Tiny Trainable Instruments

by

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Abstract

How can we build flexible and reusable multimedia instruments that we can train instead of program? How can we build and publish our own personal databases for artistic purposes? What are the new choreographies and techniques that machine learning running on microcontrollers offer for artists and activists?

Tiny Trainable Instruments is a collection of multimedia devices, running machine learning algorithms on microcontrollers, for artistic purposes. It includes techniques for capturing data, building databases, training machine learning models, and deploying on microcontrollers. The software library created for this project allows for the creation of instruments that react to different inputs, including color, gesture, and speech, to control different multimedia outputs, including sound, light, and movement, using machine learning and embedded sensors.

This thesis has a strong emphasis on open source software and artificial intelligence ethis, and includes all the steps on creating these bridges between machine learning and media arts, that are respectful of privacy and consent because of their offline and off-the-grid nature.

Thesis Supervisor: Tod Machover
Title: Muriel R. Cooper Professor of Music and Media

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Contents

Acronyms

AI artificial intelligence. 16, 19, 20, 22, 24, 57, 61, 62, 65

BLE Bluetooth Low Energy. 11, 30, 32, 64, 80, 90, 94

DIN Deutsches Institut für Normung. 39

DIY do it yourself. 16, 29, 75

IMU inertial measurement unit. 35

ITP Interactive Telecommunications Program. 55–57, 60, 61, 64, 79, 80

k-NN k-nearest neighbors. 34, 60, 61

LED light-emitting diode. 30, 31, 38

MIDI Musical Instrument Digital Interface. 30, 31, 39, 55, 72

ML machine learning. 16, 17, 19, 21–23, 25–27, 29, 30, 34–36, 38, 39, 44, 46, 57, 59–62, 65, 66, 79–82

NYU New York University. 55–57, 60, 61, 64, 79, 80

PIC Programmable Intelligent Computer. 52

PWM pulse-width modulation. 38, 44

RGB red green blue. 26, 27, 34

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Chapter 1

Introduction

Me caí, me paré, caminé, me subí
me fui contra la corriente
y también me perdí

Soy Yo
Bomba Estéreo, 2015

1.1 Context

This thesis is the capstone project of my Master's program between the academic years 2019-2021 in the Media Arts and Sciences program at the MIT Media Lab, where I am a Research Assistant in the Opera of the Future and Future Sketches groups.

This thesis is a collection of media arts instruments made with microcontrollers and machine learning (ML), with a strong emphasis on artificial intelligence (AI) ethics and do it yourself (DIY) methods. Its main audience - besides the academic one - is beginners and artists, and it is my hope that this work can inspire a new genera-

tion of instrument makers, artists, designers, educators, programmers, policy makers, activists, and enthusiasts.

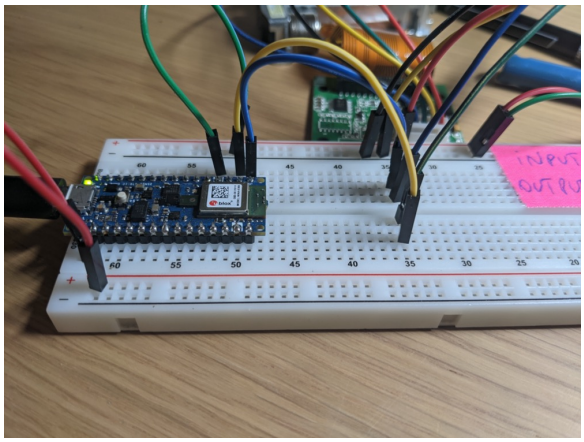


Figure 1-1: Early prototype of Tiny Trainable Instruments
Picture taken by myself

ML has several barriers of entry, including cost, complexity, and difficulty. Since my practice is based on sharing and working on openly with different communities, I am not a fan of the current state of industrial ML that relies on proprietary software and hardware. This tends to happen because their ML models are aiming for high precision and need to be trained for long periods of time, using expensive non-open computational resources, with huge datasets that often are scraped from the internet without the explicit consent of users, and representing - in my view - a byproduct of surveillance capitalism.

The release of the library Arduino TensorFlow Lite in late 2019 made me aware of the tiny ML field, a subset of ML that focuses on hardware and software able to run calculations both on-device and with low power, a stark contrast to many industrial ML applications. The tutorials published by Arduino showed how to build your own database to detect colors and gestures using a microcontroller, and I decided to make this thesis an artistic exploration of these emerging techniques.

One aspect that deeply resonated with me was **data agency**, and being in control of your own data, in particular its capture, storage, publication, and use. In this thesis I propose the microcontroller as a way of building our own databases and deploying

Figure 1-2: Surveillance camera in a park in Boston MA
Picture taken by myself

our models to bypass any corporate or government surveillance. During this year and more of pandemic lockdown context, I have found myself several times working alone in my room, capturing data of myself and my living environment, and then building databases for other people to use, in a way that reminds of one of my favorite artists and activists, Ai Weiwei, who in 2012 - while facing government surveillance - decided to livestream from his house. I also see this today as a way of reclaiming data agency.

Figure 1-3: Weiweicam, by Ai Weiwei, 2012
Retrieved from [1]

I am an underrepresented minority in the USA, and it often happens that supposedly

automatic neutral technologies fail to detect me. Here is an example of the popular software Zoom, where I spoke out loud: "This is a test to show that Zoom speech to text transcription does not work with my voice because of my accent." Indeed the words "Zoom" and "voice" were transcribed as "soon" and "boys", respectively.

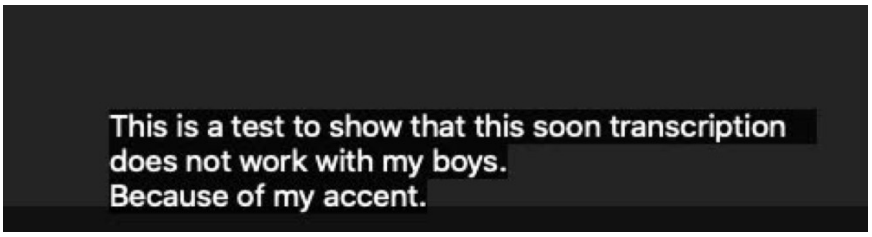


Figure 1-4: Screen capture of speech-to-text on Zoom, introduction
Screen capture by myself

Here is a further experiment with more unusual words, the names of the members of my thesis committee: Tod Machover, Mitchel Resnick, and Zach Lieberman, where the transcription had even more errors.

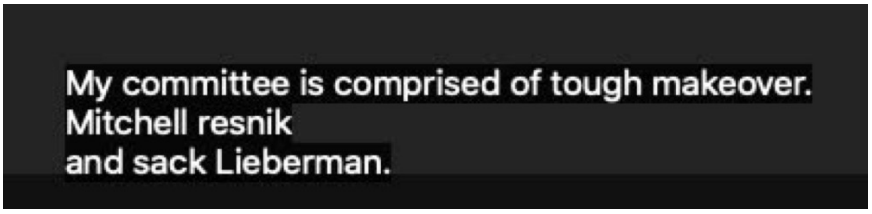


Figure 1-5: Screen capture of speech to text on Zoom, committee
Screen capture by myself

Despite these ML algorithms being promoted by corporations and governments as unbiased and effective, most probably these algorithms have never been exposed to Chilean people with my accent, so they fail. Because of these errors, but more importantly because of not wanting to renounce my privacy, I routinely turn off voice assistants and text completion in my devices (if you have interacted with me over text, I typed every single character :)).

These examples do not affect me negatively, but these algorithmic decisions can easily have devastating effects in equity and discrimination. A famous example of this was the scrapped internal recruiting tool that Amazon developed with AI, which

systematically discriminated against women applicants, thus in fact reproducing and amplifying the existing biases of their own hiring teams[2].

Figure 1-6: Meme about biased data
Retrieved from [3]

Sadly, we often cannot turn off or opt out of these computational or AI systems. We should in fact be able to, because there is even more at stake than losing our privacy! We could be subjected to harmful **algorithmic bias**, as the Algorithmic Justice League explains on their website:

> In today's world, AI systems are used to decide who gets hired, the quality of medical treatment we receive, and whether we become a suspect in a police investigation. While these tools show great promise, they can also harm vulnerable and marginalized people, and threaten civil rights. Unchecked, unregulated and, at times, unwanted, AI systems can amplify racism, sexism, ableism, and other forms of discrimination.[4]

I highly recommend watching the Coded Bias documentary on Netflix, to inform oneself about the important and necessary digital advocacy of the Algorithmic Justice

League, who have helped me learn the language for navigat these important topics of civil rights.

The final catalyst that led me to this thesis happened a year ago, when I watched a video [5] of a conversation between artists Rafael Lozano-Hemmer and Dorothy Santos. At 36:28 in the video, Rafael says "Face recognition needs to be banned in all applications except art."

