on direct experience of working with sounds, rather than on writing on paper. New possibilities are discovered and can develop so much faster, when someone works in a studio and produces the sounds himself, and transforms them. Many musicians today know a lot about recording techniques and they penetrate right into the sound, using transforming devices, synthesizers, filters, modulators, dynamic controls, all of which make it possible to live with the sound to a far greater extent than has been the case for a long time in our musical tradition. [10]

Both Cage and Stockhausen use elements of algorithmic generation and chance in their work. At the time, this method was controversial in that the music was not simply transcribed from the page or improvised. But it also raises the question, why does the tradition of western notation have to dominate music in general? This notation created an artificial barrier to entry into the field that most contemporary popular artists don't adhere to anyway. People feel that they must know how to read music note for note in order to be a musician. This couldn't be further from the truth. Music has always been about listening and communicating with people. Sonic Artifacts builds on this idea and allows an engaging entry point for listeners to learn about and contribute to the composition.

An even more recent development is the idea of reactive music. This paradigm is at the heart of the Sonic Artifacts approach. Michael Breidenbruecker who is known as co-founder of Last.fm and founder of RjDj coined the new term, *reactive music*. Reactive music is a non-linear form of music that is able to react to the listener and his environment in real-time.[11] Reactive music is similar to generative music but it uses modern technologies to achieve its goals. Similar to music in video-games, that is changed by specific events happening in the

game, reactive music is affected by events occurring in the real life of the listener. Reactive music adapts to a listener and their environment by using built in sensors in mobile media players. The main difference to generative music is that listeners are part of the creative process, co-creating the music with the composer [12]. It is this idea that propels Sonic Artifacts, the main difference being that instead of being a mobile application, the experience is achieved through hardware.

What is distributed in reactive music is not the music itself, but software that generates the music [13]. Applications made by RjDj were available on Apple's iOS platform, but the company was ultimately unsuccessful. Luckily the company open sourced the Pure Data abstractions that were used for the project. Sonic Artifacts builds upon these elements but instead of being run on the iPhone, the code is executed on a local linux single board computer that synthesizes the music in real time. The open source libraries used are called rjlib and the technology behind it was based on the Pure Data digital signal processing framework. These reactive music pieces, or what Breidenbruecker calls 'scenes' are crafted as abstractions in Pure Data which in turn can interface with a micro controller for the purposes of listener interaction [14].

2.3 Integrating the Idea of Flow

We have introduced the genesis of the album art cover, and also discussed the genres of generative music and reactive music. Now we introduce a framework from another field, that of humanistic psychology. The framework is called flow. In positive psychology, flow, also known as the zone, is the mental state of operation in which a person performing an activity is fully immersed in a feeling of energized focus, full involvement, and enjoyment in the process of the activity. In essence, flow is characterized by complete absorption in what one does. The idea was made popular by the positive psychologist Mihaly Csikszentmihalyi [15]. Going further, flow introduces a concept of eustress which is defined a state of positive stress, needed to accomplish meaningful, and successively more difficult goals. Those in flow are constantly attempting and accomplishing tasks of increasing difficulty and that require more and more skill. If the tasks are not to difficult (causing anxiety or worry) or the tasks are too simple (causing boredom or apathy) then the participant may achieve a sense of flow.

In Csikszentmihalyi's studies, we found that every flow activity, whether it involved competition, chance, or any other dimension of experience, had this in common: It provided a sense of discovery, a creative feeling of transporting the person into a new reality. It pushed the person to higher levels of performance, and led to previously undreamed-of states of consciousness. In short, it transformed the self by making it more complex. In this growth of the self is the key to flow activities.

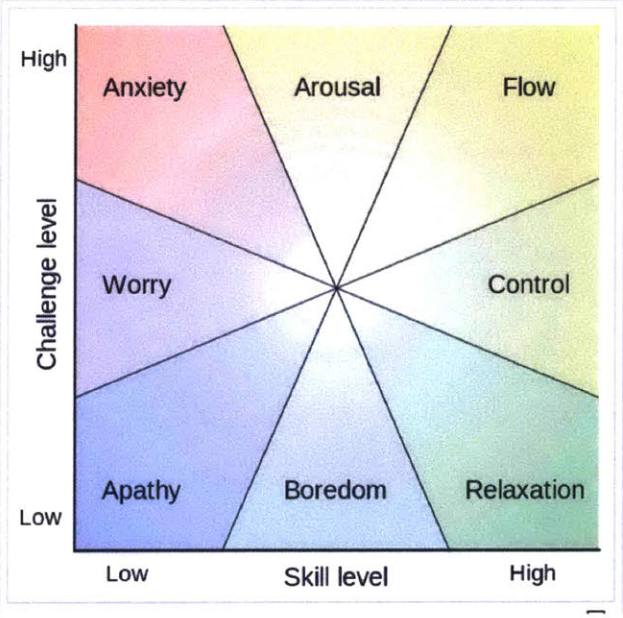


Fig 7. Challenge level versus skill level

A simple diagram might help explain why this should be the case. Let us assume that the figure below represents a specific activity-for example, the game of tennis. The two theoretically most

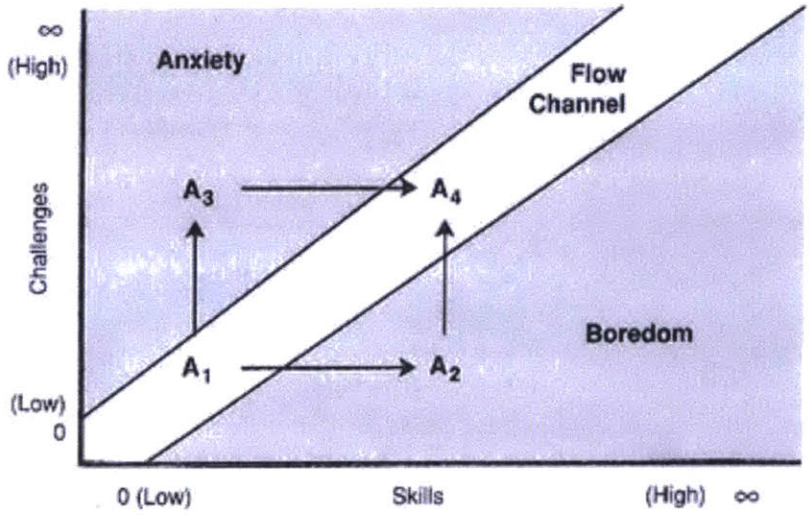


Fig 8. Maintaining Flow

important dimensions of the experience, challenges and skills, are represented on the two axes of the diagram. The letter A represents Alex, a boy who is learning to play tennis. The diagram shows Alex at four different points in time. When he first starts playing (A1), Alex has practically no skills, and the only challenge he faces is hitting the ball over the net. This is not a

very difficult feat, but Alex is likely to enjoy it because the difficulty is just right for his rudimentary skills. So at this point, he will probably be in flow. But he cannot stay there long. After a while, if he keeps practicing, his skills are bound to improve, and then he will grow bored just batting the ball over the net (A2). Or it might happen chat he meets a more practiced opponent , in which case he will realize that there are much harder challenges for him than just lobbing the ball at that point, he will feel some anxiety (A3) concerning his poor performance.

Neither boredom nor anxiety are positive experiences, so Alex will be motivated to return to the flow state. How is he to do it? Glancing again at the diagram, we see that if he is bored (A2) and wishes to be in flow again, Alex has essentially only one choice: to increase the challenges he is facing. (He also has a second choice, which is to give up tennis altogether-in which case A would simply disappear from the diagram.) By setting himself a new and more difficult goal that matches his skills-for instance, to beat an opponent just a little more advanced than he is-Alex would be back in flow (A4).

If Alex is anxious (A3), the way back to flow requires that he increase his skills. Theoretically he could also reduce the challenges he is facing, and thus return to flow where he started (in A1), but in practice it is difficult to ignore challenges once one is aware that they exist.

The diagram shows that both A1 and A4 represent situations in which Alex is in flow. Although both are equally enjoyable, the two states are quite different in that A4 a more complex experience than A1. It is more complex because it involves greater challenges, and demands greater skills from the player.

But A4, although complex and enjoyable, does not represent a stable situation, either. As Alex keeps playing, either he will become bored by the stale opportunities he finds at that level, or he will become anxious and frustrated by his relatively low ability. So the motivation to enjoy himself again will push him to get back into the flow channel, but now at a level of complexity even higher than A4. When compared to learning an instrument, the idea is the same, with a steeper initial learning curve reinforced by direct audio feedback. Sonic Artifact introduces an intermediate in which listeners not yet proficient with an instrument are able to add sounds to an existing composition.

It is this dynamic feature that explains why flow activities lead to growth and discovery. One cannot enjoy doing the same thing at the same level for long. We grow either bored or frustrated; and then the desire to enjoy ourselves again pushes us to stretch our skills, or to discover new opportunities for using them [16].

Sonic artifacts looks to integrate the idea of flow with the ideas of generative music and reactive music. We learned from generative music that it is possible to define systems for music. One of Cage's seminal works was based on the book of changes or the I Ching. The format was that chance was introduced into the composition. This was ground breaking and a move away from playing music note for note from a page. Systems thinking, and thus eventually computers can be introduced into the fold. Couple this with the idea of reactive music, or music that changes with user interaction via sensors, and the foundation for a new type of interaction is born. But without the concept of flow, this new type of music experience may be too inaccessible for day to day listeners.

Introducing flow into the experience means catering to all skill levels. If a novice interacts with the artifact they should feel engaged and not overwhelmed. Ideally the backdrop of their favorite song would serve as a learning platform for sonic and mathematical properties. Similarly, the experienced musician needs to feel challenged as well. This can be achieved through varying modes of difficulty integrated into the experience.

One way to think about this integration is to study both musical works and software through time. Several artists began experimenting with generative music in 1960's including John Cage, Steve Reich and Terry Riley [17]. Around 2012 Michael Breidenbrueker began collaborating with artists and composers to augment their music with his RjDj app. Collaborators included Hans Zimmer, the french electronic group Air and Christopher Nolan, the director of the movie Inception. There were other pioneering people who were already meshing the genres, notably Brian Eno in 1996 whose work generative music 1 was developed using SSEYO Koan Software, a project Eno was involved in. In 2005, MIT Media Lab Alumni Eran Egozy and Alan Rigopulos shook the music and gaming world with their hardware based musical games Guitar Hero and Rock Band which introduced varying skill level sets in a collaborative rhythm detection gaming scenario. Figure 10 is not exhaustive but gives a feel for the direction and overlap of this trend toward the integration of the three core ideas.

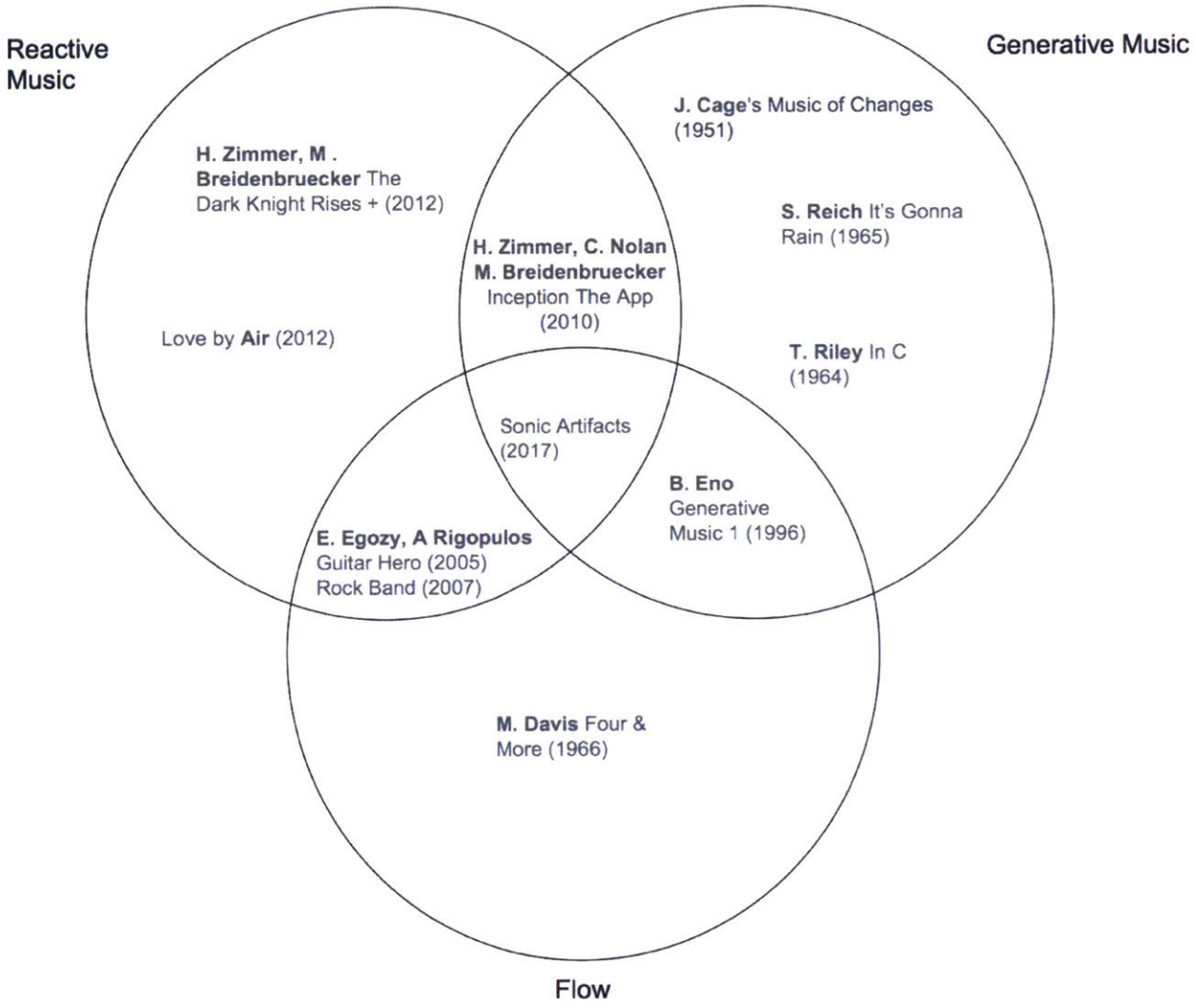


Fig 9. Intersection of Generative and Reactive music with framework of Flow

3 Related work

3.1 Existing Artifacts

3.1.1 Tristan Perich : 1 Bit Symphony - Technology and aesthetic Rolled Into One

Tristan Perich's 1-Bit Symphony is an electronic composition in five movements on a single microchip. This is a physical representation of generative music. The circuit is housed within a CD case. 1-Bit Symphony is not a recording in the traditional sense; it literally "performs" its music live when turned on. A complete electronic circuit which was programmed by Tristan Perich, this project plays the music through a headphone jack mounted into the case itself. The music is created in assembly language, a low level programming language that sits just above machine code. The code itself is published in booklet form and included with the object. Discovery of this project was a major source of inspiration for Sonic Artifacts. A relatively simple circuit is presented in an aesthetically pleasing see through CD jewel case with a built in battery and audio jack for output [18].