This was the perfect spark for starting to work on this project, inspiring me to make more accessible these computational techniques to beginners, enthusiasts, and educators. Despite the creative and artistic applications that I will show during this thesis, let's keep in mind that as ML becomes cheaper and more pervasive, it is not the solution to all problems, and might not even be needed in many scenarios.

Figure 1-7: Meme about need of machine learning
Retrieved from [6]

In this 21st century artists have unprecedented access to tools for making more new tools and instruments, and I intend this thesis to be a foundation for a new generation of instrument makers for manipulating audiovisual material, using ML. I think this approach is really exciting because it allows beginners and artists to train their instruments instead of programming them, by inputting data for tuning instead of having to write lines of code, and then fixing thresholds for changing their behavior.

1.2 Objectives and dreams

Infrastructure and cooperation are key to society. I love how I can bike on roads and hike on paths that were built as shared resources for the benefit of everyone. I hope this thesis work can be adopted by fellow artists and educators to create new instruments for arts, and to inspire critical and ethical thinking about AI.

I am convinced there is a huge educational value in creating your own databases, and in this thesis I propose techniques and software so that people can build their own databases, in order to train models that are tailored to each person's voice or environment, instead of using widespread databases and their inherent biases. Also I hope this work will help appreciate the craft of making databases, or even the exploitation and problematic lack of consent behind them.

Finally, as a non US citizen subjected to all sorts of regulations during my studies here, as a programmer working with software under various licenses, and as a musician repurposing other people's work via sampling, I know first hand that navigating legal documents is very hard. As an anecdote, in 2010, GameStation added a soul clause to their terms of conditions as an April Fool's prank, making them legal owners of thousands of customers' souls [7]. And in 2007, it was estimated that people would need around 250 hours every year to actually read the privacy policies shown to them [8]. That is why in this thesis I have tried my best to cite every work that I am either

using as a building block, or that served as a direct or indirect inspiration.

I hope this work can be taken to the next level by others, through building a new generation of private and smart devices, like one of my first dreams, a drum machine I can talk to, and that would let me ask for different rhythms mid-performance, or let me use my body gestures to write poems.

1.3 Thesis outline

This thesis has cover the following chapters:

1. Chapter 1 - Introduction: the context and summary of this thesis.
2. Chapter 2 - Tiny Trainable Instruments: description of the design strategies for the software and hardware, description of the support team working on this thesis.
3. Chapter 3 - Early experiments: my earlier work that led to this thesis, in the topics of media arts education, microcontrollers, and ML, among others.
4. Chapter 4 - Background and inspiration: work by other people which has informed my work.
5. Chapter 5 - Project evaluation: user feedback, field notes.
6. Chapter 6 - Conclusions and future work: next iterations of the instruments, and their proposed use for educators and artists.

Chapter 2

Tiny Trainable Instruments

All the modern things
have always existed
they've just been waiting

The Modern Things
Björk, 1995

This chapter describes the process of conceptualizing and developing this antidisciplinary thesis project, drawing from the fields of artificial intelligence, electrical engineering, computer science, media arts, music, and pedagogy, among others.

First, let me explain my definitions of the words that make up the title of this project.

2.1 Definition of Tiny Trainable Instruments

2.1.1 Definition of tiny

By *tiny* I mean lightweight handheld instruments that you can fit in a backpack, or take for a walk. This is inspired by my personal practice: for years I have accumulated many small tools for arts that I perform gigs with, or that I carry with me while traveling, mostly small electronic synthesizers, sound mixers, and battery-powered speakers.

Here is an example of a yellow handheld sampler with an included microphone and speaker that I enjoy for field recordings, complete with a green battery pack for portability.

Figure 2-1: Sampler with microphone and portable battery
Picture taken by myself

Tiny is also a nod to the emerging field and community of tiny ML, including - most importantly for me - the tinyMLx professional certificate[9] offered by HarvardX, that I completed while working on this project.

With that, the *tiny* in *Tiny Trainable Instruments* comes from them being handheld devices built on breadboards, from their being able to be powered from a generic USB power bank, and from their using tiny ML processes for mediating their inputs and

outputs.

2.1.2 Definition of trainable

By *trainable* I mean a device that can learn by example. This name comes from the ML lexicon, where training is a process whereby an algorithm iteratively finds the numerical values of all parameters (weights, biases) of a ML model.

Training a device is particularly attractive for artists working with sensors. The Arduino microcontroller that this thesis uses has several embedded sensors, which can be used to produce huge streams of data, like this screenshot showing the output of raw data from its RGB color sensor.

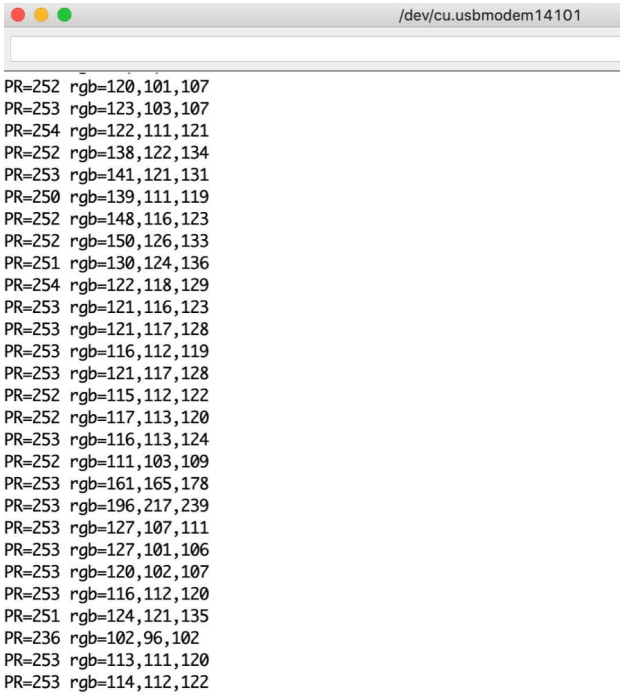


Figure 2-2: Data stream from embedded sensors in an Arduino microcontroller
Screen capture by myself

If we wanted to use this sensor at home to detect a red object, we would start by taking notes of the RGB values of the sensor when the red object is close to it, and would then include this value as a threshold for detection on the software uploaded to the

microcontroller. Since the RGB sensor needs consistent lighting to work effectively, we need to be especially careful with the lighting conditions; if they change, we have to look at the stream of data to find the new value for red, and then update the code and reprogram the microcontroller.

This is a tedious process, and it inspired me to work on this thesis, so that I could help artists use ML and microcontrollers to capture data, and then train a model, letting the algorithm figure out the correct answer without one having to write more code!

An educational and creative example I recommend consulting is Teachable Machine by Google [10], a web application that allows you to use your computer's microphone and webcam to generate data, and then to train models that can detect different words, images, or body postures without having to write any line of code.

In particular, I became interested in tiny ML examples that require small databases and that can be trained on-device, for the use of making an instrument whose behavior can be changed mid-performance, like guitar players do with their guitars when they change their tunings between songs. With this thesis, one can program a device that can detect an apple, and then five minutes later, an orange, and then for your last song, a grapefruit. Hat tip to Sonic Youth, a band that used to tour with more than a dozen guitars, each one of them with a different tuning; they would switch instruments between songs.

2.1.3 Definition of instruments

By *instruments* I mean devices that transduce energy across different media. Instruments receive an input, process it, and then produce an output. For musical instruments, I like to think that instruments are able to not just produce musical Western scales, but a wide spectrum of sounds encompassing the broad vocabulary

Figure 2-3: Sonic Youth guitar with custom tunings
Retrieved from [11]

of experimental electronic music and electroacoustic music.

On top of that, my personal definition of *instrument* includes having freedom and liberty, not censorship. This is why I consider my bicycle to be an art instrument that transduces my pedalling input into multimedia output: adventure, sweat, and wind in my face. Also, while I am riding it, I am not subjected to the restrictions of any corporate or government playground, there are mostly no rules besides gravity, and there are no backdoors that anyone can use to track me, exploit me, or limit my speed (we have smartphones for corporate and government surveillance, but that's another story).

The liberties that *instruments* make me feel are a huge contrast to the computational tools I am using for crafting this thesis. I am typing on an Apple Macbook, and even though I like its keyboard and portability, I am aware that I face restrictions: Apple wants developers to pay to be certified developers, and if I update my operating system I won't be able to run 32 bits apps anymore. This thesis is hosted on GitHub, which is a service blocked for developers in certain countries due to U.S.A. sanctions [12]. I am from a country recently affected by a dictatorship and human rights violations and some of my relatives have been exiled, so I am particularly sensitive to policies

that limit people's freedom of speech and computing.

This discomfort was also a catalyst for the creation of *Tiny Trainable Instruments*, which are based on open source off-the-cloud microcontrollers, and nobody can censor me when I use them for arts, thus being *instruments*, as gratifying as playing with my guitar and bicycle, and I hope you feel that joy too while spending time with this thesis.

2.2 Components of the project

In this section I will explain the process and the result of each component of this thesis:

1. TinyTrainable Arduino software library
2. Code for training ML with DIY databases
3. Workshop and educational material

2.2.1 TinyTrainable Arduino software library

This project's main contribution is the TinyTrainable Arduino software library, which allows you to create flexible multimedia instruments, where you can combine any input with any output, and it runs on the microcontroller Arduino Nano 33 BLE Sense. This microcontroller was chosen because it is currently the only Arduino supported by the Arduino TensorFlow Lite library.

The TinyTrainable library is flexible, since it allows one to combine any of the three available inputs with any of the 7 possible outputs, for a total of 21 possibilities summarized on 2.1:

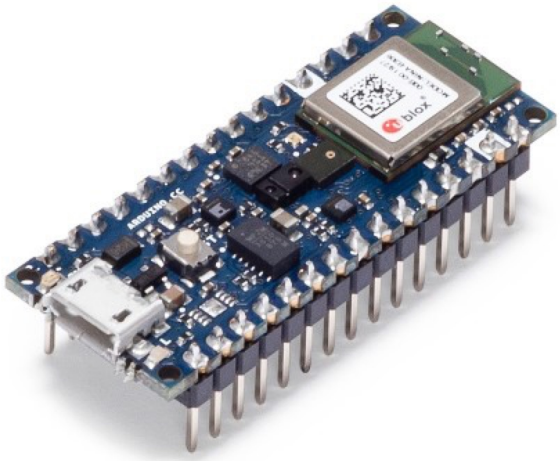


Figure 2-4: Arduino Nano 33 BLE Sense microcontroller with headers
Retrieved from [13]

Input \ **Output**	Buzzer	LED	MIDI	Printer	Screen	Serial	Servo
Color							
Gesture							
Speech							

Table 2.1: Matrix of inputs and outputs

For the inputs I used the embedded sensors of the Arduino microcontroller with their corresponding open source libraries, and processed the input data with two recently released open source ML libraries, summarized on 2.2:

Input	**Sensor library**	**ML library**
Color	Arduino_APDS9960	Arduino_KNN
Gesture	Arduino_LSM9DS1	Arduino_TensorFlowLite
Speech	PDM	Arduino_TensorFlowLite

Table 2.2: Software dependencies for inputs

The outputs are actuators that rely on extra hardware, and in some cases, external libraries, which are summarized in 2.3.

The behavior of the TinyTrainable library is already designed, and is explained in this chapter. The software implementation is in flux, and I do my best to publish new releases with notes on how the library has changed over time, including bug fixes, clearer language for the examples, and different ways of interfacing with the methods

Output	Actuator library
Buzzer	-
LED	-
MIDI	-
Printer	Adafruit Thermal Printer Library
Screen	Adafruit_SSD1306
Serial	-
Servo	Servo

Table 2.3: Software dependencies for outputs

and variables of the TinyTrainable library.

Repository structure

The TinyTrainable library is a repository hosted at `https://github.com/montoyamoraga/TinyTrainable`, where one can review all the history and commits through time, and where anyone can see how the whole library or each file has evolved over time.

The structure of the folders follows two simultaneous specifications: it includes the necessary file and folder names for being packaged and indexed as an Arduino Library, and on top of that it complies with GitHub guidelines for licensing libraries, and for automatic workflows for code testing.

The source code of the library is written in C++ and is located in the src/ folder. The examples live in the examples/ folder, and are written in the Arduino language. The examples are divided into four folders: one for each input, and one extra for checking the wiring of each output. In the assets/ folder, I included some C++ files with trained models for the examples.

Installation

The library can be downloaded from the Releases section of the repository at `https://github.com/montoyamoraga/TinyTrainable/releases`, where you also have access to the complete history of releases over time. To install it, you need to uncompress the .zip into a folder, and then make it discoverable by the Arduino IDE.

Since that method is not automatic and could be prone to errors, I made the effort to publish the TinyTrainable library, by complying with the latest Arduino Library Manager specifications, detailed on their repository `https://github.com/arduino/library-registry/`. With that, from the Arduino IDE you can open their Library Manager and do a 1-click installation of the library, or as an alternative use arduino-cli, the Arduino command line tool on your terminal.

Hardware basics

The TinyTrainable library at its current iteration has only one strict hardware requirement: it only runs on the Arduino Nano 33 BLE Sense, a microcontroller released in 2019. For powering it you need a generic micro USB cable to provide the necessary input of 5V. To upload code to the microcontroller you can use the same USB cable to connect to a computer running the Arduino IDE.

To build a Tiny Trainable Instrument, you also need a breadboard, where you can place the Arduino microcontroller, and some jumper wires to connect it to one of the many possible output devices that I will describe soon.

Figure 2-5: Micro USB cable
Retrieved from [14]

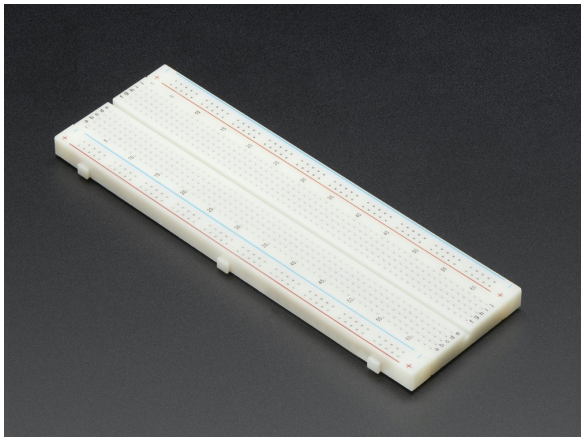


Figure 2-6: Breadboard
Retrieved from [15]

2.3 Inputs

As I mentioned before, for the inputs no extra wiring is needed, since we are using the embedded sensors of the Arduino microcontroller to detect the three possible inputs: color, gesture, and speech. These inputs were designed to foster different behaviors with the library, which are detailed in the following sections.

I decided that each different method will be able to detect three different categories, because I thought hat more categories would make the instruments more cumbersome to train, by needing larger databases, and longer training. Hopefully in the future I can adapt the TinyTrainable library to make this a variable number of categories it

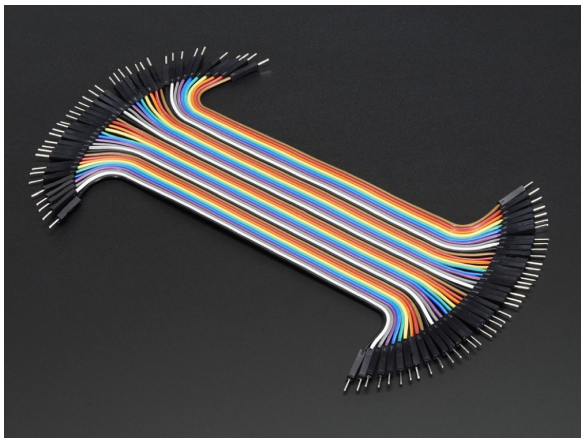


Figure 2-7: Jumper wires
Retrieved from [16]

can classify, but for now this is hardcoded in the library. Nonetheless, if you want to use the library for your own project with a different number of categories, the library is open source and documented, so that it should not be too difficult to adapt it to your needs.

2.3.1 Color input

The color input allows artists to build Tiny Trainable Instruments that can detect three different colors of objects near the microcontroller. I recommend that this is the first input that people try, since it is the easiest and fastest of the other inputs to learn and use. It is based on the examples included with the Arduino_KNN library.

When detecting color, the library acts as a wrapper of the Arduino_APDS9960 library, needed to access the data of the embedded distance and color sensor of the microcontroller. This allows the instrument to detect nearby objects, and then when they are close to the microcontroller, it reads a one pixel RGB value, detecting how red, how green, and how blue any object is.

The RGB data is stored in the microcontroller, to build a database that then is used to train a ML algorithm, in particular a k-nearest neighbors (k-NN), implemented

with the Arduino_KNN library. After the algorithm is trained, the instrument is able to detect between the three different colors.

The main difference between this input and the other ones, is that both the data capture and the model training happen on the device, and it is not persistent: every time the Arduino microcontroller is turned on it needs to be trained again.

2.3.2 Gesture input

The gesture input allows artists to build Tiny Trainable instruments that can detect three different motion gestures, by moving the microcontroller in space. It is based on the magic wand example of the Arduino TensorFlow Lite library.