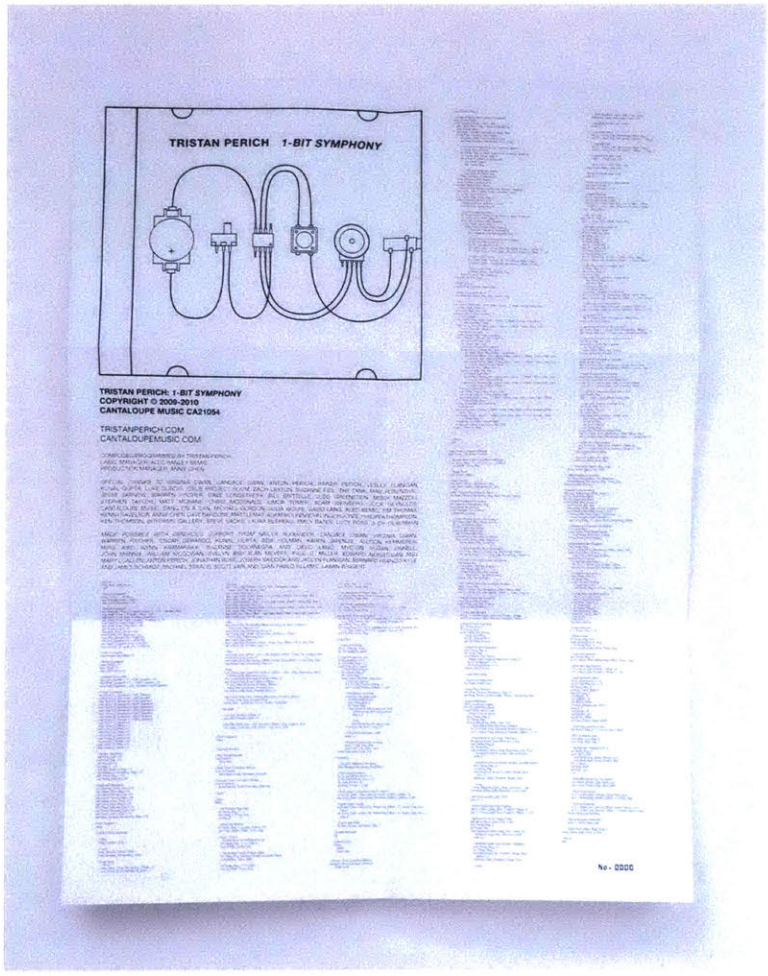


Fig 10. Tristan Perich 1-bit Symphony booklet with code

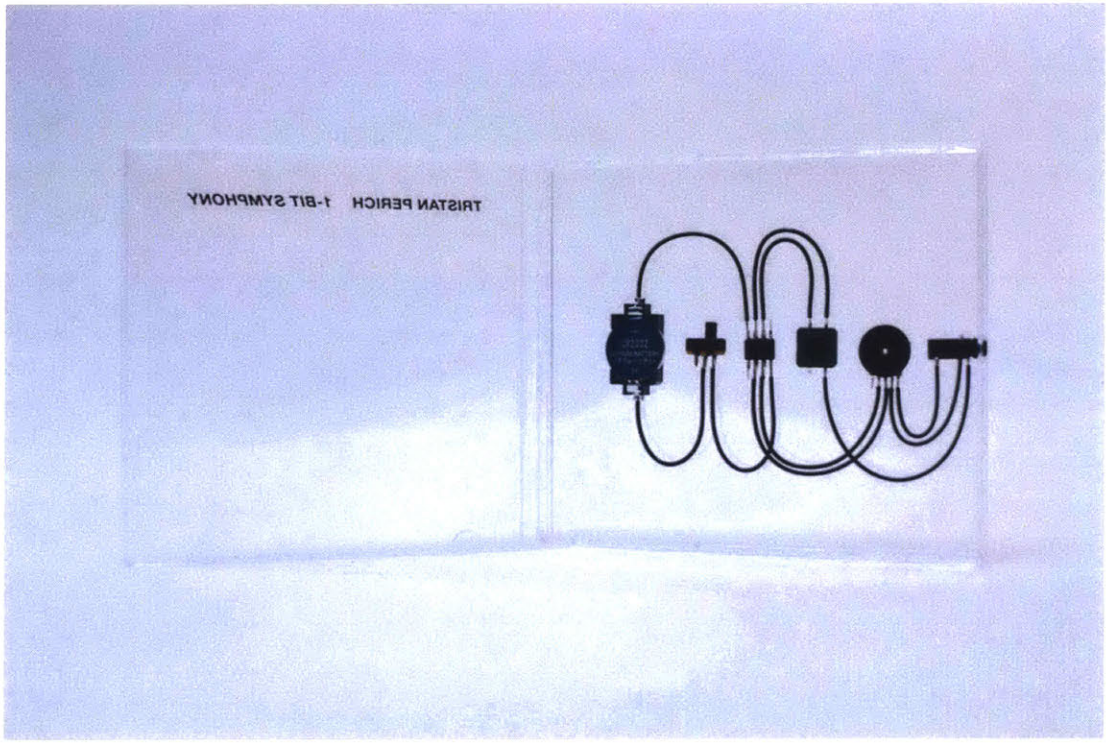


Fig 11. Tristan Perich 1-bit Symphony CD case

3.1.2 Bjork's Biophilia Application Based Album and Artifact

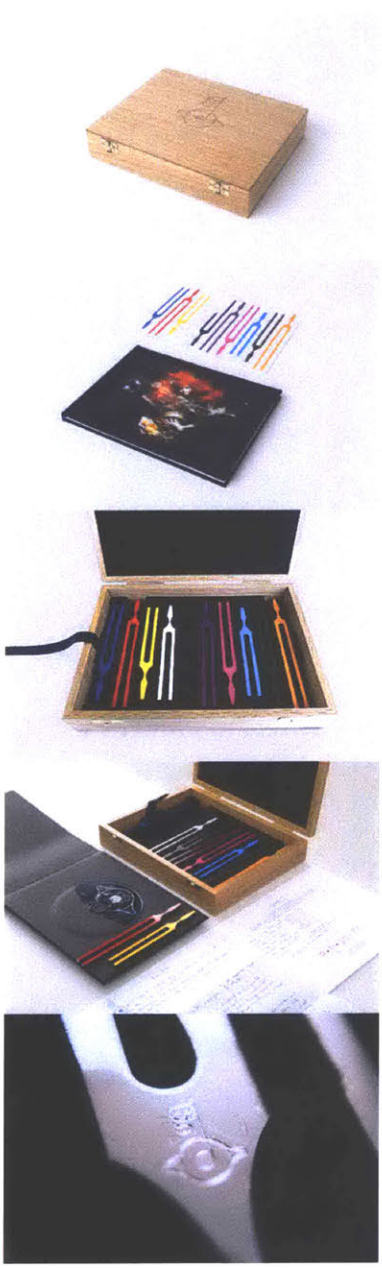


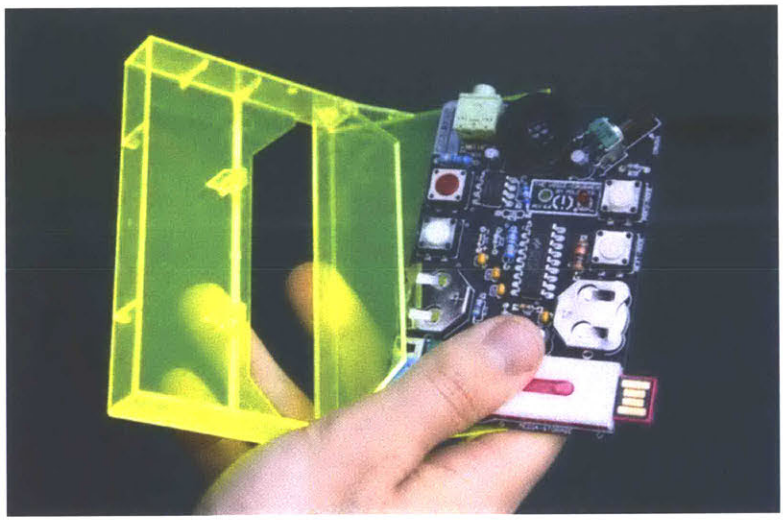
Fig 12. Bjork's Biophilia App and Tuning Fork Artifact

Bjork is known for being an innovative artist. In 2005, she released the first 'app album' called Biophilia, which explores the links between nature, music and technology. Biophilia is a multimedia project released alongside a series of apps linking the album's themes to musicology concepts. It was followed by a series of educational workshops in four continents. The app was used in European schools as a learning tool. She explored the use of a limited edition version with special tuning forks that shipped with the app [19]. The limited edition tuning forks are not integrated with the app, but rather show the use of an external artifact that augments the album experience.

Biophilia was well received by critics and was named one of the best albums of 2011 by several publications; it was nominated for two awards at the 55th Grammy Awards in 2013, winning Best Recording Package. It debuted in the top 40 of every chart it entered worldwide, topping the Taiwan chart and peaking in the top 5 in Iceland, France and Denmark. In 2014, Biophilia became the first app included in the permanent collection of the Museum of Modern Art in New York. Each song is an app based exploration, with game like play and graphics [20] Drawing from elements of both generative and reactive music, this app demonstrated that popular music could be delivered in app form and that fans and critics resonated with its approach.

3.1.3 Moldover's "Four Track" and Self Titled Theremin Record

Moldovers' projects are also a major influence on Sonic Artifacts. His work makes use of existing recording form factors, namely the cassette tape and CD case. In his project 4 Track, which he kickstarted, the album is available on a dedicated USB drive. [21] The rest of the board looks like a cassette but is in fact a voice synthesizer circuit with microphone. It its important to note that the music is static in this case, and the voice synthesizer circuit is separate and stand alone. But the aesthetics and idea are novel. Before this project, Moldover created a similar project which was packaging for his self titled CD. The surrounding packaging of the CD case is a circuit that is mostly aesthetic but never less pushed the medium of album artwork forward. The Four Track packaging circuit was a light based Theremin like instrument based on a cadmium sulfide photo resistor.



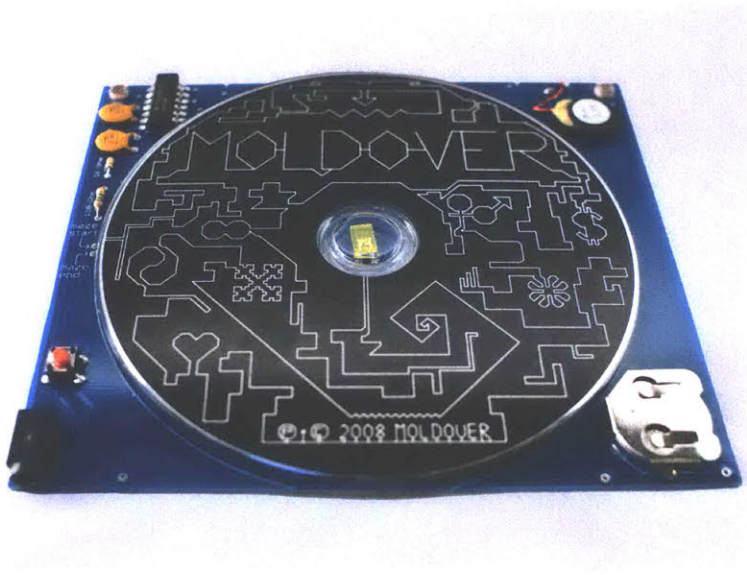


Fig 13. Moldover's Four Track and Self Titled Album Objects

3.1.4 Critter and Guitari Organelle

This project is not a album but a versatile musical instrument. Critter and Guitari make custom musical synthesizers. This version comes equipped with a linux machine that runs Pure Data patches, which can be custom designed to make a variety of sounds, and also has an HDMI port. Seeing this application of Pure Data in the wild, making good sounding music, was pivotal in the idea that Pure Data can be used to synthesize records locally, with hardware input and output capabilities.

This product has an online community that shares patches, an idea that eventually will be included with Sonic Artifacts in future work. It provides a step towards users and listeners becoming composers and sharing their mixes, using sophisticated methods. The module has a built in screen and menu function, which interfaces with the Pure Data patch's parameters to display patch variables and their state [22].

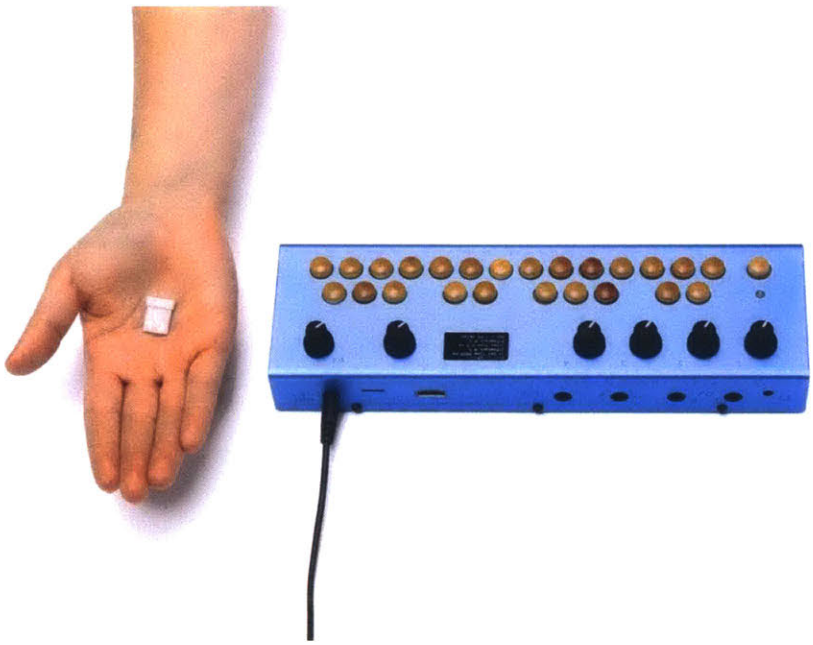


Fig 14. Critter and Guitari Synthesizer with Pure Data Patches

This product demonstrates that Pure Data patches embedded on a single board linux processor have the potential to deliver high quality real time audio experiences. For example, this product has the following specifications:

Critter and Guitari Audio Specifications:

- Sampling Rate: 44.1kHz; 16-bit (In & Out)
- 2x ¼" Mono Sound Output Jacks (L & R channels)
- ¼" Stereo Sound Input Jack
- ⅛" Stereo Headphone output Jack
- ¼" Footswitch Jack

Interface:

- High-Contrast OLED Display Screen
- Four Parameter Knobs
- Rotary Selection knob with Push Button Select
- Volume Knob
- 25x Maple Keys
- RGB LED

Processor Specifications:

- 1GHz ARM Cortex A9 with 512 MB RAM
- Linux Operating System
- Boot time: ~12 seconds

3.2 Existing Projects

3.2.1 RjDj Reactive Music

The company RjDj delivered reactive music experiences through smartphones. These experiences, called scenes, use the open source Pure Data graphical programming language to create music that changes according to listener choice and behavior. This project is the foundation for the software written for Sonic Artifacts. It introduces, free for use, a library of Pure Data abstractions that make it relatively easy for a programmer to create their own musical scenes. This library was utilized in Sonic Artifacts. RjDj collaborated with Moldover on an app-based version of one of his songs called Toast for RjDj, which transferred his physical controller interface capability into app form for one of his songs, which was distributed as an app. RjDj was entirely app based but since it uses Pure Data, physical interactions are possible. More on the details of how Pure Data works in the Software section [23].

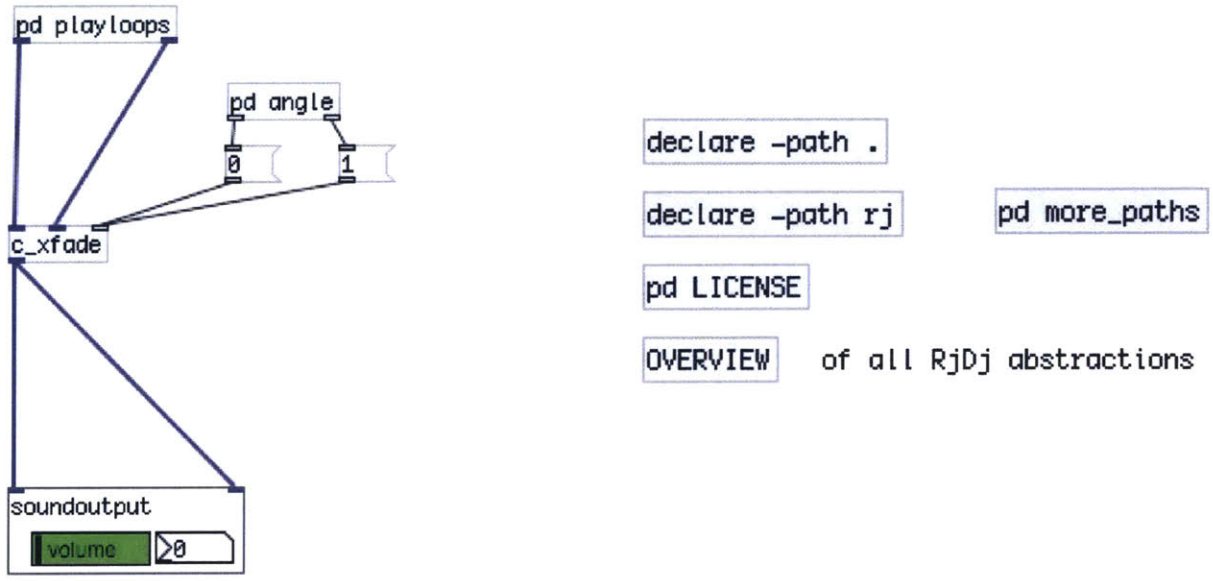


Fig 15. RjDj Pure Data Patch that crossfades two tracks

3.2.2 Harmonix Rock Band and Drop Mix

Eran Egozy and Alex Rigopulos created an interactive game called Rock Band, a followup to the hugely successful Guitar Hero video game series which allows people to play in a band in a rhythm matching game setting. Rock Band also uses peripherals and existing rock songs to give a group of people the gaming experience of performing and working together in a band to perform a live show. The system is console based and includes it's own peripherals including drums, guitars and vocal mic. Abstracted rhythm and pitch interaction allows players to play along with the songs, creating in real time their instruments' portion of the song.

A new project by Harmonix called DropMix uses peripheral RFID paying cards to mix and match rhythm sections from real songs which are all being tempo matched in real time. A new take on mashups, this project leverages the computing power and connectivity of a mobile phone with its peripheral [24]. This is also a major influence on Sonic Artifacts in that it makes use of individual stem tracks of bands and external peripherals.

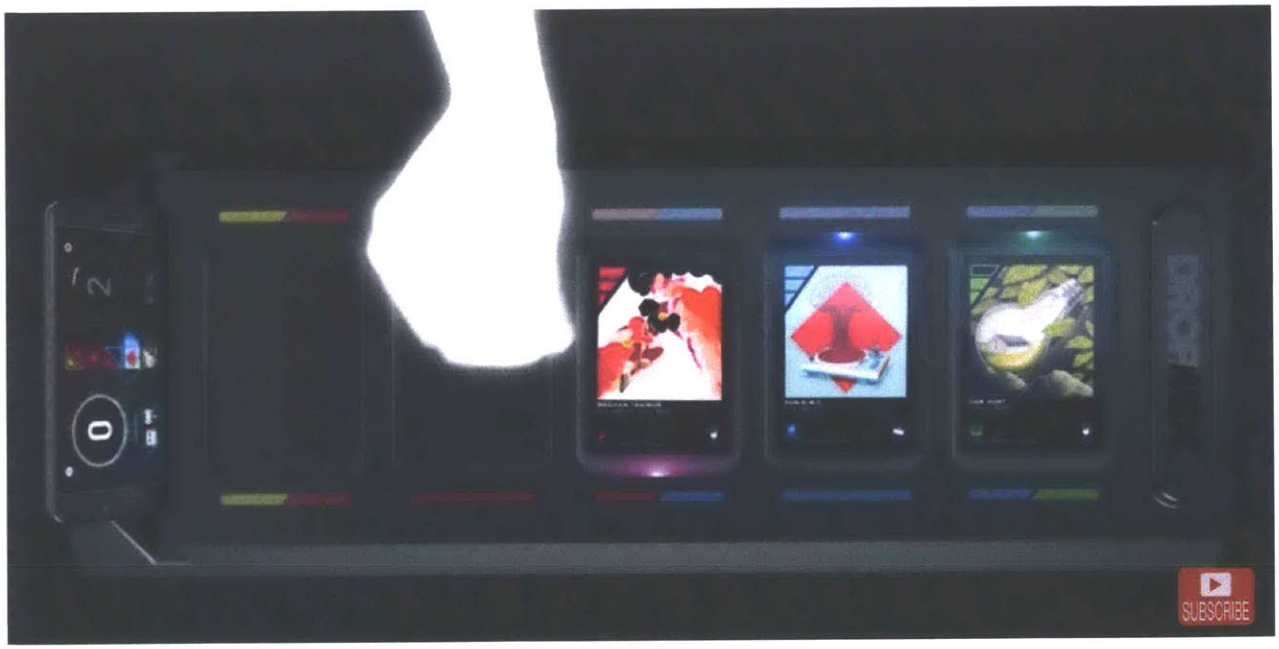


Fig 16. DropMix Harmonix game with RFID Playing Cards that represent rhythm sections of songs.

3.2.3 Todd Rundgren - No World Order Interactive Album

Fig 17. Todd Rundgren's interactive record No World Order

Todd Rundgren, an eclectic and wonderful rock artist, made a very early attempt in 1993 at interactive music. He created a composition called No World Order, where the listener, if they chose, could alter various parameters of the music. This made use of an interactive version on Philips' short-lived CD-i format, as well as the Macintosh and Windows operating systems. The interactive version included the ability to alter the playback of the music by selecting a pre-determined sequence by either Rundgren or one of his four guest producers - Don Was, Jerry Harrison, Hal Wilner and Bob Clearmountain. [25] The interface allowed the listener to control various aspects of music playback. If the user did nothing, the Rundgren mix would start and play through to the end. Compact Disc Interactive, or CD-i was developed by Phillips in 1991 but was discontinued in 1998.

The user was allowed to select in real time from the following options:

Program:	TR-i, Hal Wilner, Bob Clearmountain, Jerry Harrison, Don Was
Direction:	Very Fast Forward, Fast Forward, Forward, Hold, Reverse
Form:	Creative, Standard, Conservative
Tempo:	Fastest 132 BPM, Faster 126 BPM, Fast 120 BPM, Medium 110 BPM, Slow 100 BPM, Slower 92 BPM, Slowest 96 BPM
Mood:	Bright, Happy, Thoughtful, Sad, Dark
Mix:	Karaoke, Thick, Natural, Spacious, Sparse
Video:	Blank, Warp, Swarm, Title, Editor

3.2.4 McDonalds McTrax

The McTrax was developed by the interactive studio This Page Amsterdam. With paper printed using conductive ink, the McTrax contains a small battery and thin circuit board with 26 digital touchpoints offering in-house produced audio loops, synths and other musical effects. The users smartphone acts as the speaker and screen and the user can also record their own voice. [26] All the listener needs to do is put your phone on the mat, download an app and sync it to the placemat via Bluetooth. This concept is similar to DropMix in that in leverages the phone, but shows how the use of conducive inks can allow for links to relatively inexpensive packaging.