When detecting gestures, the library acts as a wrapper of the Arduino_LSM9DS1 library, needed to access the data of the embedded inertial measurement unit (IMU). The library includes an Arduino sketch to capture the data of the three gestures we want to recognize, which then needs to be saved on a computer. These files with the database are imported in a Jupyter notebook to train the ML model with Google TensorFlow. The trained model is then used with the TinyTrainable library and uploaded to the Arduino microcontroller to detect the three different gestures.

Even though for both the color input and the gesture input we use the Arduino to capture the data, for the gesture input we do need a computer to process the data; the drawback is that we still need a computer for training the model. A positive aspect is that the training is persistent: the Arduino microcontroller only needs to be trained once for the same database, and remembers the model every time it is turned on, unlike the color input which forgets the trained model.

A contribution of this thesis is that previously existing examples rely on the cloud, in particular the freemium service Google Colab for training the model on the cloud. Training on the cloud has its own perks; for example, in my case the Google Colab

resources are faster than training on my own computer, but I think this comes at the expense of losing privacy.

The gesture database we are handling is not compromising and does not make you identifiable for governments or corporations, unlike your fingerprints or DNA. Since the gesture information is low-stakes, I don't disencourage people from using Google Colab with this thesis, but I do want to stress that we can circumvent these corporate systems. For this reason I also included code for being able to train on your own computer, in a more private and secure way.

2.3.3 Speech input

The speech input allows artists to build Tiny Trainable instruments that can detect three different sounds or utterances, by emitting sound next to the microcontroller. It is based on the micro_speech example of the Arduino TensorFlow Lite library.

When detecting speech, the library acts as a wrapper of the PDM library, needed to access the data of the embedded microphone. This input is the only one where we are not using the microcontroller to capture the data: the documentation includes instructions for building your own database with the microphone in your computer, in order to capture the data of the three different words we want to recognize.

In a similar fashion as the gesture input, the database files are then imported in a Jupyter notebook to train the ML model with Google TensorFlow. The trained model is then used with the TinyTrainable library and uploaded to the Arduino microcontroller to detect the three different words.

The speech input is the most complex and time-consuming one to implement, and we need a computer for both capturing the data and training the model. A positive aspect is that just like the gesture input, the training is persistent, the Arduino microcontroller only needs to be trained once for the same database, and remembers

the model every time it is turned on, unlike the color input which forgets the trained model.

Just like the gesture input, the speech input can be trained either on the cloud using Google Colab, or can be trained on your machine. Because of its complexity, I do advise that the time difference is significant: on my Macbook the model took between one and two days to train, in comparison with the gesture model which takes around two hours in my machine.

The speech database we built is the most compromising one, since it is identifiable, and it could even be used for cloning our voice with deepfake techniques. So this is the one I encourage people to be more mindful about when publishing their custom databases.

2.4 Outputs

The 7 possible outputs of the TinyTrainable library were chosen to showcase many artistic mediums, with the hope that this library can be incorporated into the practice of artists working with light, visuals, sound, sculpture, dance, and poetry, among others.

The TinyTrainable library includes four examples for each one of the seven outputs: one for checking that the wiring is correct on the breadboard, and combinations with each one of the three inputs. Each example is an homage to the classic *hello world* examples of computer science education; that is, they are introductory building blocks, intended to teach artists the basics of each output so then they can continue on their own.

All the materials for the outputs are illustrated by the corresponding image of the product page on the website Adafruit, which I recommend for beginners and artists

interested in building their own Tiny Trainable Instruments.

2.4.1 Buzzer output

The buzzer is a device that can vibrate and that emits sound. The TinyTrainable library allows you to output a different sound for each of the three different input classifications, by controlling two fundamentals of the sound: frequency and duration.

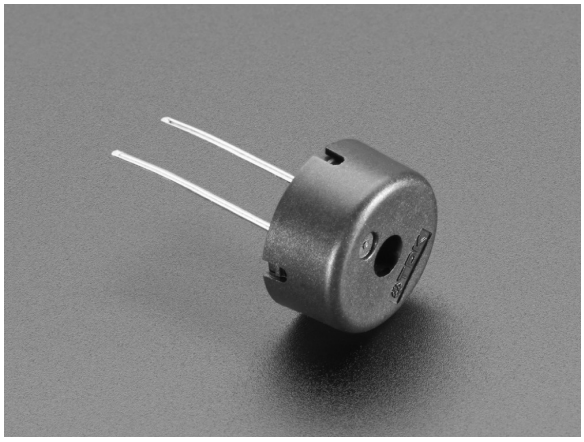


Figure 2-8: Buzzer
Retrieved from [17]

I wanted to include the buzzer because of its low cost and low fidelity sound, which make a big constrast with the complexity of the technology involved in doing tiny ML, resulting in cutting edge technology driving a cheap buzzing sound.

This output requires no additional libraries, the Arduino microcontroller by itself is able to generate the pulse-width modulation (PWM) output required to drive the buzzer.

2.4.2 LED output

The LED is a device that emits light. The TinyTrainable library allows you to toggle on and off three different LEDs, depending on which of the three possible inputs was

detected by the ML algorithm.

Figure 2-9: LED
Retrieved from [18]

This output requires no additional libraries, the Arduino microcontroller by itself is able to provide enough power to light up most hobby LEDs.

2.4.3 MIDI output

Musical Instrument Digital Interface (MIDI) is a protocol invented in the 1980s to allow musical instruments to be interconnected and share information, including musical notes, control parameters, and timing. Traditionally, MIDI instruments have a 5 pin DIN connector, (from the German Deutsches Institut für Normung), like the one pictured here for use on a breadboard.

MIDI can be used for transmitting all sorts of data, and thesis examples how to use MIDI to control different aspects of MIDI-enabled instruments, including synthesizers and drum machines. As a bonus, I wrote examples to interface with three synthesizers from the volca series by Korg: volca bass (analog bass machine), volca beats (drum machine), and volca keys (polyphonic synthesizer). I picked these synthesizers to haveboth melodic and percussive musical elements, because of their huge popularity, their relatively low price of 150.00 USD, their extensive MIDI capabilities, and because I am a huge fan of the instrument designs by Tatsuya Takahashi.

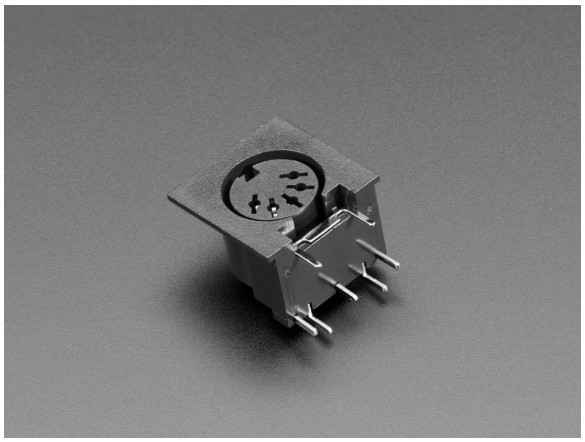


Figure 2-10: MIDI DIN connector
Retrieved from [19]

This output requires no additional libraries, since the Arduino microcontroller by itself is able to communicate via serial protocol, and the MIDI protocol is a subset of serial, at a particular baud rate.

2.4.4 Printer output

I used to associate printing with expensive toners and ink cartridges, and mostly frustration. This radically changed when I took a physical computing class, where I learned about thermal printers and how I could use Arduino microcontrollers to drive them! I find these thermal printers amazing because they are mostly a one-time investment and they don't need anything besides paper and power, so I have used them for interactive art installations since then. That is why I decided to include support for them on this project.

The thermal printer kit I recommend on the bill of materials is around 60.00 USD, and includes the power supply and paper roll. I picked this one because it is sold and supported by Adafruit, and I am a huge fan of their software libraries and tutorials.

With this output, you can create a Tiny Trainable Instrument that can print different texts and in various fonts and formatting, depending on the classification of the input.

Figure 2-11: Thermal printer kit
Retrieved from [20]

I hope this inspires a new generation of computer poets and interactive literature!

This output requires 1 additional library, the Adafruit Thermal Printer library, which is open source and includes several examples for expanding the functionality of it. If you want to use an alternative hardware or software for thermal printing, you can fork the TinyTrainable library and make it your own way.

2.4.5 Screen output

In contrast to the static nature of the output of the thermal printer, which prints a fixed message on a piece of paper, I included support for using a screen for dynamic messages on a surface.

This output requires 1 additional library, the Adafruit_SSD1306 library (and its own dependencies), for the particular screen I recommend on the bill of materials. The same vendor Adafruit offers many alternatives in different sizes, technologies, and color support. I encourage people to use different screens from different vendors, and fork and adapt the TinyTrainable library to accomplish it.