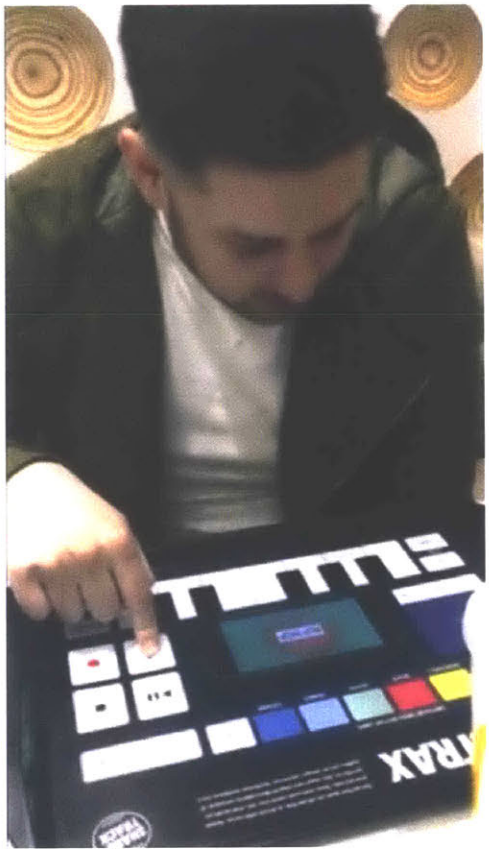


Figure 18. McTrax interactive DJ placemat created by This Page Amsterdam

4 Design and Implementation

The hardware and software platforms developed for two specific Sonic Artifacts are introduced and explained. Individual hardware modules and design considerations are discussed as well as the software and firmware code used. A one parameter Sonic Artifact with form similar to a cassette tape is presented along with a multi parameter Sonic Artifact that shares the form factor of a vinyl LP. Section 4.3 discusses the generalized approach taken and differentiates this approach from previous projects and products.

4.1 Hardware

Sonic Artifacts uses an embedded systems approach for its hardware. Localized processing allows for realtime synthesis and general purpose input and output. Several open source projects were utilized for hardware and software development, including a linux based single board computer, an open source micro controller, and a third party digital to analog converter. Together these three modules create a flexible hardware platform that is used in several versions of the Sonic Artifact, notably the Cassette Tape artifact and The Vinyl artifact. Inspiration is drawn from several prior art projects, notably the Critter and Guitari Organelle device as well as Moldover's Four Tracks project. The system is built around the Raspberry Pi Zero, a $5 flavor of the popular Raspberry Pi family. the RPi Zero's form factor is small enough to be embedded into packaging and powerful enough to generate reactive music in real time.

4.1.1 Single Board Linux Machine RPi Zero

The project requires realtime synthesis of audio as well as digital and analog input / output capability. This is achieved by leveraging the open source Raspberry Pi Zero single board project for audio processing. The Pi Zero was selected for both its size (65mm x 30mm) and speed characteristics (1GHz, Single-core CPU with 512MB RAM) Downsides of the module include its lack of a dedicated audio port and lack of an internet connection which larger models of the Raspberry Pi possess.[27]

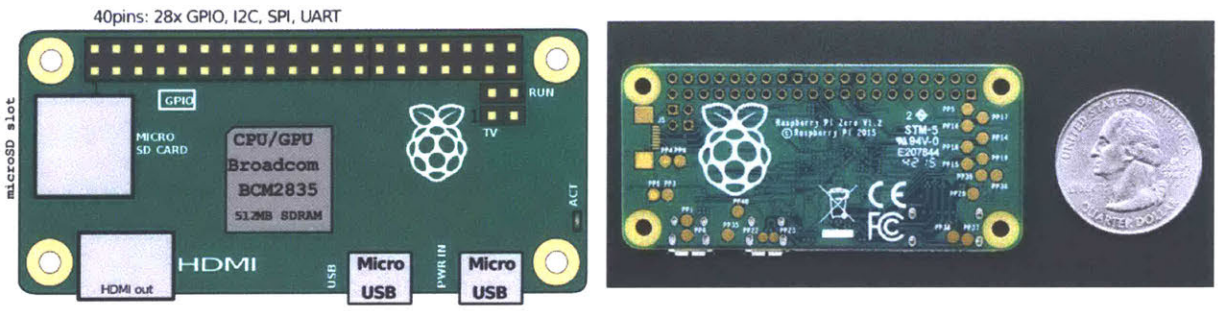


Figure 19. Raspberry Pi Zero Single Board Linux Machine

The Raspberry Pi Zero: Technical Specifications:

CPU: Broadcom BCM2835, which can run at up to 1GHz.

RAM: 512MB

Power: 5V, supplied via micro USB connector, drawing 160mA

Dimensions: 65mm x 30mm x 5mm

Video & Audio: 1080P HD video output. Audio output via mini-HDMI connector.

Storage: MicroSD card.

Operating System: Linux

4.1.2 Digital to Analog Converter

To achieve high quality audio a third party digital to analog converter is used. A Digital-to-Analog Converter or DAC is a device that converts digital audio information into an analog audio signal that can be sent to a headphone amp. In most cases, the user can not connect a headphone directly into a DAC. Thus, a headphone amp must serve as the intermediary step between a DAC and the listeners headphones or speaker.

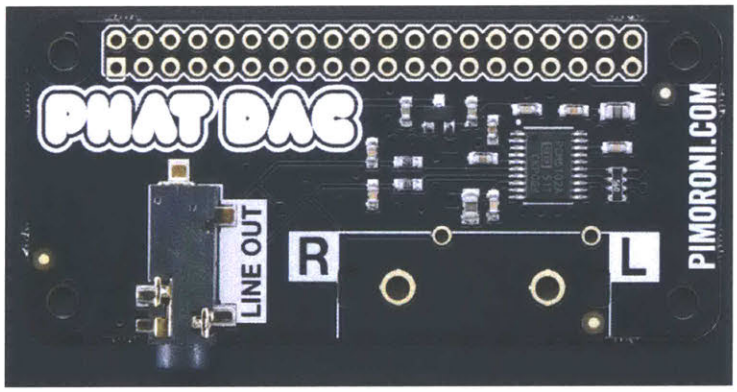
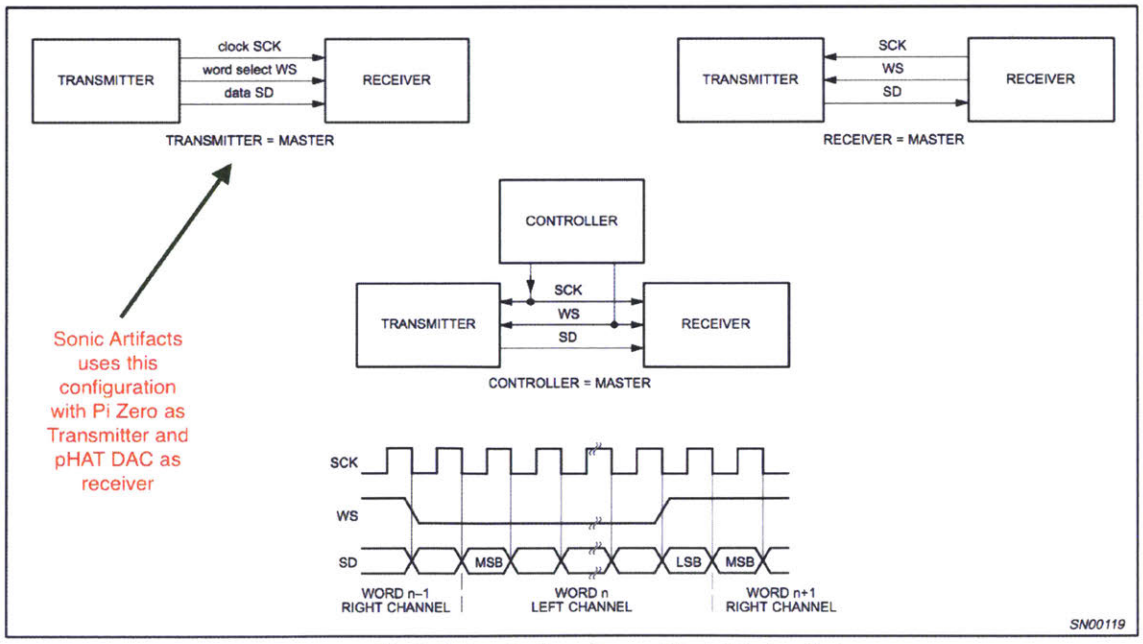


Figure 20. pHAT DAC Analog to Digital Converter

This project requires a high quality DAC that can interface with the Pi Zero. The Pimoroni pHAT DAC was chosen for its audio quality and ease of connection with the Pi Zero. The pHAT DAC generates a 24-bit audio at 192KHz and comes equipped with a line out stereo 1.8mm audio jack. The module is build around the PCM5102A chip which connects with the Raspberry Pi via the I²S communication protocol discussed next [28].

4.1.3 I²S Protocol

The I² S communicates between the Raspberry Pi and the DAC using the Inter-IC-Sound protocol or I²S protocol developed by Philips. This is a serial protocol developed especially for audio communication between integrated circuits which utilizes one dedicated serial data line SD and two clock lines, the continuous serial clock SCK and word select WS. The data bus only handles audio data. To minimize the number of pins required and to keep wiring simple, a 3-line serial bus is used consisting of a line for two time-multiplexed data channels, a word select line and a clock line. Since the transmitter and receiver have the same clock signal for data transmission, the transmitter as the master, has to generate the bit clock, word-select signal and data [29]. Figure 21 illustrates some simple system configurations and the basic interface timing.



Simple System Configurations and Basic Interface Timing

Figure 21. I2S Configuration

4.1.4 Arduino Pro Micro

The Raspberry Pi Zero is a decent tool for embedded engineers who desire quick development, but it lacks an on board analog to digital converter. One more drawback is all its IO's operate at a 3.3V level. To overcome this obstacle, Sonic Artifacts has a separate Atmel based 8-bit micro processor module to handle both digital and analog input and output. To get benefits of both the systems, we interface them using a serial connection. One benefit of using the

Arduino Pro Micro over other Arduino flavors is that it has an ATMega 32U4 running at 3.3V/8MHz on board. This chip has integrated USB 2.0 capability and the printed circuit board houses a micro USB connector for programming and communication, which alleviates the need for a separate USB to Serial Chip. In addition, this micro controller board has 9 x 10-bit ADC pins and 12 x Digital I/Os (5 are PWM capable). [30]

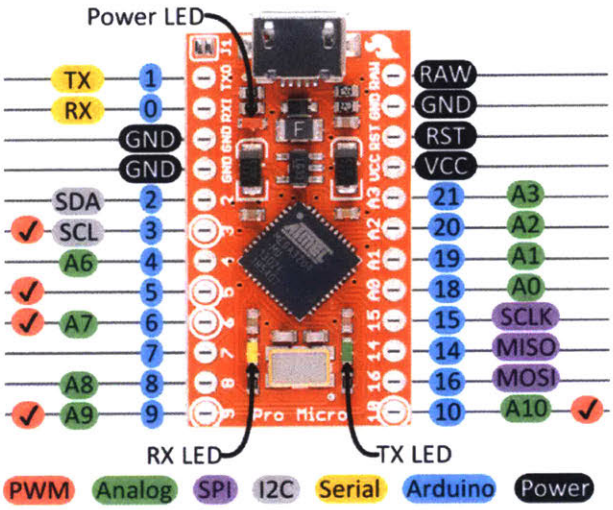


Figure 22. Arduino Pro Micro Pinout Diagram

4.1.5 Hardware System Architecture

The Raspberry Pi Zero and pHAT DAC combination handles music creation and audio output. A micro controller is needed to handle both digital and analog inputs and outputs. For this task, the 5V 8Mhz Arduino Pro Micro is chosen for its form factor, integrated USB and because of its relatively simple integration with the pure data software, which is explained in more detail in the software section.

These three components, Raspberry Pi Zero, pHAT DAC and Arduino pro micro join to form the platform upon which individual Sonic Artifacts can be created. The system diagram is shown in Fig. 23.

Sonic Artifacts Hardware System Architecture

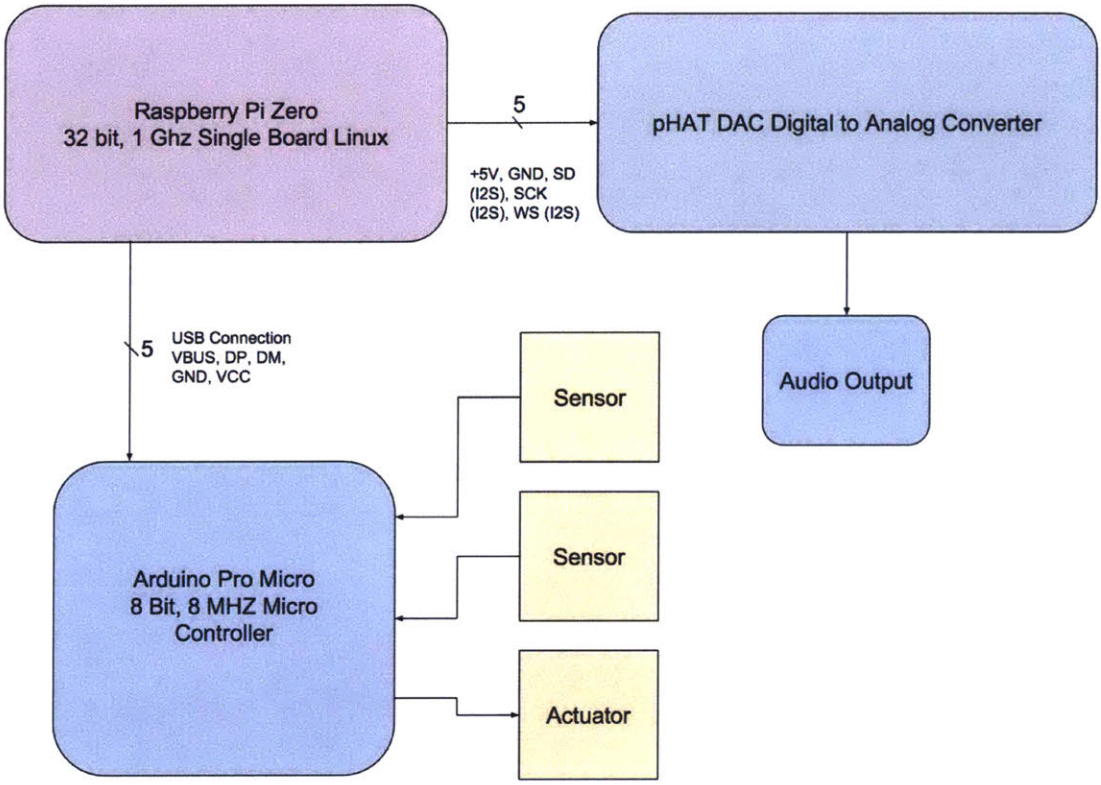


Figure 23. Hardware System Architecture

Connections between Raspberry Pi Zero and the pHAT DAC are as follows:

Pin Number	Pin Function
Pin 4	5V
Pin 6	Ground
Pin 12	GPIO 18 used for I2S
Pin 35	GPIO 35 used for I2S
Pin 40	GPIO 21 used for I2S

With corresponding description and connection photo here:

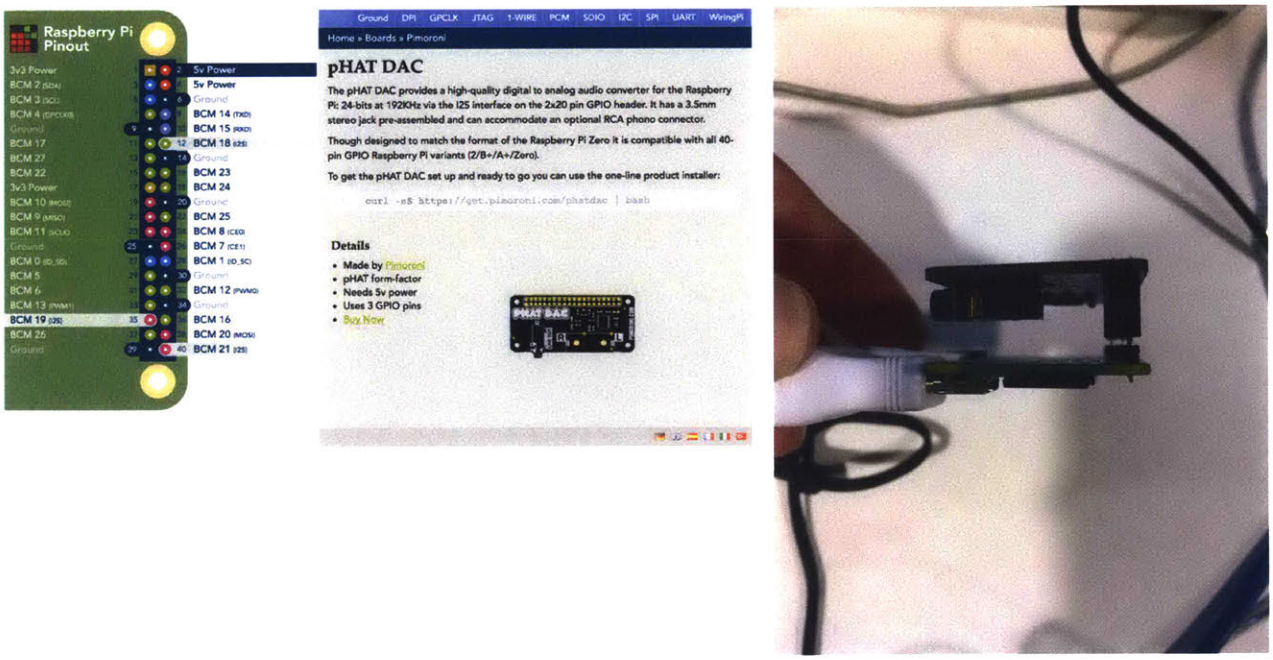


Figure 24. Connection Diagram and Photo for RPi to pHAT DAC

4.2 Software

4.2.1 Pure Data

A realtime audio environment is required which also has capabilities for hardware interaction. After evaluating several options including Processing, JavaScript, MaxMSP and Ableton/ Max4Live for early prototyping, PureData was selected as the environment for Sonic Artifacts because of its accessibility and availability. Code was written in either a Mac OS X or Linux environment and can run on the Raspberry Pi Zero with a serially connected micro controller. The Pure Data software is free to use.

PureData or Pd was developed at UCSD by Miller S. Puckette [31]. It is a real-time graphical programming environment for live interactive computer music. Pd works on SGI machines,

Microsoft Windows, Linux, and Mac OSX. Pd is copyrighted but is free for any reasonable purpose under the GNU GPL version 3. Pd enables musicians, visual artists, performers, researchers, and developers to create software graphically without writing lines of code. Pd is used to process and generate sound, video, 2D/3D graphics, and interface sensors, input devices, and MIDI. It can easily work over local and remote networks to integrate wearable technology, motor systems, lighting rigs, and other equipment. Pd is usable for learning basic multimedia processing and visual programming methods as well as for realizing complex systems for large-scale projects such as Sonic Artifacts.