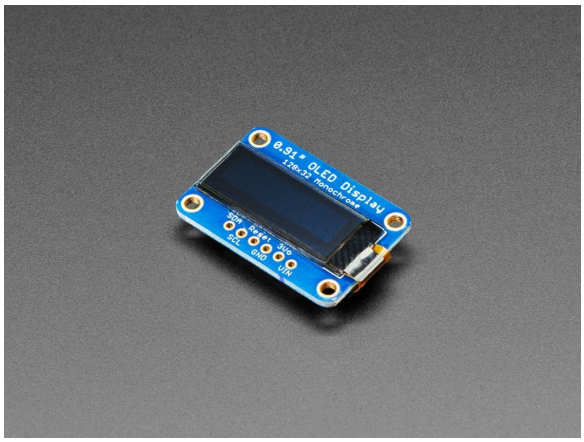


Figure 2-12: Screen
Retrieved from [21]

2.4.6 Serial output

This output uses the same USB cable we mentioned earlier, for delivering the power and uploading code to the Arduino microcontroller. We can use the same cable to send messages over the serial protocol, and receive them on the Arduino IDE, or in any other software that reads from the serial port.

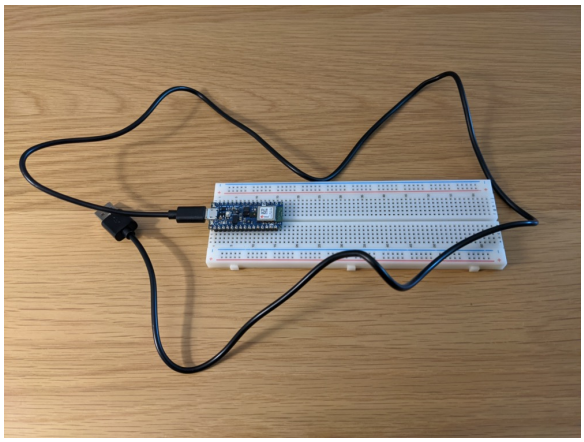


Figure 2-13: Tiny Trainable Instrument with serial output
Picture taken by myself

This output is useful for proofs of concept, for quick testing of the input classification before wiring a more complex output, and also for doing low-level communication with other serial software on your computer.

This output requires no additional libraries, since the Arduino microcontroller by itself is able to communicate via serial protocol, and the MIDI protocol is a subset of serial, at a particular baudrate.

2.4.7 Servo output

This final output is one of the cheapest ones, along with the buzzer, and that is why both are included on the workshop that I will mention later on this document. This is another example taken from the tradition of learning how to use servo motors on physical computing classes when learning how to program Arduino microcontrollers, and that is why I inlcuded support for them on the library.

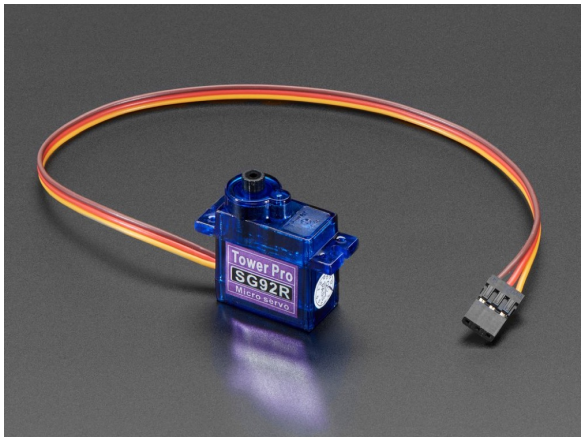


Figure 2-14: Micro servo motor
Retrieved from [22]

I see the servo motor as a very versatile output, which can be thought of as a generator of movement, so our Tiny Trainable Instrument can dance in space, or point at different places. For this library I programmed support for moving the servo at different tempos, even with some random noise for hiccupy movement, so that the servo motor can be thought of as a robotic arm for drumming or tapping on different surfaces for music. In this image you can see an example of this with some tape and wire for extending the arm of the servo motor.

This output requires no additional libraries. The Arduino microcontroller by itself

is able to generate the pulse-width modulation (PWM) output required to drive the servo.

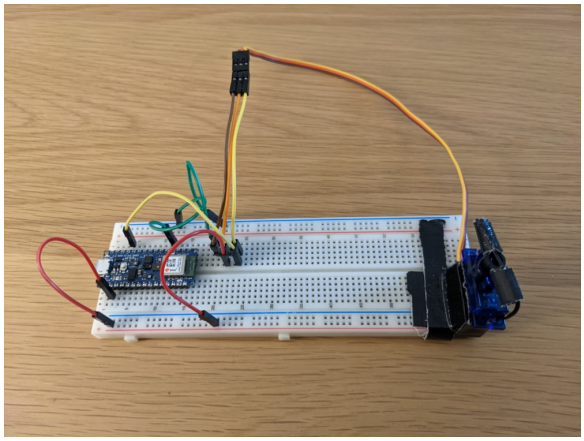


Figure 2-15: Tiny Trainable Instrument with servo output
Picture taken by myself

2.5 Code to build databases and train ML models

One of the biggest challenges I have encountered when working with ML is to find a suitable database, that I am comfortable to work with, and that I know how to use. Often, the solution to my artistic project is building my own databases, which I have done in the past by scraping the web, or doing very tedious manual work, and I do these experiments on my computer, and not publish them becasue I don't want to infringe anyone's copyright.

This project does not include techniques for web scraping, since I don't want anyone to run in trouble, and also because I enjoyed to use the Arduino microcontroller and my computer at the privacy of my room, to build the necessary databases for gesture and speech recognition, and I want to share that with artists.

In the repository that holds this thesis, available at `https://github.com/montoyamoraga/tiny-trainable-instruments`, I included a folder called *notebooks/*, with Jupyter notebooks written in Python 3 and using the Google TensorFlow library for

training.

2.6 Workshop and educational material

A big part of my practice is teaching computation to artists and beginners, so I included as much documentation as I could think of during the making of this thesis. I also hope the fact that this thesis was built in small increments, which were saved and published in the repositories that make up this project, can be considerd as having educational value. Many of my favorite things I have learned has been thanks to other artists' generosity of sharing not only the output of their work, but also their process.

This thesis includes documentation all through it: the source code is commented, there are README files for helping navigate each repository and folder, the library includes examples with each section commented and explained, and the library complies with the Doxygen standard for generating automatic documentation.

I also designed, wrote, and taught a remote workshop for beginners with the Tiny-Trainable library. This workshop was four hours long, spread over two sessions of two hours each, and they were attended by 6 or 7 people each time. I taught the workshop three times at the end of June 2021, twice in English for people based in the U.S.A., and once in Spanish for people based in Chile, to a total of 20 participants. All the materials were funded by a generous grant from the Council for the Arts at MIT.

2.7 Design principles

Here is a summary of the main design principles I followed when making decisions and building this thesis project.

2.7.1 Affordable

The software library is virtually free, and it can be downloaded from the internet at no monetary cost; only bandwidth and time and hard drive costs.

The materials picked were the cheapes ones I could think of, and they are often used in similar educational contexts because they can be reusable and are forgiving to mistakes. The microcontroller is a one-time investment, and the outputs range from 2.00 USD to 60.00 USD.

The materials for the workshop for building Tiny Trainable Instruments with buzzer, serial, and servo outputs had a cost of only 60.00 USD, including shipping.

2.7.2 Open

All examples included with this library were written with the aim of showing the fundamentals of how to build the instruments and different ML-enabled manipulation of multimedia material, so that people could build on top of it and make it their own, by changing the values of variables and adding more functionalities.

2.7.3 Remixable

All the process and the code is open, and I wish that the TinyTrainable library can be used as a dependency on other people's projects. I also hope that people modify this project and make it their own, building their own spin-offs.

2.7.4 Private

A huge emphasis I wanted to stress is to make people feel safe while handling the data. Maybe nowadays we are used to being surrounded by surveillance cameras when we are in public, or even at our homes with devices that listen to us and are connected to the cloud. I hope that this thesis can provide a computational experience that feels safe, respects your privacy, and makes you critical and aware of the issues of modern industrial machine learning applications.

2.8 Development

This thesis has been developed in collaboration with MIT undergrad researchers Peter Tone and Maxwell Wang, and funded by the MIT UROP office and the MIT Media Lab. Peter Tone helped with research in data structures, library writing, and programming different sections of the library, from the most experimental features to the most polished ones, and also helped with the design of the user-facing methods and variables. Maxwell Wang helped with proofreading the code, making sure the language of the examples and documentation were appropriate for beginners, and helped with the planning and conceptualization of the workshop.

This collaboration was remote, and made possible over issues and pull requests in repositories, and notes in shared Google Drive documents.

The most difficult bottlenecks that I faced while programming this library were solved by office hours with Chilean artist and programmer Roy Macdonald.

2.9 Code details

This thesis is distributed as a repository, hosted on the GitHub platform, and available at https://github.com/montoyamoraga/tiny-trainable-instruments.