Algorithmic functions are represented in Pd by visual boxes called objects placed within a patching window called a canvas. Data flow between objects are achieved through visual connectors called cords. Each object performs a specific task, which can vary in complexity from very low-level mathematical operations to complicated audio or video functions such as reverberation, FFT transformations, or video decoding. Objects include core Pd objects that perform math an signal transformations, external objects or externals (Pd objects compiled from C or C++), and user written abstractions which Pd loads as objects. [32]

4.2.2 PDuino Abstraction

Subpatches are used to encapsulate code into modules, and have input and return parameters, much like functions that are used in traditional text based programming. However, sometimes one uses code blocks repeatedly, in which case an abstraction is more convenient. PDuino is an abstraction that allows direct access to the input and output pins of an arduino connected to the system via a serial port [33]. Once the serial port connection is open, the program can immediately receive data from the arduino board. First, the user needs to enable sensor data to pass through arduino object and later separate the sensor data types. In the patch below, we focus on analog input sensors; therefore the [route] object only enables analog sensor type. The later route object separates the analog input data so

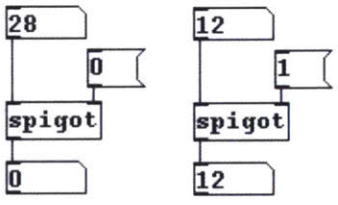


Figure 25. Spigot PD object with two inlets and one Outlet

that the patch can receive each sensor data in a separate number box. The spigot object acts as a gate that is either on or off. A zero input to the objects' right-most inlet means no data transfers through. A value of one means the object acts as a pass through all pass filter.

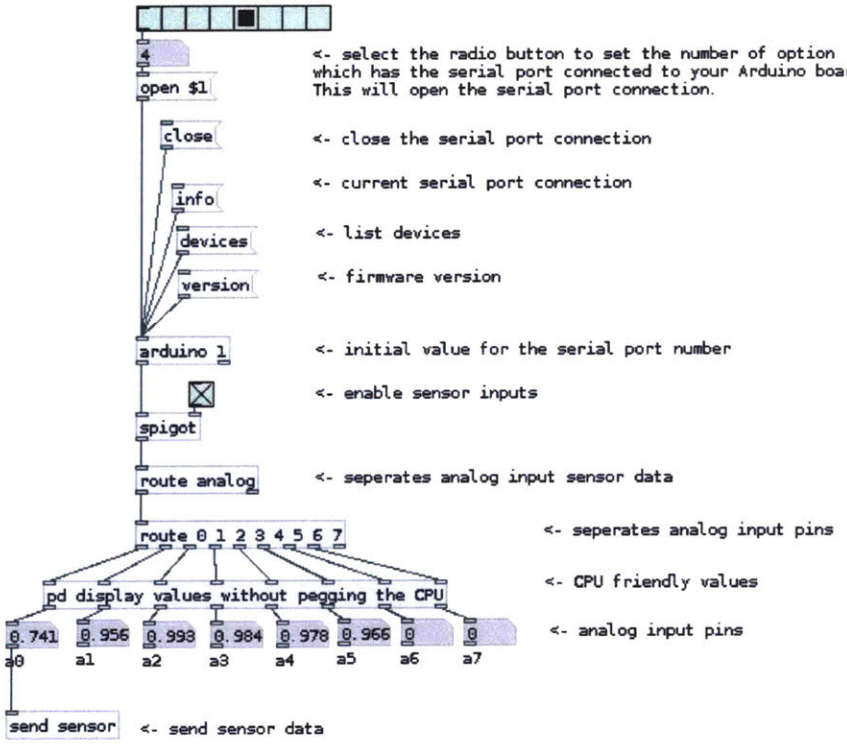


Figure 26. Spigot PD object with two inlets and one Outlet

We now present an implementation of the PDuino abstraction for an early Sonic Artifacts version. Left and right audio .wav files are opened and read into ram. These files are then triggered to play simultaneously using ~tabplay objects actuated by a bang message. The left channel volume is controlled by the Ao analog input of an arduino which is read by the PDuino abstraction and available to the patch in real time. This input was connected to a slider and a resistor voltage divider circuit.

Sonic Artifacts has a custom abstraction written specifically for it called arduino_magic that handles the connection between the raspberry pi and the arduino pro micro. Think of this

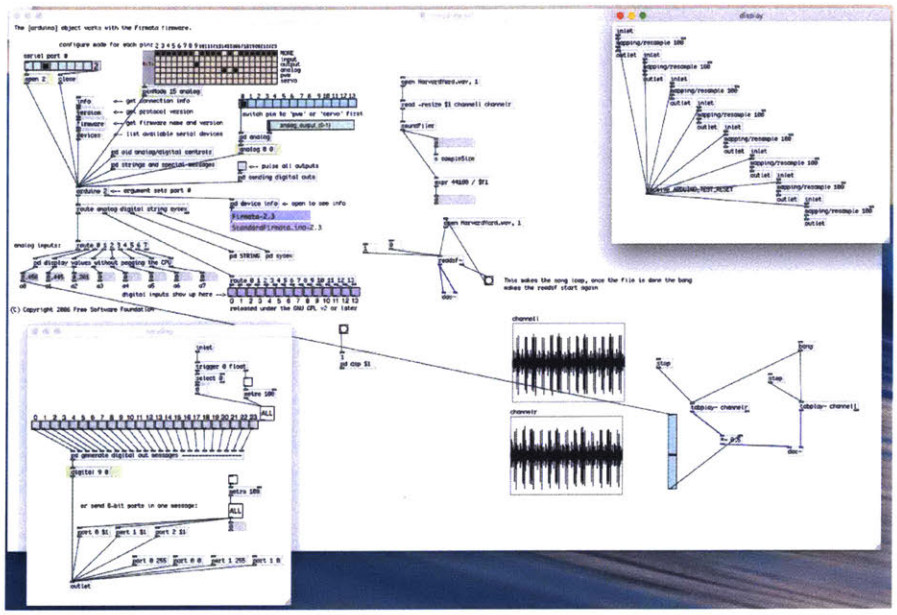


Figure 27. PDuino using an analog input to control left channel volume level

abstraction as a black box. All of the serial connectivity is handled automatically and there are 6 simple real time outlets that each output the contents of the analog input pins ao through a5 on the micro controller. The grey boxes are number boxes that allow those viewing the patch to see the values.

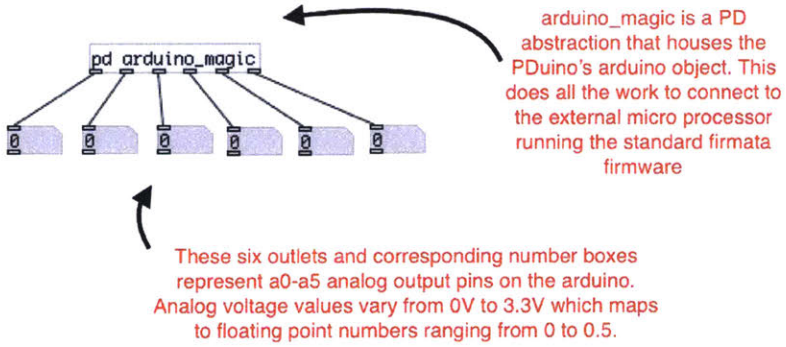


Figure 28. arduino_magic pd abstraction used in Sonic Artifacts code

4.2.3 RjDj Libraries

RjDj is the name of a project that has built out and open sources many abstractions for Pure Data that are specifically for building reactive music projects. Originally for mobile phone usage, Sonic Artifacts uses these building blocks to simplify its realtime audio tasks. An example scene is shown below with an expansion of the play loops abstraction to the right. The

playloops abstraction loads two wave files and delivers them both into the c_xfade object which accepts two tracks and a mixing value from 0 to 1. The power of RjDj can be seen when looking through the different levels of abstraction involved in this task. Let's look at the play loops abstraction next, which contains more RjDj abstractions. Here we see two wav files being passed to an abstraction called s_looper.

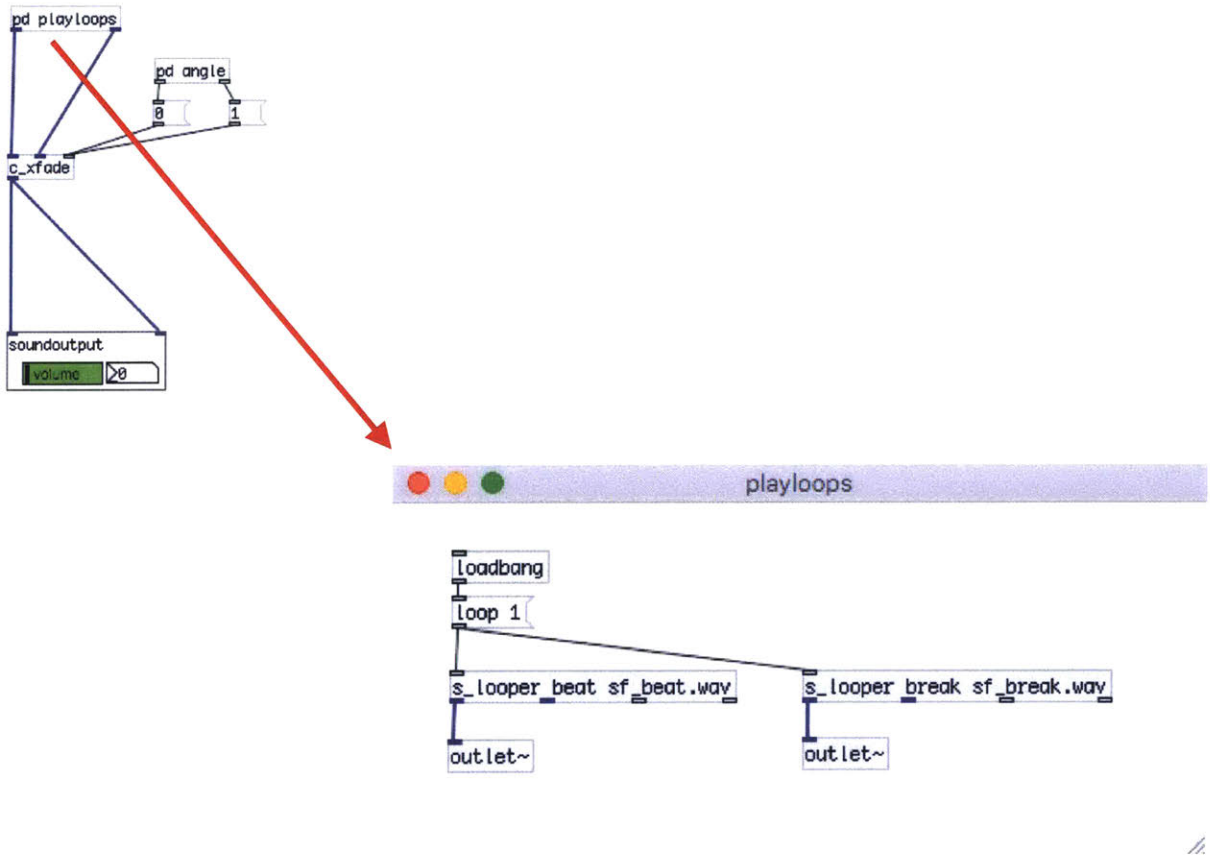


Figure 29. Example cross fade scene using RjDj

The abstractions go further and further. When we look into the s_looper RjDj abstraction we see more native pure data objects and even more RjDj abstractions. In general pure data signals flow inside abstractions from inlet to outlet. This patch allows the programmer to send other commands along with the wave file itself into the abstraction. For example, the programmer can send start times, fade times, split the track into several parts and more. In practice knowledge of this level of abstraction is not needed unless one is customizing. A well

documented Pure Data patch usually has documentation showing which commands are available. Figure 31 shows this documentation.

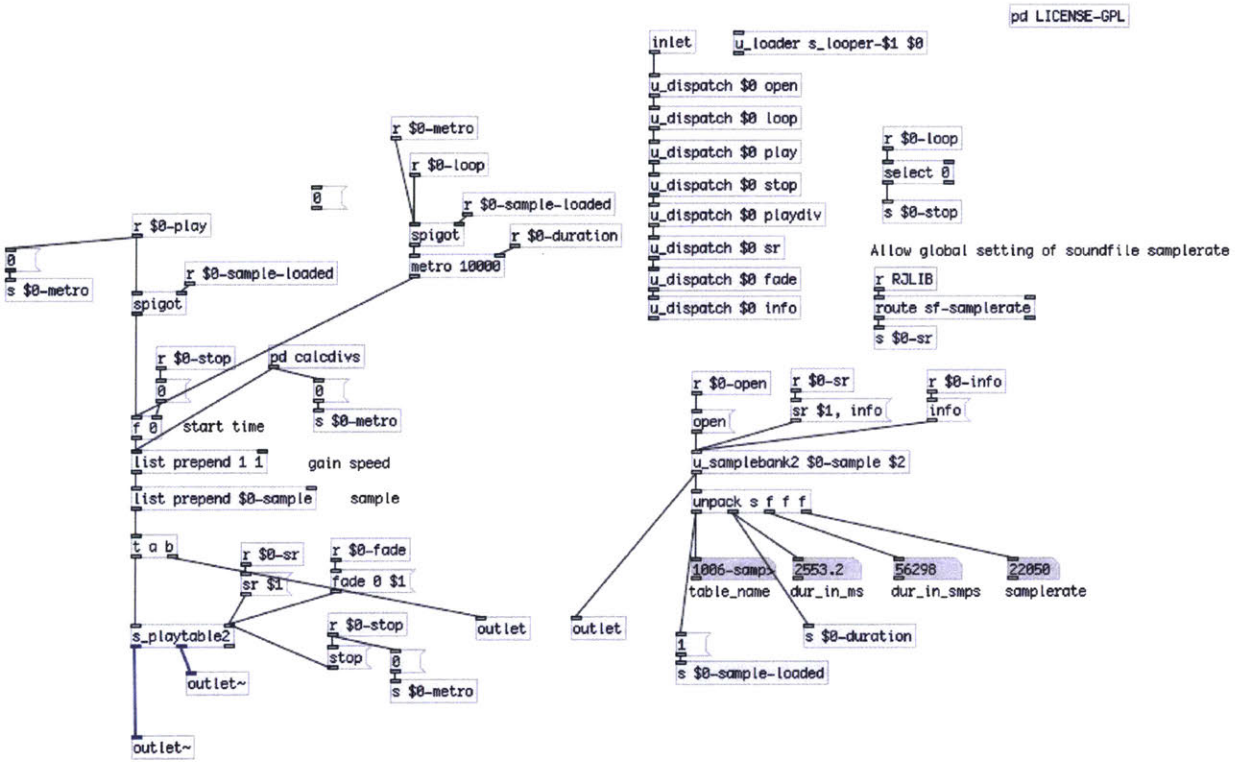


Figure 30. Inside the s_looper function

Keywords messages to the inlet of s_looper invokes different behaviors. For example, sending open, opens a file. Sending loop, loops a file. More complex operations like playdiv divides the file into equal length parts and starts playing.

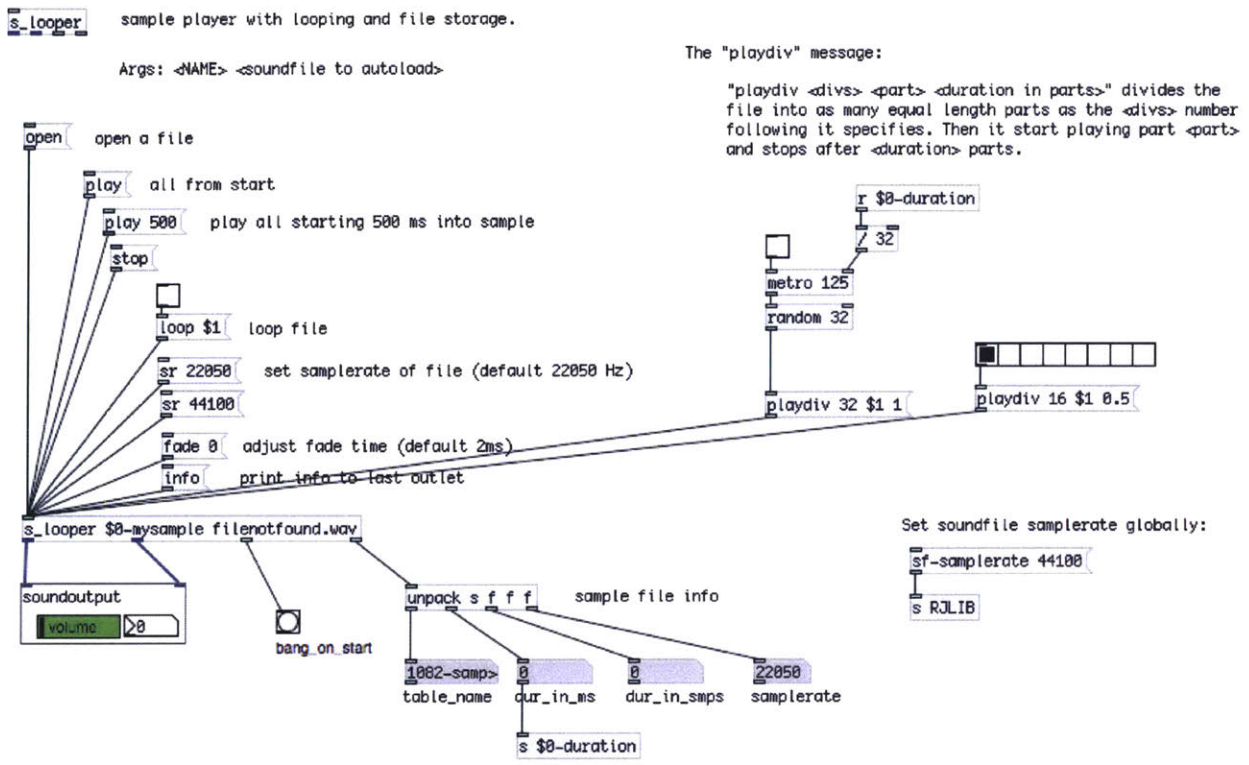


Figure 31. Built in s_looper Documentation

The RjDj has dozens of abstractions built specifically for reactive music applications. The abstractions are documented and a sample of what is available is seen to the right. Pure Data has many of its own built in audio abstractions, but RjDj is tailored specifically for creating a real time reactive audio experience.

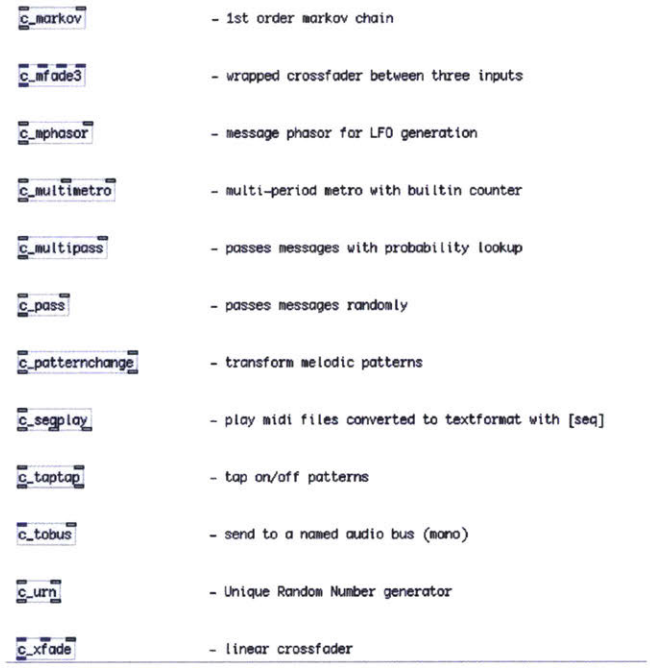


Figure 32. List of some of the RjDj Abstractions

4.2.4 Micro Controller and Firmware

We now discuss the micro controller portion of the sonic artifacts platform. A micro controller is a computer present in a single integrated circuit which is dedicated to perform one task and execute one specific application. It contains memory, programmable input/output peripherals as well a processor. In our application the micro controller is dedicated to handling the input and output. In the arduino environment, firmware programs are called sketches and are uploaded to the microprocessor. Once uploaded, these sketches loop as long as the voltage is provided and the reset button is not pressed. These sketches tell the arduino what pins are available, and programs their functionality. For this project, a sketch called Firmata is used [34]. Firmata is a generic protocol for communicating with micro controllers from software on a host computer. In the sonic artifacts instance, the host computer is the raspberry pi. For this application, the firmware reports the values of the pins. It can also be used to actuate pins as well via control from the host computer. This firmware code is written in C. A sample is provided below.