The auxiliary files, such as the LaTeX project for this document, and the auxiliary Jupyter notebooks, and documentation and tutorials are included in this repository.

The main software component of this project is the TinyTrainable library, available at https://github.com/montoyamoraga/TinyTrainable and also through the Arduino IDE.

The code included in this library is distributed through the folders:

1. examples/
2. src/

2.9.1 src/

The source code for where there is a TinyTrainable.h and TinyTrainable.cpp file where we included all the basic functionality of the library. Additional subfolders include

inputs/

This folder contains the C++ files for the output base class, and the files for each of the 3 inputs that inherit from the base class. Each input file imports the necessary library dependencies and acts as a wrapper for them.

outputs/

This folder contains the C++ files for the output base class, and the files for each ofthe 7 outputs that inherit from the base class. Each output file imports the necessary library dependencies and acts as a wrapper for them.

tensorflow_speech/

This folder contains auxiliary files for the speech input, copied from the examples from the Arduino TensorFlow Lite library. Unless other otherwise noted, are included without modifications and distributed through the Apache License included on each file's headers.

2.10 Auxiliary tools

This is a summary of some auxiliary tools I used for making this project.

2.10.1 clang-format

Tool for automation of formatting to source code. More information at `https://clang.llvm.org/docs/.ClangFormat.html`.

2.10.2 Doxygen

Tool for generating documentation from the source code. More information at `https://www.doxygen.nl/`.

2.10.3 GitHub Actions

Every time we push code to the TinyTrainable repositories, a GitHub action creates a virtual machine, and runs a script to generate the Doxygen documentation and push it to the gh-pages branch, hosted at `https://montoyamoraga.github.io/TinyTrainable`.

2.10.4 Jupyter

Jupyter is a free, open-source browser application that allows users to easily read and write code in a clean, accessible environment. Code is segmented into cells, which users can run individually by clicking into and selecting the triangle "play" button at the top. Subsequent code runs based on operations done in previous cells. Basically, Jupyter notebooks allow programmers to create clean, step-by-step interactive walkthroughs for their code. More information at `https://jupyter-notebook-beginner-guide.readthedocs.io/en/latest/index.html`.

2.10.5 Markdown

Markdown is a lightweight markup language with simple, intuitive syntax. Aside from a few key differences, it is largely the same as plaintext. The documentation of this project is written using Markdown, including this document! More info at `https://guides.github.com/features/mastering-markdown/`

Chapter 3

Early experiments

> And you may ask yourself
> "Well... how did I get here?"
>
> Once in a Lifetime
> Talking Heads, 1981

In this chapter I showcase early experiments in the different fields I worked on this thesis, with a strong focus on the different aspects of my education and artistic practice. I include many of my breakthroughs and pitfalls that eventually led me to working on this thesis, in an open, detailed, celebratory, and critical narrative.

3.1 Learning microcontrollers

I learned how to program microcontrollers around 2010 in Chile as an undergraduate student of electrical engineering. I was taught how to program PIC microcontrollers with Microsoft's tools, including the operating system Windows and the C# programming language. Around the same time, with my classmate Braulio we made our

first project with an Arduino Uno microcontroller. It consisted of a robotic guitar tuner, where the Arduino detected the pitch of a string, analyzed the frequency, and then made a servo motor move the tuning gear of the string, in order to match the desired pitch.

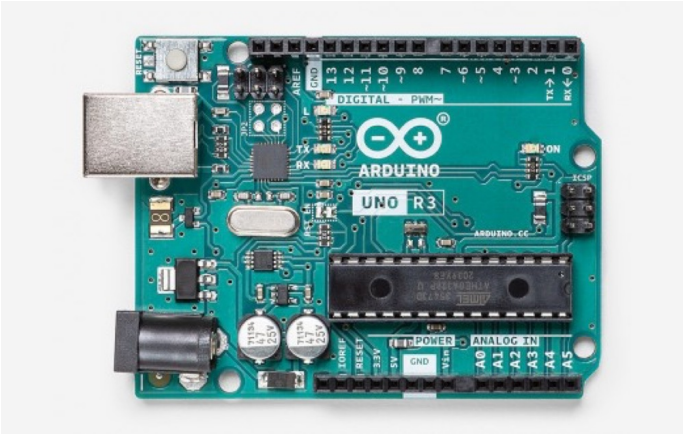


Figure 3-1: Arduino Uno microcontroller
Retrieved from [23]

Fast forward to 2013, for my undergraduate thesis I had to complete a capstone project and implement many low-level programming techniques, and Arduinos were not allowed because they were considered a shortcut. For this thesis I worked with my classmate Guillermo, and we built a robotic device with a PIC microcontroller programmed with C#. Our code was very specific to that particular chip and project, and hardly reusable or interesting for a wider audience.

Since graduation I haven't programmed with PIC microcontrollers. I realized I wasn't excited about making one-off devices, with non-reusable code that I couldn't share, or having to use propietary or bulky interfaces for writing for deploying my code. In contrast, Arduinos became a huge part of my practice, because of their low cost, open source nature, ease of programming and uploadin the code with a generic USB cable, and because of the enormous and growing available documentation and user contributed libraries, which now also include the TinyTrainable library developed for this thesis project.

The Arduino ecosystem fostered many aspects of my practice, and now looking at it

in retrospect, I realize that what I love is not computers but computation, making small machines that can crunch numbers for art, and making them openly and in collaboration with friends.

A huge argument that I see people on the internet making against Arduino microcontrollers, is that they are too expensive (30.00 USD) in comparison to the 1/10th of the cost of the bare bones chips and parts you need to build your own microcontroller unit. I am against this argument, since it invisibilizes the effort put in documentation by the Arduino community, and also it assumes that everybody is comfortable soldering and with high advanced electronics degrees. Even if you factor in the cost of hours you need to make your own, it doesn't pay itself. Obviously I see and the educational aspect of building your own things, but it's a slippery slope and involves subtle discrimination to think that if you build a project with an Arduino, it's not good because it's not from scratch, and I think it's rude t say it's not worth it, as rude as yelling at someone buying bread and making fun of them for not buying the ingredients and cooking it themselves.

Another strong argument against Arduino microcontrollers is about efficiency: that Arduino is too high-level and over-bloated, and that applications and projects could be faster if you programmed in a lower-level language. I also see this argument when comparing different programming languages for graphic arts. Once again, knowing how to program with lower-level programming languages is amazing, and there is value and fun on it. But in my practice, I put a high value on my time and energy, and I'd rather make my code slower or less efficient so I can spend more time making art or resting.

I'd rather that we all have non-painful programming experiences, so that we can spend more time away from screens and doing more important things!

3.2 Computer music and physical computing

During undergrad studies, I took classes and did research with professors and computer musicians Rodrigo Cádiz and Patricio de la Cuadra. With them I learned the fundamentals of computer music, including languages such as Max and Pure Data, which I still use to this day. For a class project I created a spoon synthesizer with masking tape, cardboard, and a Makey Makey, a device created in 2021 by Eric Rosenbaum and Jay Silver from the MIT Media Lab's Lifelong Kindergarten research group. This was my first hands-on introduction to physical computing, as a way of building my own custom playful interfaces for manipulating sound with computers.

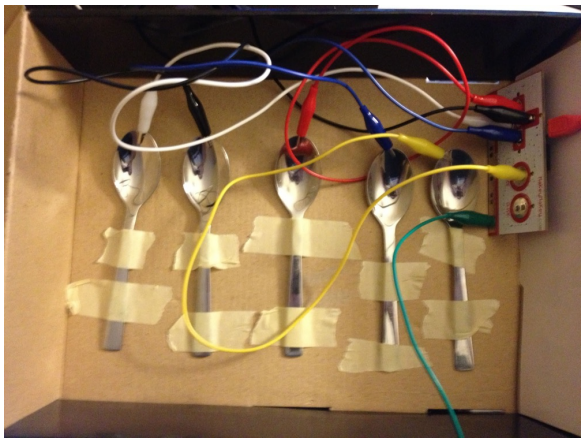


Figure 3-2: Spoons and Makey Makey synthesizer
Picture taken by myself

For this project I applied my practice as a guitar player, where I am constantly mixing and matching different devices on my pedalboard. This inspired me to make this flexible synthesizer with objects lying around me: spoons, masking tape, and cardboard. They also are forgiving, and I was able to change their physical position. The Makey Makey acted as an interface with the computer, where I could assign on the fly different sounds to each spoon.

In retrospect, this project was an instrument an amazing experience that followed Mitchel Resnick's 4 P's: it was a Passion Project that I built for Playing with my Peers, which is a constant in my artistic practice.