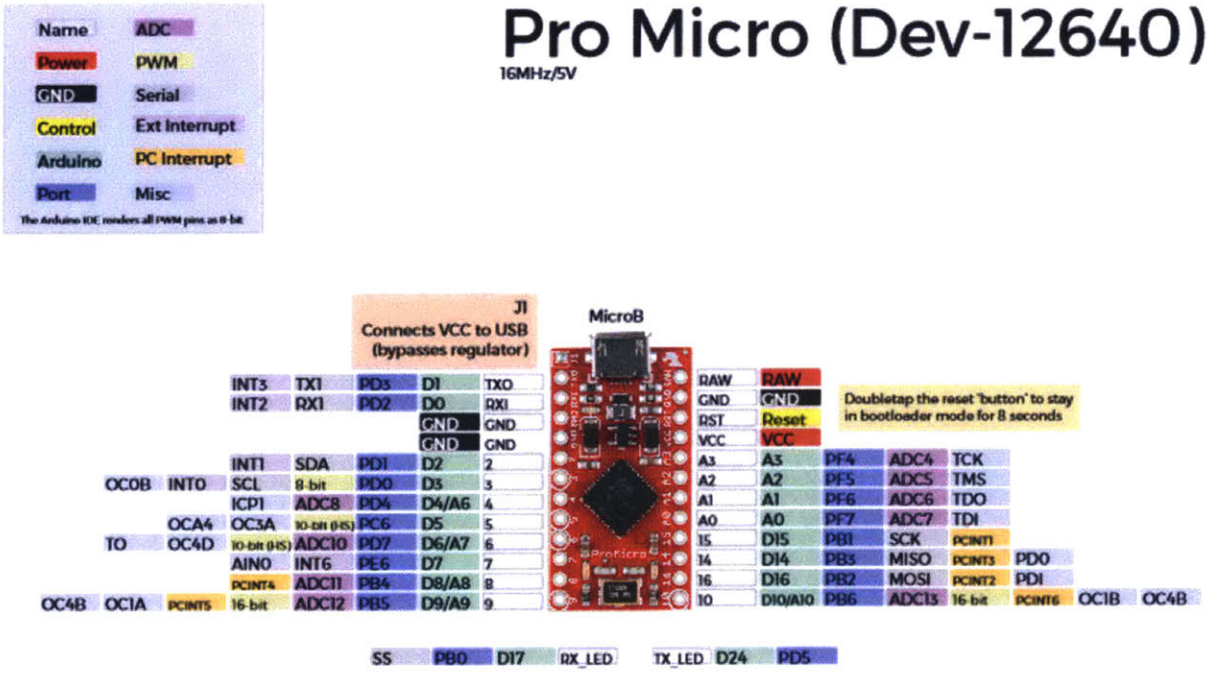


Figure 33. Pin Mapping for the Arduino Micro

Once the arduino is powered and running the firmata standard sketch, then the PDuino Pure Data abstraction can communicate directly with the micro controller. This connectivity allows the Pure Data sketch to control the board in software. The PDuino sketch allows the Pure Data programmer to decide whether pins are inputs or output and allows the patch to actuate pins with digital signals or pulse width modulated signals, which is a method to simulate analog output voltages. The PDuino abstraction can also assign pins as inputs, used to read sensor values. I²C peripheral communication is also possible.

```
/*==============================================================================
 * LOOP()
 *============================================================================*/
void loop()
{
  byte pin, analogPin;

  /* DIGITALREAD - as fast as possible, check for changes and output them to the
   * FTDI buffer using Serial.print()  */
  checkDigitalInputs();

  /* STREAMREAD - processing incoming messagse as soon as possible, while still
   * checking digital inputs.  */
  while (Firmata.available())
    Firmata.processInput();

  // TODO - ensure that Stream buffer doesn't go over 60 bytes

  currentMillis = millis();
  if (currentMillis - previousMillis > samplingInterval) {
    previousMillis += samplingInterval;
    /* ANALOGREAD - do all analogReads() at the configured sampling interval */
    for (pin = 0; pin < TOTAL_PINS; pin++) {
      if (IS_PIN_ANALOG(pin) && Firmata.getPinMode(pin) == PIN_MODE_ANALOG) {
        analogPin = PIN_TO_ANALOG(pin);
        if (analogInputsToReport & (1 << analogPin)) {
          Firmata.sendAnalog(analogPin, analogRead(analogPin));
        }
      }
    }
    // report i2c data for all device with read continuous mode enabled
    if (queryIndex > -1) {
      for (byte i = 0; i < queryIndex + 1; i++) {
        readAndReportData(query[i].addr, query[i].reg, query[i].bytes, query[i].stopTX);
      }
    }
  }

#ifdef FIRMATA_SERIAL_FEATURE
  serialFeature.update();
#endif
}
```

Figure 34. Main Firmata Firmware loop

4.3 Artifact Song Architecture

Sonic Artifacts is differentiated from previous work for several reasons. First it affords for interaction between users and individual stem tracks in the physical realm. For example, Moldover's projects discussed in section 3.1.3 simply adds a microphone and audio effect circuit that is not sonically linked to the recorded audio other than it has potential to be an instrument that also actuates during playback. Sonic Artifacts, however connects the hardware experience to each song as it plays and allows for multiple types of both sensing and actuation in real time. It does this through a process by which each song is separated into its constituent parts, called stem tracks. This process creates several independent communication links throughout a given song. Figure 35 shows this process in a hypothetical song architecture.

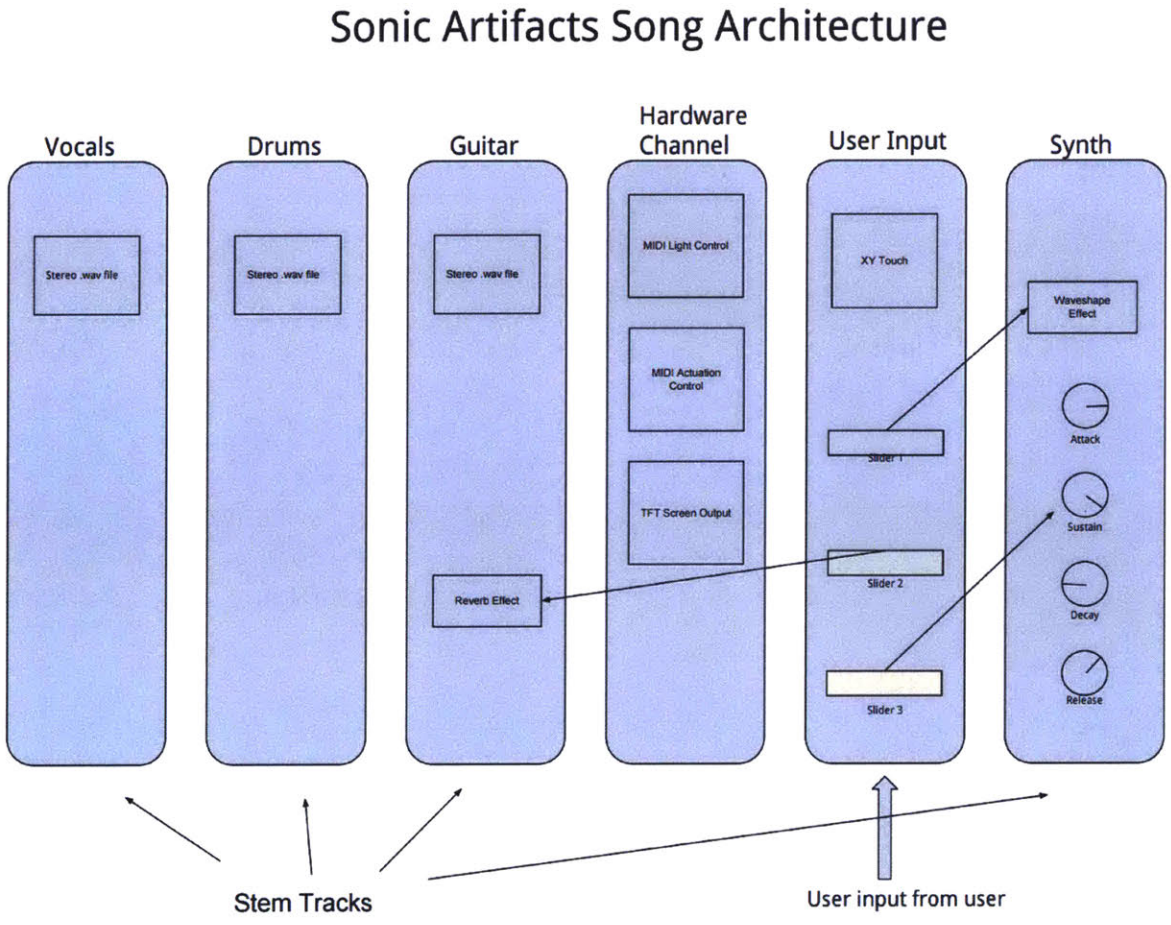


Figure 35. User Input access to stems

Starting from the left of the figure, the first three vertical columns and the farthest right vertical column represent musical tracks, or stems, when combined in superposition, create a song. Vocals and drums are traditional static recordings, such as .WAV files of a particular performance. The guitar track is also a recording, but has a reverb effect associated with it that is being controlled in real time by the user input of the Sonic Artifact, in this case slider2 located somewhere on the artifact, in a place accessible to the listener. Reverb, an audio effect which has many styles, artificially adds echo to a recorded sound, adding the impression of a different sized room for example. If the user does not manipulate slider2, then the guitar track plays as recorded. If the user decides to manipulate the slider2 during playback, the reverb effects parameters change all while the other stem tracks stay the same. Typical reverb parameters like room size or wet/dry mix are available for exploration by the user during playback. More complex interactions are possible as well. For example, both slider1 and slider3 are linked to a synthesizer stem track. In this song, the note patterns may have already been recorded, what changes is the timbre of the sound. Slider1 is controlling the wave shape of an oscillator that ranges from a pure sign wave to a pure triangle wave. Slider3 is linked to the sustain parameter, which determines how long a particular note is held before the decay phase initiates. Lastly the hardware channel is available for actuation on the Sonic Artifact. Real time light control, and screen output allow the user to receive visual as well as audio feedback from the changes they make in the audio.

The parameter sweep intervals, precise effects, and locations when interaction are possible are determined by the musician and the engineer. A study was conducted polling musicians on whether they would like this type of interaction associated with their music and 75.6% of musicians indicated that they are interested in working with an interactive version of their music. See section 8 for more details and results of the survey.

This work is further differentiated by previous work such as the RjDj platform, discussed in section 3.2.1, platform because it resides in physical space and not in the browser or in an app. The hardware interaction is key to the experience. Figure 36 compares traditional audio to Sonic Artifacts audio. The medium of music is augmented on a song by song basis, with

interactions defined by the artist, this is a novel approach and potentially a new way to distribute and experience music.

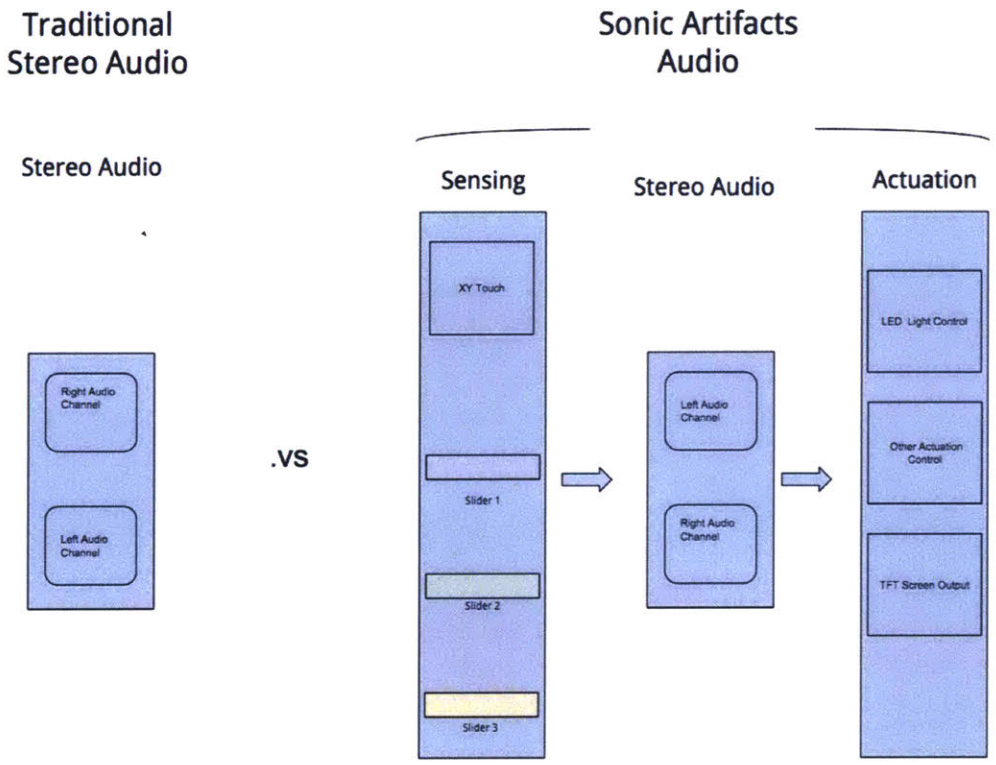


Figure 36. Comparing Traditional Audio with Sonic Artifacts Audio

4.4 Vinyl Artifact

4.4.1 Vinyl Artifact Hardware

The vinyl sonic artifact augments the cover art and adds controls for the listener to change the music they hear in realtime. Individual access to the stem or instrument tracks allows custom mixes and effects to be made, creating a unique experience during each listen. This artifact looks like a traditional vinyl sleeve but has built in touch linear potentiometers built into the cover. The controls act as slider, much like on a mixing console except they are flat and flexible.

Figure 37. Vinyl Artifact Cover

Spectra Symbol soft potentiometers are pressure sensitive yet flexible and are used for user input. They can work with the aesthetics of the associated album art, eventually being situated underneath the printed illustrations. These sensors form one half of a voltage divider circuit with another static 10k resistor and are then read by the analog pins of the micro controller. The radial soft potentiometer are functionally equivalent to the linear soft pots but allow for a different style of user interaction.

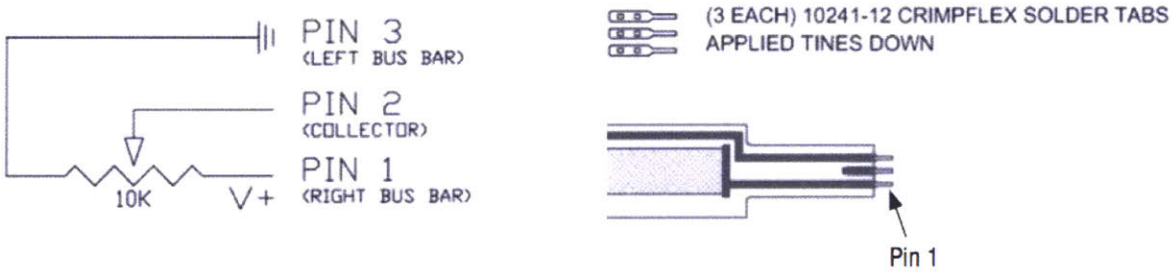


Figure 38. Pinout and Internal Structure of Soft Pot

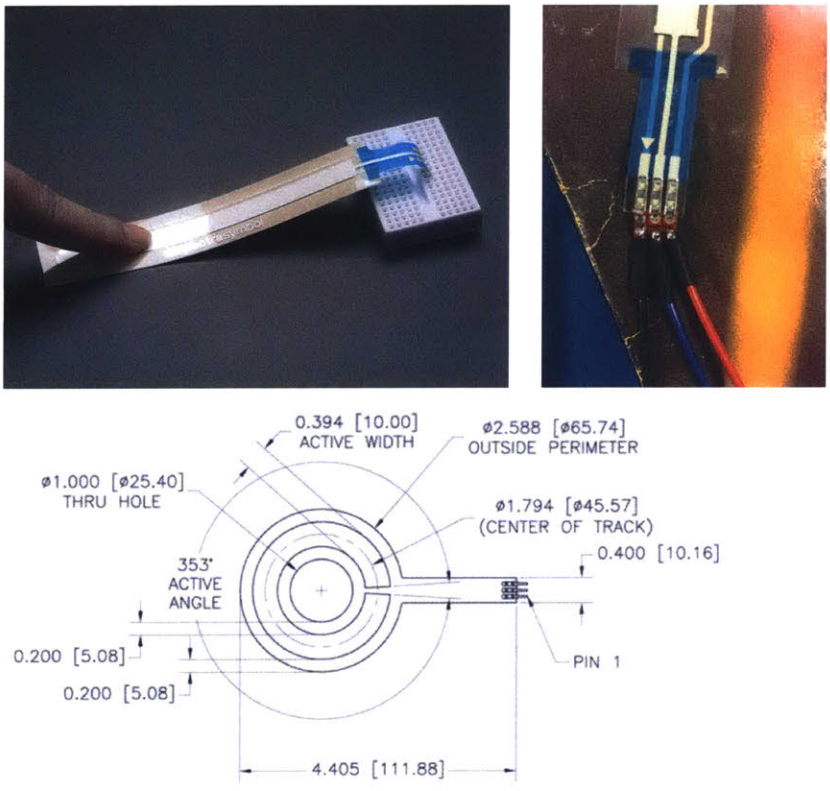


Figure 39. Radial Soft Pot is a 10k linear potentiometer

Here is a lab bench setup running the entire system on the raspberry pi zero. Development was done with a regular computer setup including keyboard mouse and HDMI monitor. This device was tested with multiple listeners at the MIT Media Lab members event where the listener got to mix one of the electric guitar volume levels in real time.

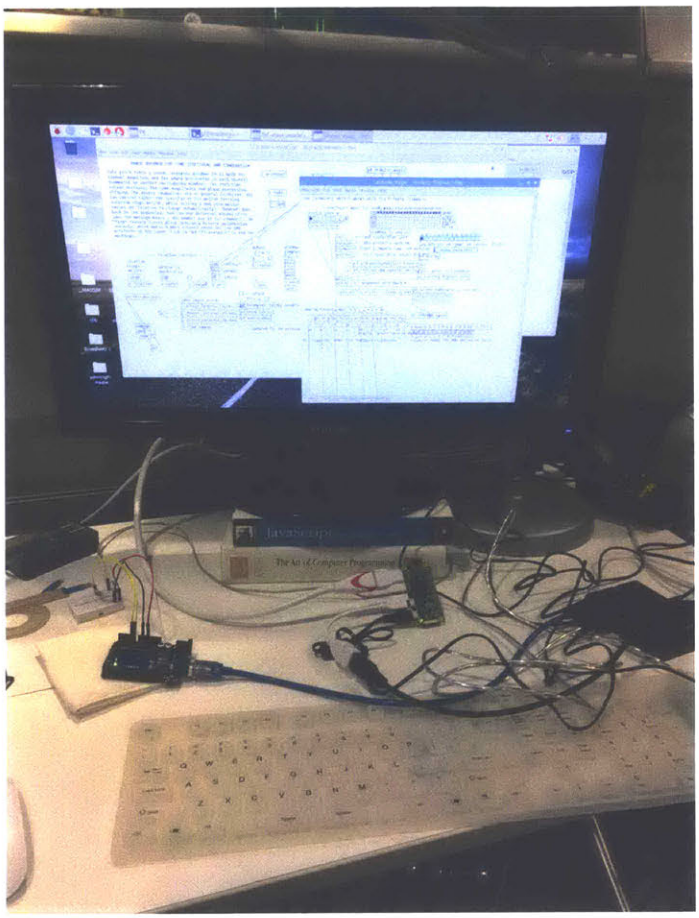


Figure 40. Lab bench prototype with Pi Zero, Arduino and sensors

4.4.2. Vinyl Artifact Software

The prototype is constructed augmenting a recorded song. The song chosen is called Wild Machines and was recorded by engineer and producer Colin Stewart and the Hive Studios in Vancouver British Columbia, Canada in 2010. Stewart sent all of the individual wave files to be reconstructed. In Pure Data the files are loaded and played simultaneously. For example one track has just cymbals, another has just electric rhythm guitar, and often times one live instrument has multiple associated tracks, which correspond to different microphones used. The method is then used to allow user control and manipulation of each individual track during playback in a way that is still pleasing to listen to and still maintains the integrity of the composition [35]. This created experience could be as simple as turning up or down guitar volume during sections, and can be as complex as adding digital audio effects like reverb and delay to vocal lines, individual drums, etc. If the listener wanted to hear what the vocals sounded like in a cavern or a stadium while maintaining the same backing music, this would be possible. For this example there are over 40 stem tracks.

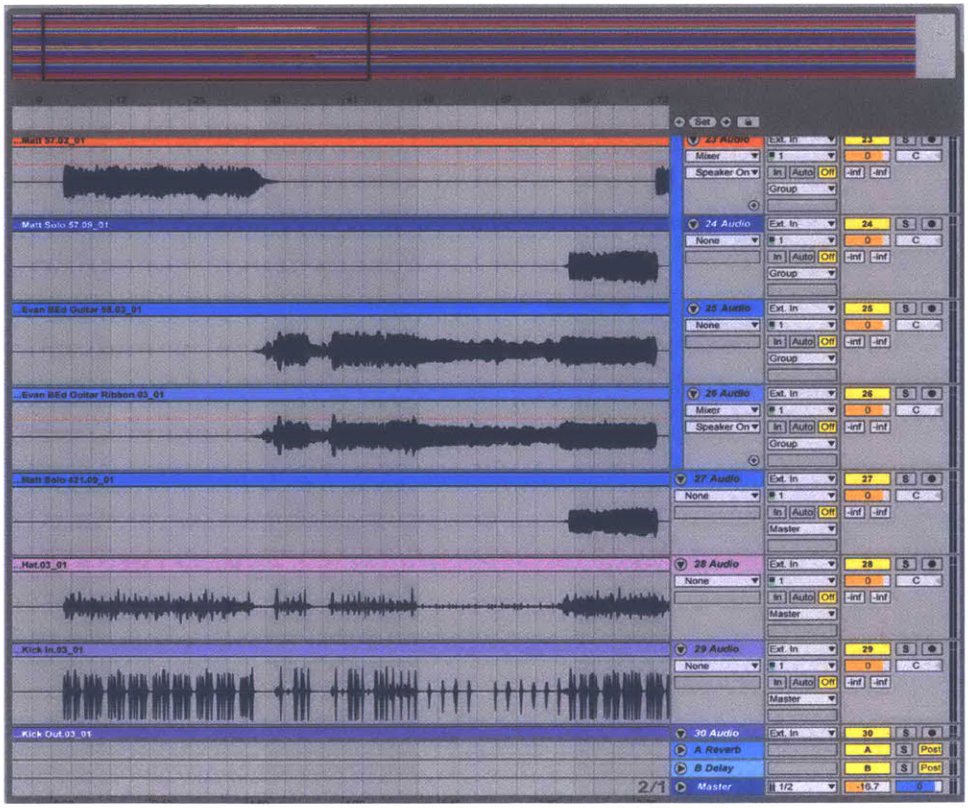


Figure 41. Section of Wild Machines Track showing Stems

In many instances an instrument is recorded with several microphones, all of which have their own track. By allowing the Sonic Artifact to have access to these individual files, the designer of the interaction can create a myriad of different types of interactions based upon volume level, omission, creation of new sounds as well as effecting existing sounds.

The software developed integrates RjDJ, PDuino and Firmata firmware to create the experience. The loadbang, delay 100, pd dsp 1 section automatically starts audio playback. Since the artifact will not have a screen, it must play automatically upon power up.

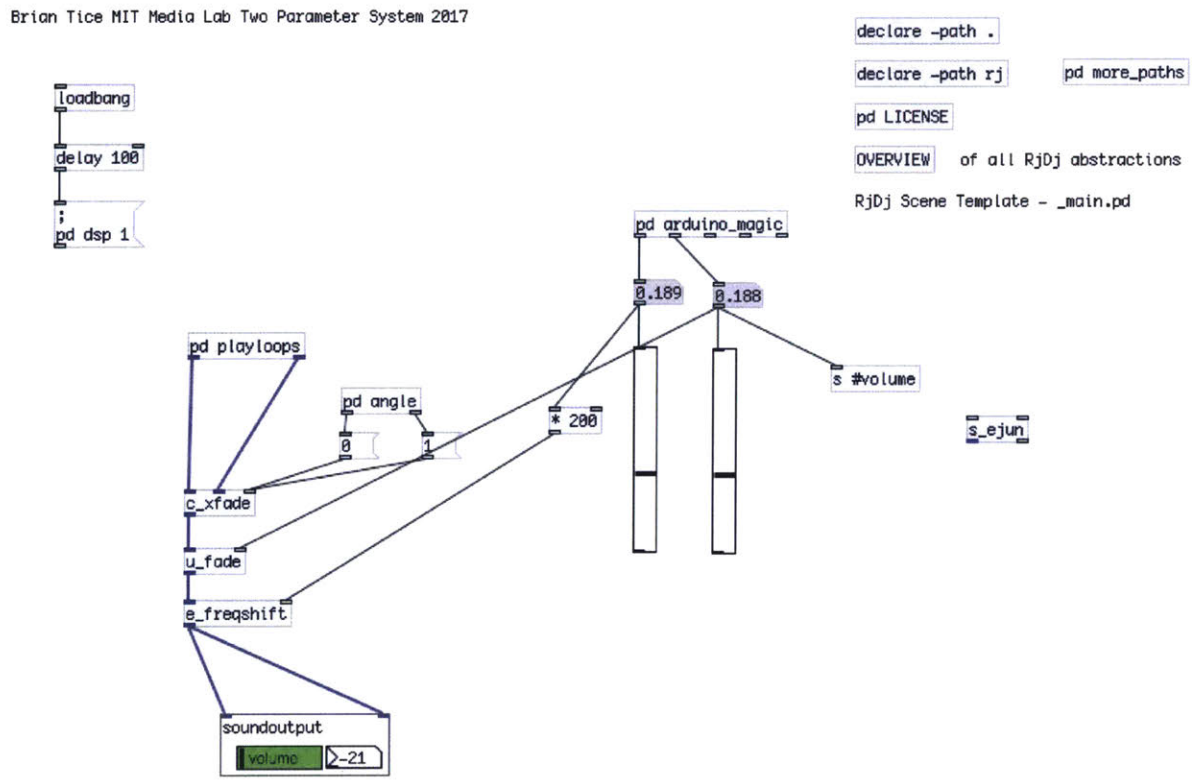


Figure 42. Pure Data Patch for Wild Machines Vinyl Artifact

4.5 Cassette Artifact

4.5.1 Cassette Artifact Hardware

In collaboration with Grace Leslie a postdoc in the Affective Computing group at MIT Media Lab, a cassette tape artifact was manufactured. The tape has mock magnetic tape which is actually stretchable conductive fabric connected via conductive thread to the Sonic Artifacts hardware system. This was a 1 parameter system. As the resistance of the fabric changes, the pitch of a record voice changes while still maintaining the original length of the sound in time. All of the electronics are housed in a cassette tape form factor for physical distribution. First a 3d CAD model of the cassette tape was created and then 3d printed using a Form Labs resin based 3d printer.

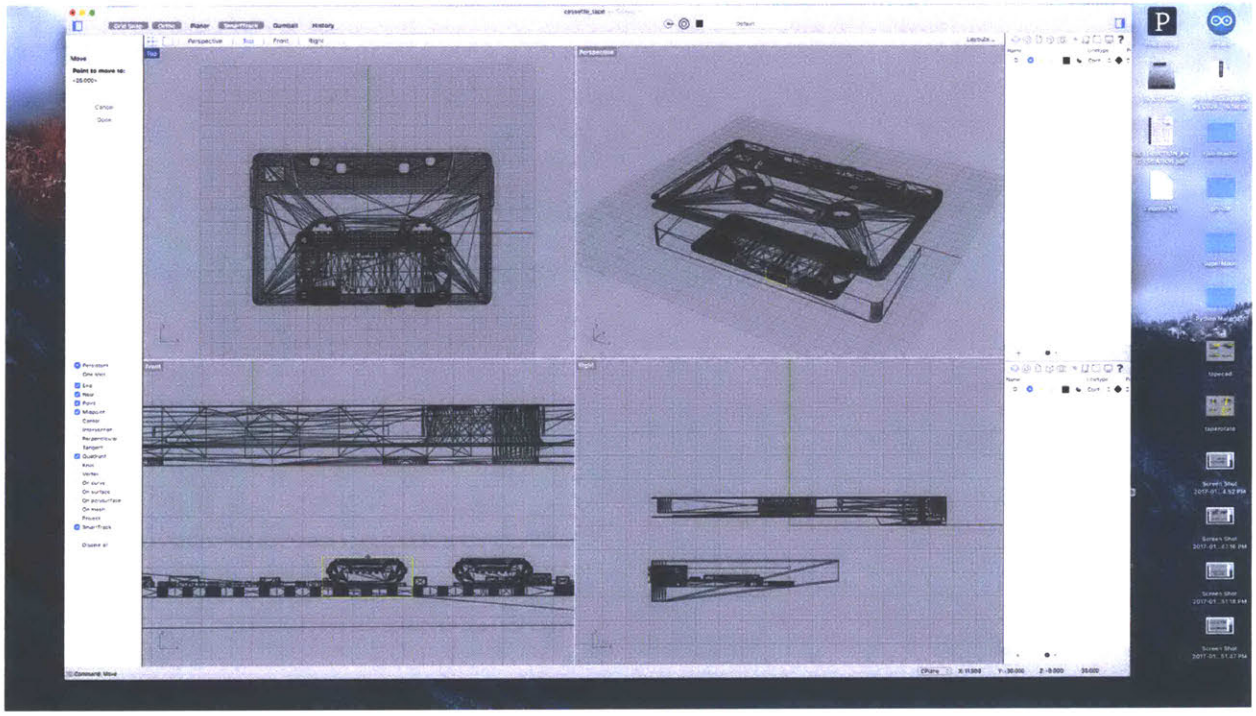


Figure 43. Section of Wild Machines Track showing Stems

The model was then printed:

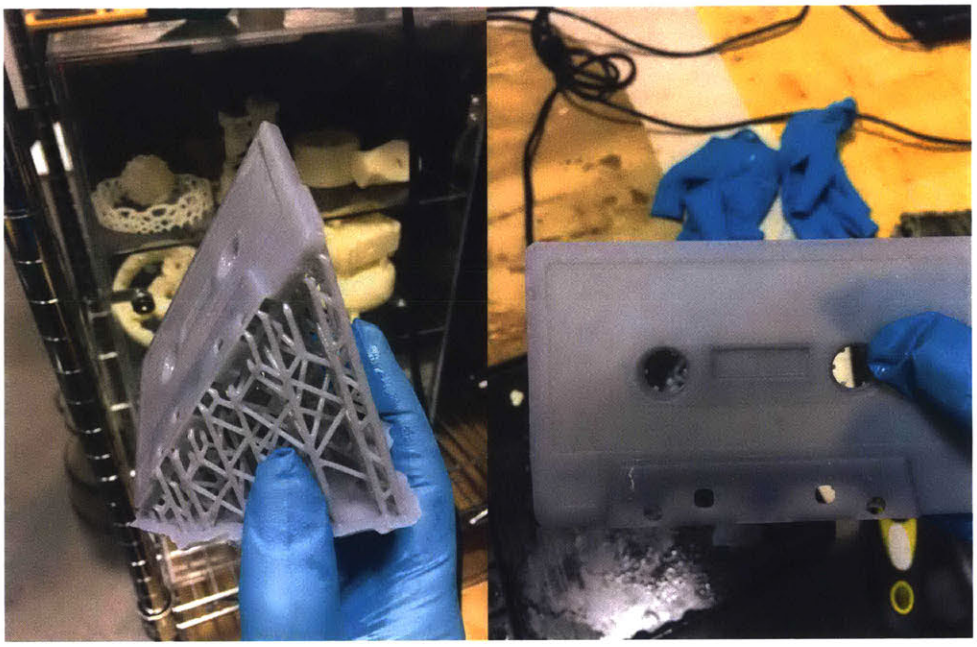


Figure 44. Printed Cassette Tape Artifact

Conductive thread and resistive stretchable fabric was used to simulate the magnetic tape. The idea being the stretching of the fabric would map to a pitch shift in the vocals of the music. Grace's music uses flutes and brainwaves, she wanted the listener to feel in tune with what it feels like to play a flute note for a long length of time, which is dependent on the breath, and how long one can maintain the note.

Figure 45. Stretchable Resistive Fabric and Conductive Thread

Features of resistive fabric:

Filament Blend: Nylon/Spandex (72/28)

Thickness: ~15 mils (0.38mm)

Sheet Size: 12"x13" (304.8 x 330.2mm)

Surface Resistivity: Tunable in the range of 10E4 to 10E7 Ohm/sq.

Mass per Unit Area: 4.8 oz/sq.yd.

Elongation: warp 198–248, warp recovery 85%

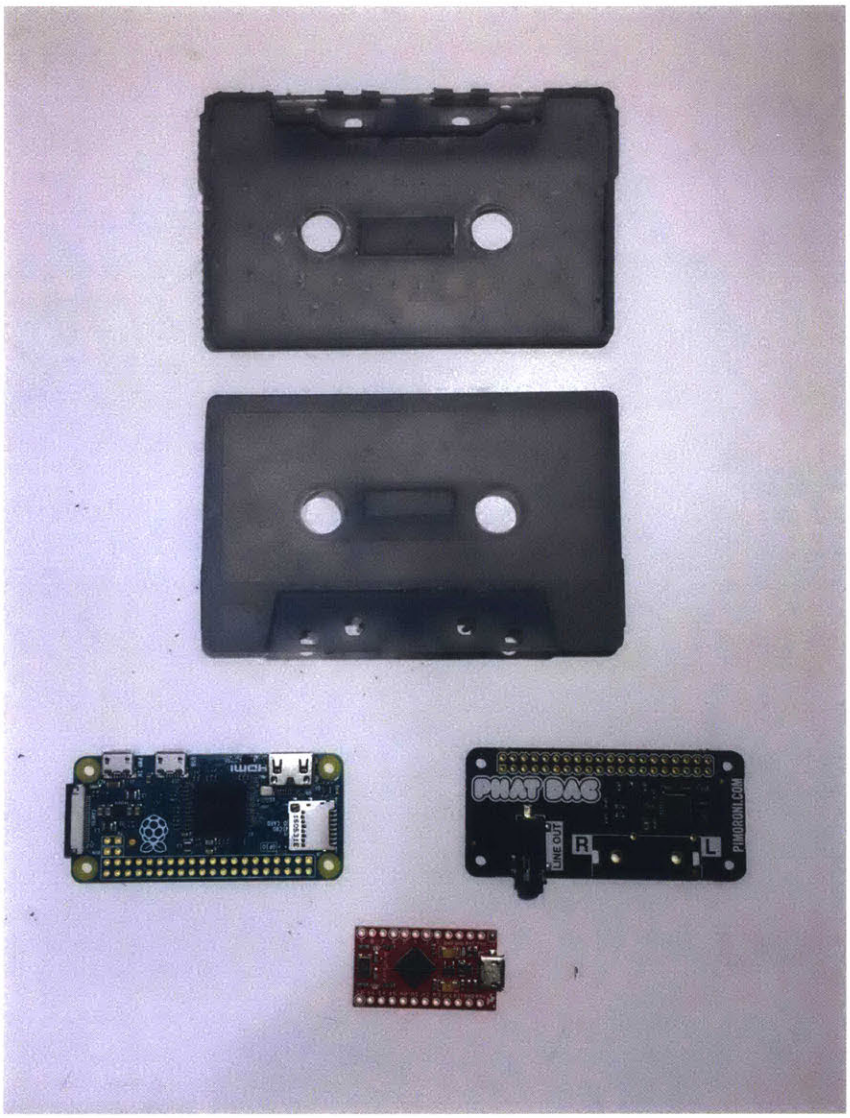


Figure 46. Casette Artifact Components

4.5.2 Cassette Artifact Software

Similar to the Vinyl Artifact, the arduino_magic abstraction polls the analog pins of the micro controller. This is then fed through a low pass filter to suppress some of the noise inherent in the fabric chasing shape.