3.3 Physical computing and more microcontrollers

After graduation in 2013 I freelanced as a software and technology designer and developer for artists. I learned computer protocols and networks, and wrote custom software for live multimedia theater and music shows. Realizing that I wanted a bigger community of people to learn media arts with, I applied to New York University's Interactive Telecommunications Program (NYU ITP), where I joined as a graduate student in 2015. In my first semester, I took the class Introduction to Physical Computing, taught by one of Arduino's co-creators, Tom Igoe. Since I was already familiar with electronics and circuits, I focused on learning interface design, human computer interaction, open source hardware and software, and physical computing education.

During my research I was introduced to a wider ecosystem of microcontrollers beyond Arduino, that were made possible because of its open source nature and the community behind it. My favorite example is the Teensy by PJRC, which captivated me by two main features: it can send and receive MIDI over USB, and it has a powerful audio library that allows you to play audio samples, create effects, and process real time audio. With the Teensy, I was able to make standalone projects in a way that before would have required me to use a full-fledged computer.

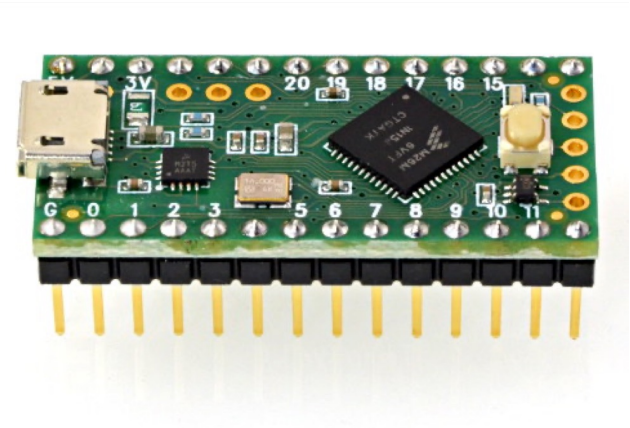


Figure 3-3: PJRC Teensy LC microcontroller with pins
Retrieved from [24]

3.4 Processing, p5.js, Processing Foundation

Processing is an open source software written in Java, and it was started at MIT Media Lab's Aesthetics and Computations group by Ben Fry and Casey Reas. Over the years I have learned Processing on my own, and through it, computer graphics and interactivity.

I was excited to learn more Processing in 2015 in my first semester at NYU ITP's Introduction to Computational Media class, like it had been taught for around a decade. I consider myself lucky, because that year they replaced the curriculum in Processing with a new one based on p5.js, another software library supported by the Processing Foundation.

p5.js was created by Lauren McCarthy as a reinterpretation of Processing, using JavaScript instead of Java, to make art that runs on web browsers and over the internet. With p5.js I learned artistic and creative ways to program web applications, and this experience led me to focus on educational outreach with the Processing Foundation, which I will mention in the next section.

I was not only in awe of p5.js and Processing, but also of the people and the communities behind these software libraries. I took Lauren McCarthy's Performing User class [25] at NYU ITP, and it was my favorite class during my Mmaster's there. She fostered a safe space for us to explore societal and political implications of software, and it led me to add more of my personal convictions, and my body, to my artwork. This class inspired me to make a self portrait, with a countdown timer to my projected death time according to the United Nations' estimates. The first version I did was a Processing app running on a Raspberry Pi computer, and I also ported it to p5.js for web access.

Figure 3-4: PJRC Teensy LC microcontroller with pins its-ok-to-die, on a browser with p5.js

3.5 Teaching media arts

While I was a student at NYU ITP, I was the recipient of two summer grants to work on an internationalization project of p5.js. Since my native language is Spanish, and I wanted to share all my passion for web programming with p5.js, I focused on translating the official p5.js website and book to Spanish, and teaching introductory workshops in Spanish in my home country, Chile. My main goal was to let people be able to learn and enjoy p5.js without having to first learn English. Since then, this project has been expanded to other languages, and I am still a contributor to p5.js.

Another reason why I wanted to teach and share p5.js is because still to this day their community statement [26] is one of my favorite documents, fostering an inclusive environment for artists. This document inspired the ml5.js community statement [27], a ML library for arts created at NYU ITP with a strong emphasis on AI ethics.

In my workshops and classes, when I have taught p5.js or ml5.js, I like to take a moment with my students to read the community statements, and also to read the

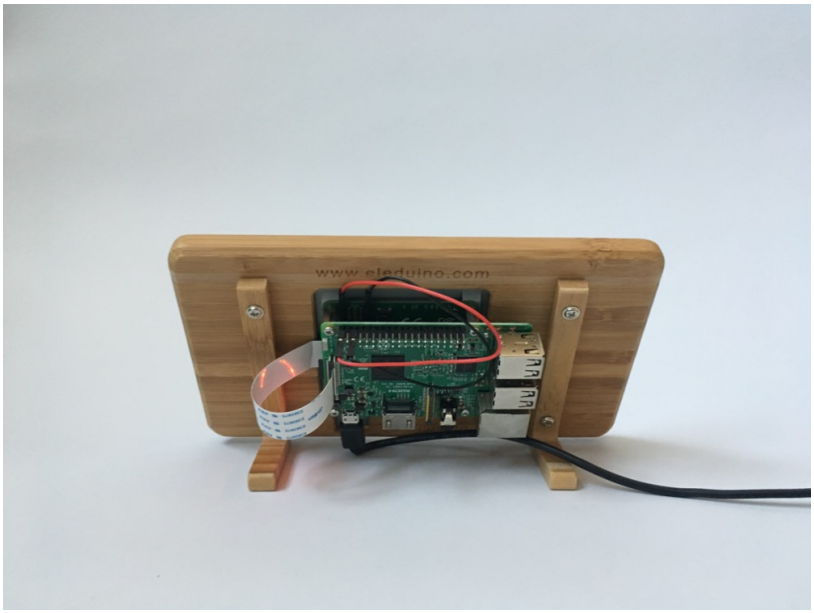


Figure 3-5: its-ok-to-die, on a Raspberry Pi computer
Picture taken by myself

source code, and show them the repositories where these libraries are developed. I think it is very educational to take a moment and acknowledge the work made by the community to build these libraries. I also like to point out that these libraries are not made out of scratch (Hennesy Youngman claims that in the arts, we ran out of scratch in the 1960s ([28]). p5.js is a wrapper for drawing and interactivity features of HTML5, and ml5.js is a wrapper of Google's TensorFlow.js.

Another feature of my classes is that even though I always like to pick a particular framework, I like to give students an overview of different software that they can use to achieve similar results, so that they can work in an agnostic way; even if they don't continue using the tools I teach, they learn fundamentals of programming and arts. Since most of my recent workshops and classes have been short crash courses on complex topics, I like to share resources with students so that they can continue learning on their own, and that is why I enjoy being a contributor and maintainer of documentation of open source projects.

I hope that people find the documentation and writing of the TinyTrainable library useful, and that even if they don't end up using it, they learn fundamentals of pro-

gramming, ML, and how to use the different outputs and protocols I showcase.

3.6 Publishing libraries

After years of working with different software libraries for arts, and publishing my code and teaching with it, I started packaging and writing my own software libraries, with the hope that people can reuse my code and learn from it. My first experiments were in the Python ecosystem, where I have published protestpy [29], a library for creating protest material, and kaputtpy [30], a library for ruining digital devices.

Figure 3-6: protestpy image for protesting against trees
Screen capture by myself

Publishing my libraries so they can be installed with one-click or a command line, and making them depend on other libraries and languages, is for me an exercise in trust, and a way to give back to other artists what I have learned. It is to me like building a skatepark or a hiking trail, you build infrastructure so that other people can use it for their own needs, mostly for fun and art :)

Apart from these software libraries, I have on-and-off made small publishing ex-

periments in other ecosystems, such as Max, Haskell, and Node.js, but the bulk of my work since 2016 is published as Git repositories on my GitHub at `https://github.com/montoyamoraga/`.

Figure 3-7: Github contributions
Screen capture by myself

TinyTrainable is my first library for hardware, and this experience has led me to publish libraries for other projects I have been working on, and also to publish alpha releases for libraries that were inspired by this thesis, but that I think are out of scope, so I plan on working on them after graduation.

3.7 ML for arts

My first project in this field was in 2016 with my NYU ITP classmate Corbin Ordel, who was a student at Gene Kogan's ML for Artists class. Together we audited Rebecca Fiebrink's ML for Musicians and Artists class, available at the Kadenze platform, and learned the Wekinator platform. As a final project for Gene's class, with Corbin we made the project Piano Die Hard, a digital sculpture consisting of a piano that is watching the trailer for the movie Die Hard, and every time it detects an explosion, it plays music as accompaniment.

The technology stack for this project was very convoluted: a computer looped the trailer of the movie and fed it to an old TV and to an openFrameworks app. This app outputted statistical descriptors about the color of each picture frame, which were then sent to the Wekinator app, which decided with a k-NN algorithm if the image

Figure 3-8: Piano Die Hard
Retrieved from [31]

was either an explosion or not. When it detected an explosion, we sent a control signal to an Arduino, which moved a motor connected to a fishing rod and a kitchen utensil, which scratched the strings of the open carcass of an old piano every time there was an explosion.