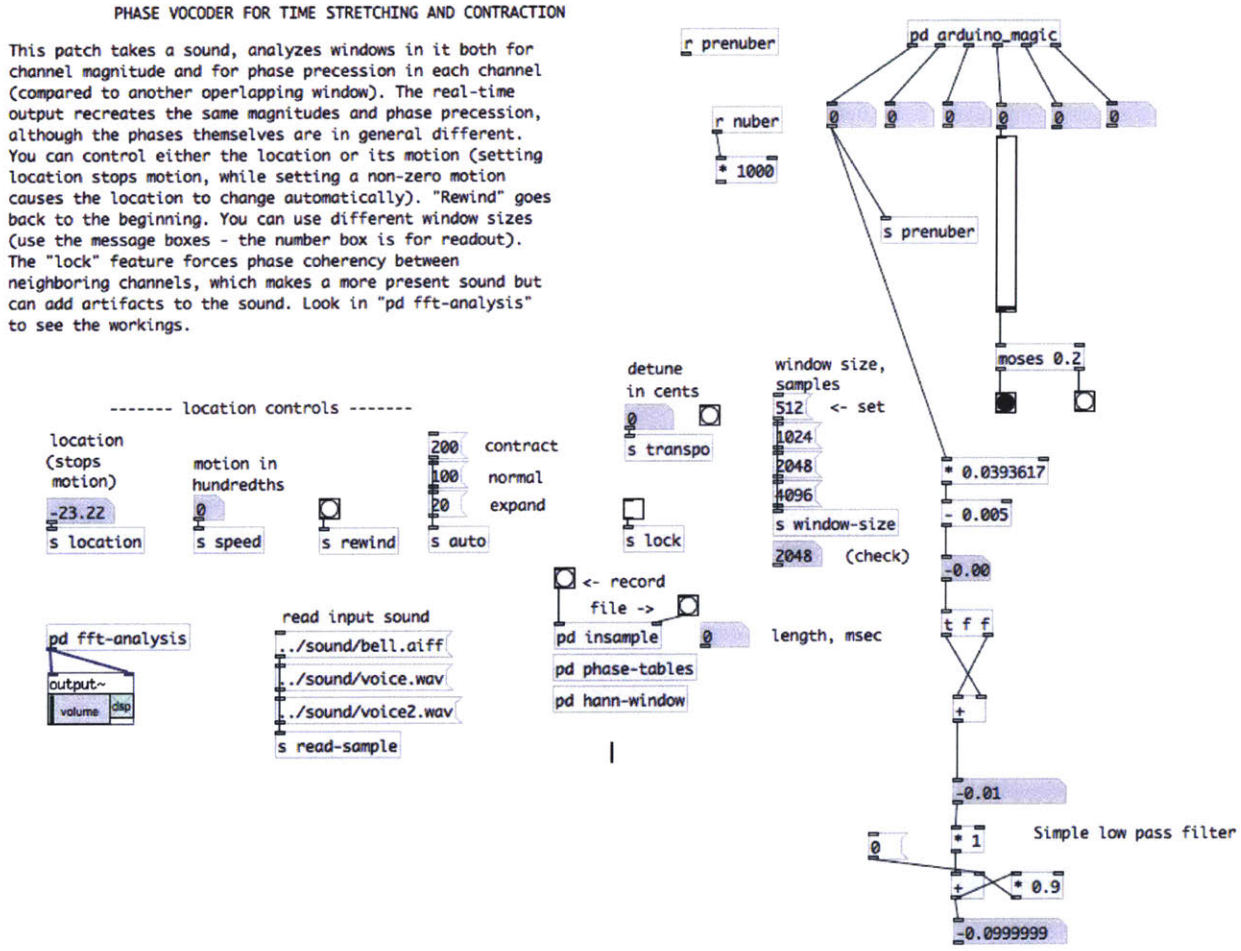


Figure 47. Casette Artifact Pure Data Patch

5 Conclusion

Research of prior art in the fields of generative and reactive music inspire new types of physical music merchandise. Sonic Artifacts synthesize ideas from projects like Moldover's four track and RjDj's Pure Data library and add the element of stem track access into the physical space. These artifacts represent the music and give the artist new lines of communication with their audience. Significance of music as a physical object is restored, allowing for exploration and active participation by the user. A study conducted confirms that musicians are receptive to the idea of allowing access to stem tracks and affording opportunities for the listener to interact with the composition. When Sonic Artifacts is deployed, ultimately the audience will decide if adding interaction and custom aesthetics into music packaging makes for a better experience as opposed to traditional stereo music [37]. Vinyl Records cost about $20 to $30 dollars USD. To compare, a Sonic Artifact will initially cost $50-$80 dollars depending on the types of interactions used.

Fig 48. Growing LP Sales in the USA

6 Future Work

Further research into varying levels of difficulty or complexity within a given song will eventually lead into a limited deployment in the field. A band will sell Sonic Artifacts at their merchandise table after a concert. The Sonic Artifact will represent a single song. Along with the purchase a questionnaire link with incentive to participate will be distributed to learn as much as possible from their interactions. Custom printed circuit boards and further refinement of electronics will eventually lead to one single hardware module that will be embedded in the artifacts.

Integration with smartphones will be explored. As was seen in the McTrax example, smartphones can be leveraged for their computing power, allowing the Sonic Artifact product to be lower in cost. Eventually, a collaboration with existing streaming and audio online platforms will be explored. Research into letting the users upload and share their personalized versions of a song will be explored.

7 Survey and Evaluations

A survey was conducted among musicians and music taste makers to introduce the idea of a sonic artifact and to gauge whether or not people understood and resonated with the idea. Sample size was 42. Summary and results to follow.

Summary of findings:

After surveying musicians and tastemakers we have been given some initial data to work with from the musicians perspective. Several patterns emerge, with majority of musicians at least open to the idea of a Sonic Artifact.

Notably:

75.6% of musicians were at least interested in having their recorded songs be interactive, with 57.9% of them definitely interested.

Summary of Musician Survey Results:

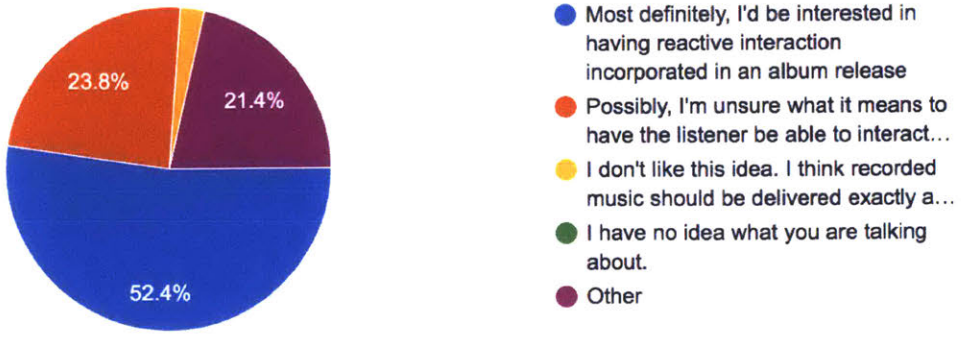
- Most musicians like the idea of interactive merchandise (57.9%)

- (71.1%) of Musicians liked the idea of allowing individual tracks to be open

- (75.6%) like the idea of limited access to the composition itself

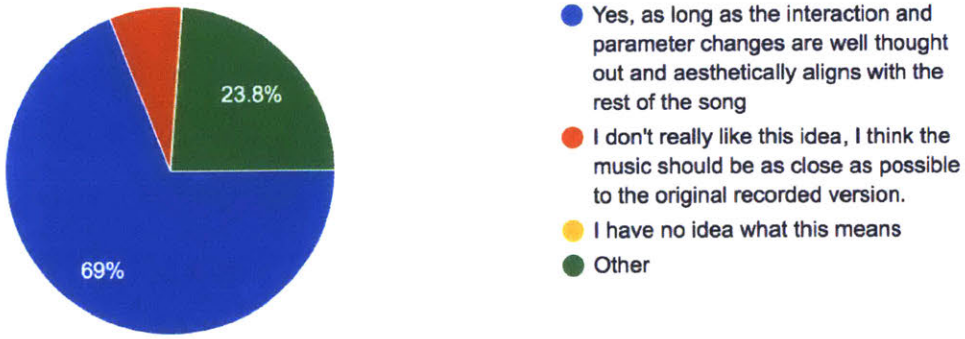
If you had the option to make some or all of your recorded songs interactive with your listeners as they experience your album, would you do it?

(42 responses)



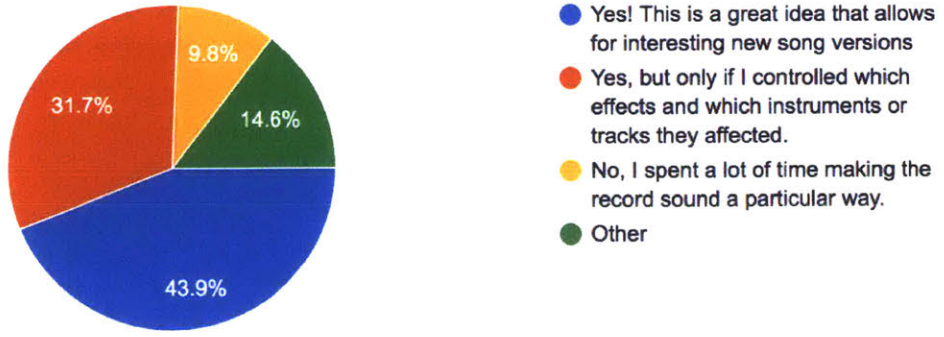
Would you allow the individual instrument constituent tracks of a song to be accessible and changeable by the listener during playback?

(42 responses)



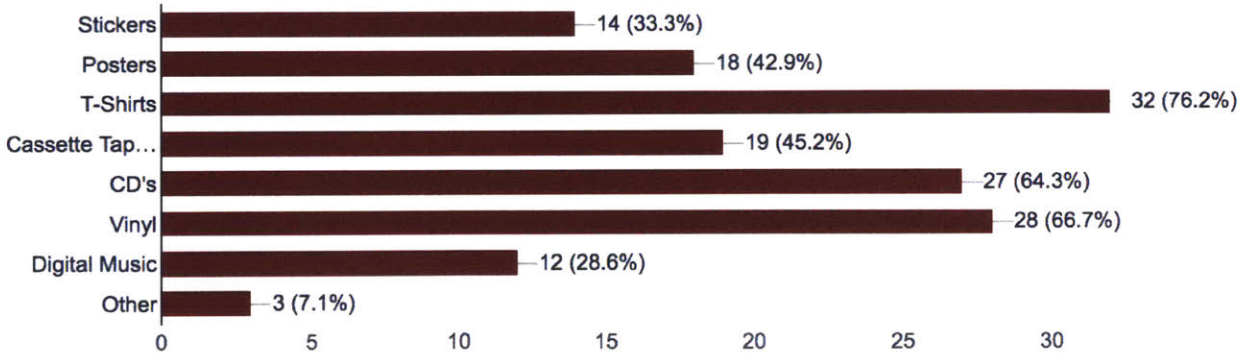
Would you be interested in allowing the user limited access to digital effects that are applied to portions of your composition?

(41 responses)



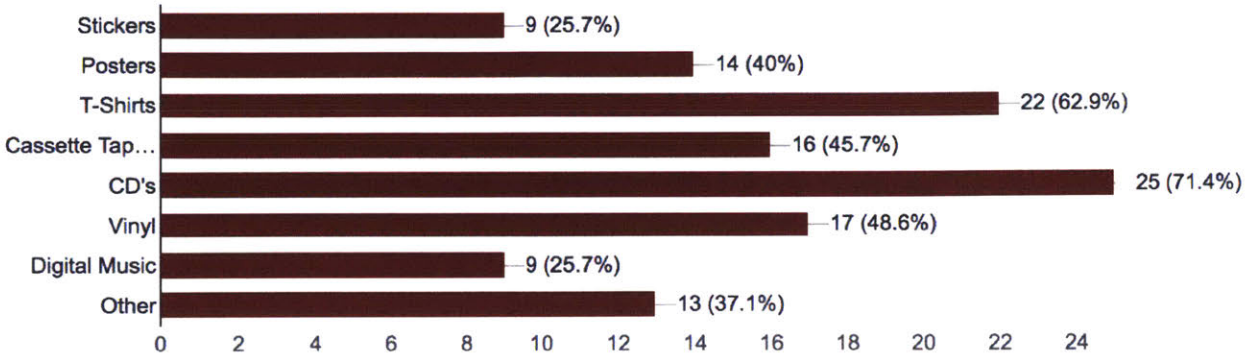
What type of music merchandise have you BOUGHT from a bands merch table?

(42 responses)

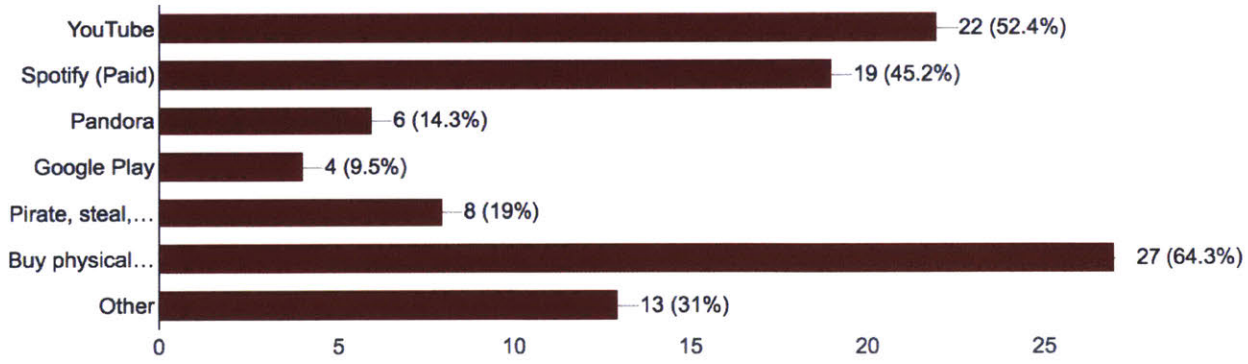


What type of music merchandise have you SOLD from your merch table?

(35 responses)



How do you consume the majority of your music? (42 responses)



Please briefly explain how you and when you justify paying for music:

(41 responses)

If I really like the band

I don't pay for music, but I make sure to watch ads. Only if the music is really rare will I pay for it

When I see/hear a talented and passionate artist performing I feel instantly drawn to their sound and the instinct to buy the music is emotional.

Going to see a band live. If I like what I hear I usually purchase either a CD or Vinyl Record.

I pay for music that is part of emerging artists or independent labels

I pay for music all the time.

Always

I pay for physical music once I've loved the album. I try it first online.

partly depends on what apps/software I'm using at the moment; currently mostly Bandcamp and Spotify. the decision to buy something might be based on availability; also if the band is smaller / more obscure, I feel more compelled to buy to support the artist. occasionally when a favorite band releases a new album I might buy on vinyl.

Anytime I like something or want to support an artist, my favorite is buying records at shows

My main motivation is usually to pay the artist more than the crappy cut they get from my spotify listens.

I like to support living artists, particularly my friends.

if I don't have something I purchase it. If I want to support an artist I purchase their music.

mostly by convenience when I want to listen to something immediately

I want to support an artist or band, I want to help them grow and make more music. Most importantly I want them to know that I think their music is worth something.

I purchase all my music as physical vinyl, usually with the hopes it contains a digital download. Occasionally I'll purchase the straight digital via iTunes, but the former is preferred.

I grew up buying records and cds before digital music and streaming sources existed to it still seems kind of normal to me. I buy vinyl at shows from bands I like and only very rarely buy digital downloads. I only use YouTube for music when I'm doing research.

I make music and facilitate the making of music but rarely get paid for it. If someone's made a piece of art for someone to enjoy, they need compensating for their time, effort and expertise and be allowed to use their time effort and expertise to make more. It costs money to make this stuff. You need money to afford the time. It's not the reason for making music (though frequently people lose sight of this) but if it's being consumed that consumption should not be free or for exposure or any of that bollocks. So when I like an album, I buy the CD or the vinyl. It's polite. They've made an effort. I shall appreciate the effort.

Going to shows!

I know the music already, and know that I like it, and would want to to

In general I don't mind paying for music since musicians need the support. As long as it's not prohibitively expensive, I'll pay for what I like. Since I mostly use Spotify for recorded music, so that covers a lot. I'll also gladly pay for concerts.

When I pay for music, it's because I appreciate that music and want to incorporate that in the ways they fit in my musical creativity!!

I pay for it via a streaming service or if it is an album I like and know I'll listen to repeatedly. I also attend as many live shows as I can

when the packaging is great (for physical) for convenience (digital)

If I can own it forever I pay for it

I need to feel an affinity with the artist first, then I want to own a piece.

I'll buy a new vinyl after I've listened to the record multiple times

I rarely buy new music unless I'm at the show of that musician, if I do its normally to support friends and independent musicians. I also buy used vinyl and used tapes.

Ive paid for music in several different ways. Art shouldnt free. Artist have to make a living as well.

If I love a record, I usually get it in vinyl. Beyond just the physical object, I understand that a lot of time and effort went into making the record and I want to support the artists I like.

When I want to support small bands directly

Always prefer to pay, but sometimes stream on YouTube etc. to decide whether to buy.

I don't need a justification to buy music. Outside of bills and food, I spend the majority of disposable income on music. I actively go to record stores and always look at band's merch when I'm at a show.

when it's a band I'd like to support. I usually buy the vinyl so I actually have something physical.

I used to pirate everything, but now I use Spotify and pay for physical copies (or digital downloads) when there's something I really like and want to expressly support.

Whenever need be

Buying vinyl records is fun and my preferred method. apple music is cheap because i'm a student and convenient.

I pay for Spotify, which while isn't great for the artist, is the best way for me to consume music. If I truly love an artist, admire their careers and connect with their work, then I will buy tickets to their show. As long as the live

show is still dope, I'll buy a physical copy of the album (just to have - I'll still listen through Spotify) or posters or T shirts. I've also purchased a few albums from iTunes; Taylor Swift's 1989, Adele's 25, and Beyonce's Lemonade. All these artists acted like their albums would never be available for streaming so I bought them (now I see they were just saying that to affect sales, and I will never buy one of their albums again).

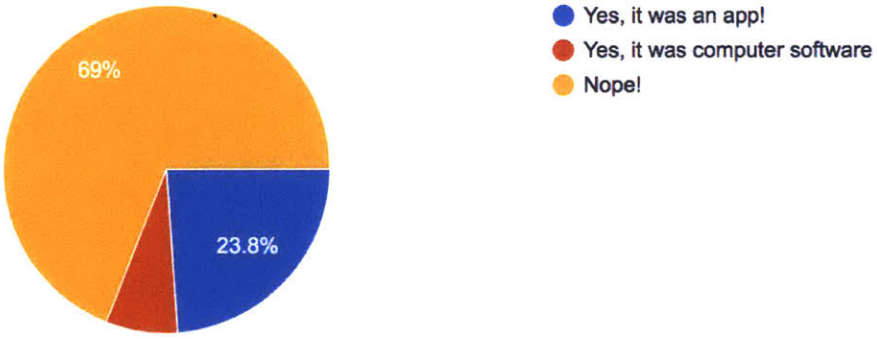
PHYSICAL MEDIA OR UNLIMITED ACCESS TO EVERYTHING ALL THE TIME

I love music.

If I particularly like a song or songs. If it's aesthetically pleasing to me.

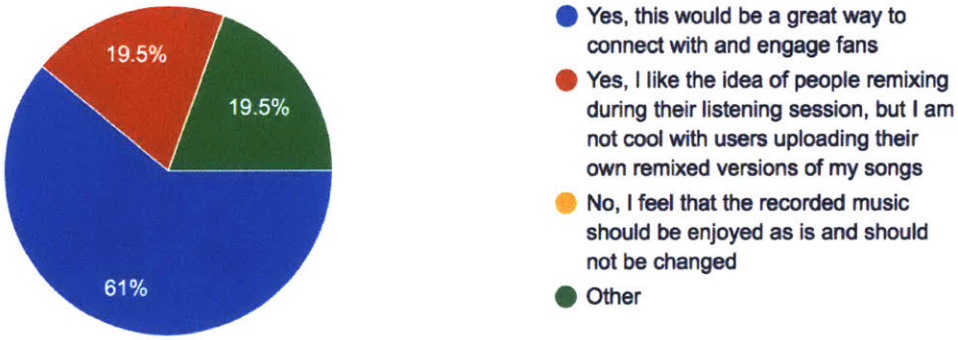
Have you ever purchased music in an interactive format? If so was it an app? Software?

(42 responses)



Do you feel comfortable having other people remix your music? If so, would you want people to upload and share their own mixed versions of your song?

(41 responses)



If the sky was the limit, what type of interactions would you like incorporated with your music. Remember there can be as much or as little interaction as you prefer. It's also possible to only have actuation, in other words, have the physical album artwork changes according to the music.

(40 responses)

Smells

I'd like to remix songs, and even add my own audio to the track

Having someone be able to improvise alongside me even if I'm not physically present, thought a kind of sonic telepresence.

I think a interactive animation might be cool but not necessarily changing the way the Music sounds.

I would like people to listen to stems and be able to mix the song differently if they wanted it. I wouldn't like for them to change sounds that I've made, but they could add their own (remix) or mix the levels differently.

Switching, scrolling, pushing buttons, painting music, recording audio on top of my tracks. Heck, I did the Patchwerk patches.

I would like the interaction but only if it creates alternative versions but an official one remains.

I'd probably want to keep it easy to listen to a static mix of the album if listeners wanted to do that. aside from that, I like the idea of making it easy to remix things / deconstruct / play with different parts of the music.

I like the idea of giving new tools for creativity and explorations along with an album: apps, interactive album covers, posters, pins, etc.

I'm most interested in interactive music when the interactions are deeply integrated into the composition itself from the beginning. I could see making an interactive piece that maybe uses sonic content from an existing straight-through noninteractive song, but I think that to work well, the compositional process needs to include thinking deeply about the affordances and constraints the composer puts on the listener, so that they're integral to the piece.

A lot of musical activity can be described by several roles:

* Instrument Designer - provides affordances to the performer
* Composer - Takes affordances provided by instruments and adds constraints on what the performer can do for a particular piece. The constraints could include playing certain notes at certain times, or just following a general chord progression, or "play nothing", etc.
* Performer - works within the affordances and constraints to execute a piece.
* Listener - receives the sound from the performer.

One way to frame what you're doing here is giving the listener some performative roles, and in creating these interactive objects you're acting as both instrument designer (providing affordances) and composer (adding constraints). I suppose this implies that listener/performer is expressing intent when they interact with the piece. This framing probably would allow for more flexibility for the listener, and possibly even allow them to do things that sound "bad".

Another way to think about it is expanding the role of the listener and allowing the piece to sort of self-perform, where the listener is still largely passive but the piece is reacting to them (e.g. using biosensors or cameras). In this framing the interactivity would probably be much more constrained, so that whatever the listener did the piece would still sound as the composer intended.

Sorry for the long response...got a little carried away. :)

(some of these ideas are inspired by some things Akito said in his proposal talk, so you might want to talk to him if you haven't already)

It's composition-specific. For pieces that lend themselves well to public reconfiguration, I'd happily release the stems or MIDI files or sheet music. With regard to your project, I would realistically sit back and try to make something that subverted some weird social discrepancy in the sharing platform before I agreed to interact with the public.

I'd like to be able to remix an album. I'd like no limitations on what was possible. If I wanted no vocals for example I'd like to have carte blanche. Same thing if I wanted to pan instruments to my liking or add effects. No limitations.

from the tip of a wine glass, "cheers" to full body interactions to reacting to the resonance on the floor to hand-held articulators, measuring breath and heart beats. the furthest thing away from Side-A hits. A medium that could include subtle background mood adjustments to well known riffs. to people bumping sound files between them. controlling light, air currents, perhaps the angle of the floor but not in a 'haunted house way" rather a subtle adjustment to the environs. the amplification of lips on a wine glass occasionally - not 120 percent duty cycle downbeat techno. measuring the crowd density at techno to programmatically change the music when a group moved to one side, for example. or when the crowd approached a stage. picking up chatter in the hallway and transposing that pitch into a soothing hue - or an agitated one.
measuring heart rates and adjusting the music subtly over time so that compositions that lower heart rates the most are favored. stuff like that.

changing the music, but also maybe seeing it change, ie lights, visuals

I would prefer visual interactions rather than aural ones, or have a visual environment thats dynamically created by the music that the listener can interact with. Maybe there would be some play within the surround sound field.

Physical cover change would be very cool. It would be nice to somehow "watermark" the file for the original composition from the artist to separate from the user remixes, if they were to share them online.

I'm not sure. Right now I can only think of possibilities: like raising and lowering the overall or individual volumes or a mood-ring type album cover that changes color but no clever options are coming to mind.

Not sure how you'd do it but something like the 65daysofstatic/no man's sky collaboration but a bit more interactive. But I'm not entirely sure what I'd be wanting to achieve or how to do it.

Knobs, Sliders and Strings!

I would like my fans (that do not really exist) to interact with each other.

Make a video game that goes with my music!

I would like the listeners to be able to mix songs and stems. In addition to that, I would like to see them also define their own musical instruments with that particular track.

pre-defined environmental interactions that the user doesn't explicitly control, e.g. change feel/tempo of piece depending on whether its in a group setting or being listened to alone. Automatic interaction

it would be good to be able to incorporate organic sounds, so record a few examples of say a lock turning, bird singing out the window, flicking through pages in a book and then work that into a track.

I'd like a hologram concert option and a high quality virtual concert experience for my fans. The toughest is to get a good piano sound as is the hardest to recreate live.

Whatever is possible. I think for many artists they would still want a 'definite' version of their music, in a traditional sense, along side any interactive piece.

I like the idea of interactions between music and environment. For example, music queued by changes in weather, ambient noise, time of day. Or if music playback could be determined by the listeners heart rate or mood, that would be cool.

I am very interested in ways for music to be a multisensory experience, and work with fragrance as it relates to sound. I'd be interested in modes of directly engaging the sonic landscape to other sensory modes of perception, like sight, touch, smell, and think that the spatial existence of the sound is important.

I believe if the artwork of my album changes according to the music that would be cool.

I love the idea of incorporating something you can just plug into your virtual reality headset and that creates an interactive world for your tracks. You could modify certain sounds by moving inside the world. There would be a 2 way interaction.

Perhaps with my long form (sleep music) something generative that would take sonic elements and adjust sonic details according to listener activation level (REM, awakening, deep sleep etc.)

I like the idea of actuation. I also like the idea of doing something that allows the person to interact with the music in order for them to feel that they have some kind of personal connection to what they are interacting with. I feel that what is lost in people experiencing music digitally is a strong personal connection to the music. It feels so disposable and cold. Seeing that people's attention span is shortening, having an interactive component might keep one's attention on the item longer.

visualizations, video edits, arrangements (instrumentation within the song), effects, ability to take out or add instruments

I think as both a musician and fan I'd be most interested in "song exploder" kinds of interactions with my favorite bands, and in doing the same with my fans and peers. It'd be particularly cool to get into the studio process, and see/hear the various takes and iterations as they occurred.

I'm not sure because I'd like to see innovation, and if I were already thinking it, it wouldn't be innovative to me.

I like the idea of a consumer making their own remix and creating their own art. If the platform was easy to use, a non-musician could get their own creative juices flowing.

I would like to create an album exactly how I want it (unchangeable mixes, arrangements, album art, etc), but then also release a virtual reality version of the song in which the instruments and mix elements are mapped out in a visual way around someone who's wearing a VR headset.

It really depends, it would take to long to answer this.

Dancing, percussion with found objects like tin cans

Being able to add effects to any instrument or track as well as being to fade instruments in and out. Almost like Dub music. Beyond that I think the actual notes and rhythms should be left alone.

What are your thoughts on remixes of songs? Do you like them and/or listen to them? Have you ever made a remix? Please cite any specific examples

(40 responses)

They are ok

I think remixes are dope. I like acappella-medleys because they're like an analog remix

I really appreciate remixes! I think its important for artists to be open to their sound being spun out in other directions that they might not have thought about themselves.

I have enjoyed a few remixes but typically do not listen to any.

I love them. In my previous music project we would always upload the songs and the stems so that people could make their own remixes. We got back varied results, sometimes full on producers would make tracks, other times it'd be someone's first attempt at music production. All of it was fun to hear.

I generally like covers much better than 'remixes' but then again, I'm old.

As a DJ I love remixes. I've done a couple myself

Yeah, I like them. I've made some and I've asked for some.

I like the idea of remixes but I don't come across that many in my own listening, for whatever reason.

What I like of remixes is that fans can add new stuff to your music. The music grows, evolves and transforms, it stops belonging to you, and I like that. I've had many remixes made of my own songs and a remixes album released. Had both good and bad results. Awesome musicians had made great remixes, and others not so good, or just different of what I like. Anyways both cases are valid and I appreciate them. I haven't done remixes myself.

I don't tend to listen to many remixes, as most of the time they don't seem to have as much creative spark as the originals. I did listen to the DJ DangerMouse Grey Album on repeat throughout most of 2004.

I've heard multiple people draw parallels between interpretations of Bach and remix culture. I've also heard the artist Jacolby Satterwhite say we're living in the age of the remix, which is to say there's no more originality; just (I'm paraphrasing) curated, cannibalized Tumblrs filled with disparate aesthetics that allow people to express their personalities. I'm definitely interested in initiating dialogues but I'm not tremendously interested in the personalities of my listeners. I enjoyed LL Cool J and Total's "Loungin'" (Remix) as a kid but only because it was a pre-Napster era and I was working with limited options. I love Grime and Footwork but dance music culture never interested me, due to its associations with synthetic drugs and associated behavior. I have never formally made a remix.

Haven't made any remixes or listened to many. I'm not opposed to them though. I think it's a fun way to interact with a song. Each persons remix of the same song will be different and I like that.

none

I listen to them on occasion

I like them when they're actually offering something new with the music, I have done remixes in the past and I try to have my own set of rules to follow. Such as, I try not to use anything outside of the recorded music I was given, at least as building blocks.

I like the idea of remixes. Sometimes they're better than the original. I've never made a remix, nor do I seek them out, but have occasionally heard some great ones.

I'm cool with remixes but I don't listen to many. Over the past year, Dave has been collecting Sugarhill Gang 12 inches and we've been listening to those but I can't think of anything current that I've been listening to. I've never remixed someone else's material.

I'm always down for a remix, I've done Arctic Monkeys, Fat Freddys Drop, Reverend and the makers, robot heart, Transfigure amongst others I always try and look at a different musical approach whilst keeping the lyrical message consistent with the original as I feel there should be some common ground and as a songwriter myself, the lyrics are probably the only bit I would consider sacrosanct. I can move the mood around with the music anyway. I do love a remix. Sometimes they do eclipse the original, sometimes they're just a nice tangent. A remix is cool if it's mutually agreed on. I wouldn't want my raw files and methodology up there for anyone to mess with, it should be somebody you respect/trust. Stems for someone to play with for their own enjoyment is different, I guess. Hmm, it's a deliciously grey area isn't it? I like being confused by recordings and wondering how the fuck they did it. By trying to replicate things in almost always the wrong way, you learn more. Maybe too much transparency is dumbing down? I dunno.

Not really interested in recorded remixes, I enjoy remixes when they are made live!

meh. rarely does a remix really add something to the original.

I love different versions of songs. It's super interesting to see how different people treat the same material. I actually "remix" classical pieces a lot by taking them apart and putting them back together on the piano.

++ is my thought. Please have this culture continue in the future whatever you do. This is where music from different 'genre' can be intermingled and it's important (my opinion), to over come the social stereotype and prejudice.

I like relatively few remixes better than the original. this is one example: https://www.youtube.com/watch?v=u3njX4nSO5U

I think they are good and can help open up music to a different audience

My friend Ivan Shopov did a Pink Floyd Remix of my classical piano arrangement of their song High Hopes.

Sometimes. They are very often sub-standard and cynical avenues for extra content. Occasionally they are inspired. Very occasionally...

I dont typically listen to remixes or prefer them over original recordings. I value artists own remixes over third party reinterpretations. However, the use of samples/loops in an alternative genre are the exception.

As a musician I think remixes are really interesting, and I appreciate when people make them of my music. I think that's kind of a contemporary version of doing a cover, which is really just an interesting dialogue among composers. I haven't ever made a remix, but I've done several covers, and I equate the two activities.

Jimi hendrix wrote a song called, "Hey Joe." In the early 2000's,the rapper T.I. sampled it and made a song called "What you know about that." I liked both the original and remixed version. However, i dont like that no one knows that T.I. remixed hendrix's song and this info isnt listed on the album.

I like when people remix songs and create something that transcends musical genres, like mixing genres, but I don't love when someone just make small changes and say they made the track "better". I guess even if you remix an EDM song into another EDM song, I like to hear a significantly different idea or approach to the song as opposed to just fine adjustments. That seems more like "re-mastering".

I have done remixes, usually stripping away or simplifying a cluttered original. Generally I dislike traditional remixes of my music because the modern concept of remix usually involves boring drum patterns and the simple pulse tends to destroy the subtle texture I strive for. Something poetic is easily lost.

Not that big of a fan of remixes. Some are good, some aren't. I don't actively purchase remixes. I will listen to them, but for the most part I find the original version of the track to be better. When I think of remixes, I tend to think of something dance oriented which doesn't always suit the song that has been remixed in my opinion.

i usually don't care for remixes actually

Generally not a fan of remixes but this concept seems particularly cool.

Remixes are cool. I always liked that vetiver neighbors remix that we had. Never made a remix.

I see remixes as no different than covers, except they use the same vocals. So I think a remix is only a valid artwork if it reinterprets and creates a truly distinct version of the song. Like taking a rock song and making it a party/club tune (Misterwives had some of their songs remixed like this) or a slow song turning into something faster (Ellie Goulding's Lights - the remix is better than the original). I've

Sometimes the remixes are better! I'm looking at you Bjork.

I like covers often when they are a different genre than the original piece

Don't have a strong opinion. I do listen remixes sometimes, but for the most part I don't think approve on the original song.

8 References

[1]D. Byrne, How Music Works, Main ed edition. Edinburgh: McSweeney's, 2013.

[2]M. McLuhan, Understanding Media:, 2 edition. London: Routledge, 2005.

[3]E. Buder and E. Buder, "Oscar-Winning Editor Walter Murch: The Man, the Myth, the Legend," IndieWire, 07-Nov-2015. .

[4]D. McCandless, "How Much Do Music Artists Earn Online – 2015 Remix," Information is Beautiful. [Online]. Available: http://www.informationisbeautiful.net/visualizations/how-much-do-music-artists-earn-online-2015-remix/. [Accessed: 11-May-2017].

[5]"Alex Steinweiss: the story of the world's first record sleeve artist," The Vinyl Factory, 31-Oct-2014. [Online]. Available: http://thevinylfactory.com/features/alex-steinweiss-the-story-of-the-worlds-first-record-sleeve-artist/. [Accessed: 19-Apr-2017].

[6]B. & Noble, "For the Record: The Life and Work of Alex Steinweiss," Barnes & Noble. [Online]. Available: http://www.barnesandnoble.com/p/for-the-record-jennifer-mcknight-trontz/1003863275/2676086405923. [Accessed: 08-May-2017].

[7]"Get to Know the Father of Album Cover Art," Creators. [Online]. Available: https://creators.vice.com/en_us/article/the-father-of-album-covers. [Accessed: 26-Apr-2017].

[8]"The Oblique Strategies Web Site." [Online]. Available: http://www.rtqe.net/ObliqueStrategies/. [Accessed: 15-May-2017].

[9]K. Silverman, Begin Again: A Biography of John Cage, Reprint edition. Evanston, Ill: Northwestern University Press, 2012.

[10]K. Stockhausen and R. Maconie, Stockhausen on music: lectures and interviews. M. Boyars, 1989.

[11]"RjDj," Wikipedia. 11-Mar-2017.

[12]A. B. S. B. Sterling, "Augmented Reality: RjDj," WIRED. [Online]. Available: https://www.wired.com/2009/08/augmented-reality-rjdj/. [Accessed: 11-May-2017].

[13] Robert Jacobs, Mark Feldmeier, Joseph A. Paradiso. " A Wireless Sensor-based Mobile Music Environment Compiled from a Graphical Language." In Proceedings of the 2008 Conference on New Interfaces for Musical Expression (NIME-08), pages 193-196, Genoa, Italy, 2008. PDF

[14]"Inception App Augments Your Reality, Acoustically," WIRED. [Online]. Available: https://www.wired.com/2010/12/inception-app/. [Accessed: 28-Apr-2017].

[15]"rjdj — Pd Community Site." [Online]. Available: https://puredata.info/downloads/rjdj. [Accessed: 11-May-2017].

[16]M. Csikszentmihalyi, Flow: The Psychology of Optimal Experience, 1 edition. New York: Harper Perennial Modern Classics, 2008.

[17]"Mihaly Csikszentmihalyi," Wikipedia. 17-Apr-2017.

[18]"Generative music," Wikipedia. 02-May-2017.

[19]"Tristan Perich: 1-Bit Symphony." [Online]. Available: http://www.1bitsymphony.com/. [Accessed: 27-Apr-2017].

[20]"Biophilia (album)," Wikipedia. 05-Mar-2017.

[21]"BjöRk's Biophilia to Be Used in European Primary Schools," The FADER. [Online]. Available: http://www.thefader.com/2014/06/16/bjorks-biophilia-to-be-used-in-european-primary-schools. [Accessed: 27-Apr-2017].

[22]"::: M O L D O V E R:::" [Online]. Available: http://moldover.com/. [Accessed: 27-Apr-2017].

[23]"Organelle," Critter & Guitari. [Online]. Available: https://www.critterandguitari.com/products/organelle. [Accessed: 27-Apr-2017].

[24]"documentation — Pd Community Site." [Online]. Available: https://puredata.info/docs. [Accessed: 11-May-2017].

[25]"Harmonix's Dropmix Card Game Is Impressive, But Is It More Than Just a Toy?," pastemagazine.com. [Online]. Available: https://www.pastemagazine.com/articles/2017/03/dropmix-has-some-impressive-tech-but-is-it-more-th.html. [Accessed: 11-May-2017].

[26]"No World Order," Wikipedia. 10-Mar-2017.

[27]"McDonald's in the Netherlands lets you DJ with your placemat," CDM Create Digital Music, 04-May-2016. .

[28]"Raspberry Pi Zero: the $5 computer," Raspberry Pi, 26-Nov-2015. .

[29]headphone.com, "What is a DAC?," headphone.com. [Online]. Available: https://www.headphone.com/pages/what-is-a-dac. [Accessed: 24-Apr-2017].

[30]"I2S Description, Inter-IC Sound interface description." [Online]. Available: http://www.interfacebus.com/I2S_Interface_Bus.html. [Accessed: 11-May-2017].

[31]"Pro Micro - 3.3V/8MHz - DEV-12587 - SparkFun Electronics." [Online]. Available: https://www.sparkfun.com/products/12587. [Accessed: 23-Apr-2017].

[32] Puckette, M. (1996). "Pure Data" Proceedings, International Computer Music Conference. San Francisco: International Computer Music Association, pp 269-272.

[33]"/chapter: Graphical-Programming / PURE DATA," FLOSS Manuals. [Online]. Available: http://write.flossmanuals.net/pure-data/graphical-programming/. [Accessed: 11-May-2017].

[34]"pduino — Pd Community Site." [Online]. Available: https://puredata.info/downloads/pduino. [Accessed: 11-May-2017].

[35]"V2.3ProtocolDetails - Firmata." [Online]. Available: http://firmata.org/wiki/Protocol. [Accessed: 11-May-2017].

[36] "Sonic Artifacts Video" [Online]. Available: http://www.brianjtice.com/SonicArtifact. [Accessed: 11-May-2017].