The training of the model was made beforehand with a selection of 1980's movies, featuring scenes with and without explosions. This project was a direct inspiration for the color input of the TinyTrainable library, mixing color data with a k-NN algorithm, and it's really fascinating for me to compress all of this complexity of 5 five years ago, needing a computer and different apps, into a single microcontroller. I hope that everybody can enjoy this too.

After graduating from NYU ITP and working for one year as a research resident and graduate teaching assistant, I was exposed to many exciting developments in AI and creativity, including witnessing the creation of the the ml5.js library and the company RunwayML by Cristóbal Valenzuela, Alejandro Matamala, and Anastasis Germanidis. Through this I became excited about the creative potential of ML, so in 2018 I took a month-long intensive class at the School of Machines in Berlin, Germany, facilitated by Gene Kogan and Andreas Refsgaard, and organized by Rachel Uwa.

During this workshop I learned many different tools for ML, and also did my first experiments in creating my own custom databases. I got a mix of excitement for the graphic and plastic possibilities that AI gives me, but the main bottleneck that I found was the databases. The algorithms I was trying to play with needed very specific requirements in terms of their data input, such as specific image resolution, file formats, and file size. So even if you found a database, you had to modify it. During this month my work focused on learning how to create databases with web scraping, which you can find at this repository `https://github.com.montoyamoraga/scrapers`. This is also the basis for the research in custom databases that I conducted during this research, and my draw towards using the Arduino microcontroller as a source for data, and I hope my contributions in how to parse data and how to build your own databases is helpful to others.

For people who are interested in the rich field of image generation with ML, I highly recommend the book on GANs by Casey Reas, published by Anteism, as of 2021 on its second edition. It's an arts-first book that contextualizes the use of ML algorithms for the creation of images, and uses the metaphor of these algorithms as being similar to the development of the camera. Artists don't necessarily need to understand all the physics or mechanics behind a camera in order to make art with it, but it can definitely help to understand it too. I think that ML is a revolutionary strategy for instrument-making and the arts, while also introducing new civic complexities, and in this thesis I have tried to follow the example of Reas' book, to introduce the technology and contextualize for a new generation of artists and instrument makers.

Chapter 4

Background and inspiration

It has to start somewhere
it has to start sometime
what better place than here?
what better time than now?

Guerrilla Radio
Rage Against the Machine, 1999

4.1 Microcontrollers as alternative to computers

When I joined MIT Media Lab in 2019, I made the decision to focus my efforts on hardware research, so I could make computational art devices, instead of software that needs to run on a laptop computer or a browser. This was fueled by the introduction of restrictive news by Apple, such as advising against the use of apps created by unregistered developers and discontinuing support for 32-bit apps, and by the ever-changing nature of the web, which makes my online artwork break often and need maintenance, and the need for additional corporate infrastructure to keep it online.

In contrast I saw hardware as a space where I could deploy my ideas and keep them running without outside intervention.

I started my research by catching up with the newer developments by Teensy. The newer microcontrollers are faster and more powerful, and I used them to design and implement many small projects. I want to mention this personal project, a standalone audiobook I made with rotary encoders and a small screen for navigation, because it led me to include software for support of this same screen in the TinyTrainable library.

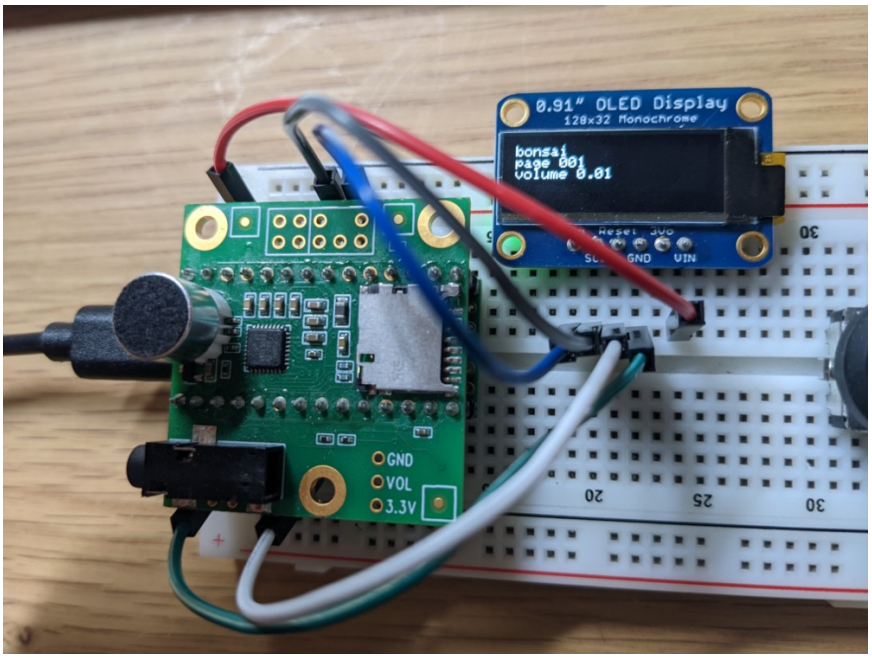


Figure 4-1: Audiobook made with Teensy
Picture taken by myself

In parallel, I researched the evolution of the teaching of physical computing at NYU ITP, and I discovered that they stopped teaching with the now classic Arduino Uno, and have replaced it with the newer series of Arduino Nano microcontrollers, which have a smaller format and and operating voltage of 3.3V instead of 5V.

While browsing this series, I discovered the Arduino Nano 33 BLE Sense that I based my thesis now. It comes with 9 emedded sensors, to measure and detect acceleration, movement, distance, color, and a microphone. This is an amazing help

for beginners, since a huge challenge when you are starting to build your own projects and learning electronics, is reading datasheets to understand what sensors you can use with your microcontroller, how to wire them and callibrate them, and then what library supports it. This makes it easier and cheaper to prototype, and this made my work on my thesis easier, since I didn't have to include instructions for wiring sensors or callibrating them, and I could focus on ML and the different outputs for arts.

4.2 Coursework at MIT

As part of the research that directly inspired this thesis, here is the coursework I took, and my notes about how they inform my theoretical and practical background for Tiny Trainable Instruments.

1. Fall 2019, CMS.901 Current Debates in Media, by professor Sasha Costanza-Chock
2. Fall 2019, MAS.S65 Recreating The Past, by professor Zach Lieberman
3. Spring 2020, MAS.826 Sound: Past and Future, by Tod Machover
4. Spring 2020, MAS.712 Learning Creative Learning, by professor Mitchel Resnick

In the class Current Debates in Media, topics covered included fake news, surveillance, algorithmic bias, data colonialism, climate justice, algorithms of oppression, among others. For my final paper I wrote on the role of the media during the 2019 Chilean protests. This class directly inspired me to look for privacy-first ML, and thinking about AI in a critical way and not as clean safe automation, but as invisibilized labor, exploitation, and algorithmic bias and discrimination in the worst scenarios.

In the class Recreating the Past, I learned about media arts history, and I dived deep in the language C++ which I used for writing the TinyTrainable library, while

working with the library openFrameworks, which is one of the most popular open source frameworks and communities for media arts.

In the class Sound: Past and Future, I learned more about the history of different computational advancements for sound, with a strong focus on projects at MIT Media Lab's own research groups including Opera of the Future, Hyperinstruments, and Music, Mind, and Machine. This class introduced me to many projects and it helped me decide on making instruments for my thesis, using the latest technologies I could find, in this case, microcontrollers and ML.

In the class Learning Creative Learning, I was introduced to the Lifelong Kindergarten's frameworks and ideas, including the 4 P's (peers, projects, passion, and play), and the design of Scratch as a home with low floor, wide walls, and high ceiling, which I highly recommend to check on Mitchel Resnick's book Lifelong Kindergarten. This class gave me the push to write a library with a community in mind, starting with the development of it, which happened because I had the pleasure of working with MIT undergrads Peter Tone and Maxwell Wang, who helped me with different aspects of research and development.

4.3 Research projects at MIT

Some other projects I created during this master's include:

1. SiguesAhi: an instrument to detect when oppressive institutions have ceased to exist. It is achieved with microcontrollers with Internet connectivity.

2. Open Drawing Machine, with Gaurav Patekar: an open source low cost programmable drawing machine

3. Introduction to networks for artists: a series of tutorials for beginners, to learn

how to set up their own networks and collaborate in peer-to-peer ways for making art.

SiguesAhi is a sibling project to Tiny Trainable Instruments. It is based on a microcontroller from the same series and format but different architecture and capabilities, the Arduino Nano 33 IoT.

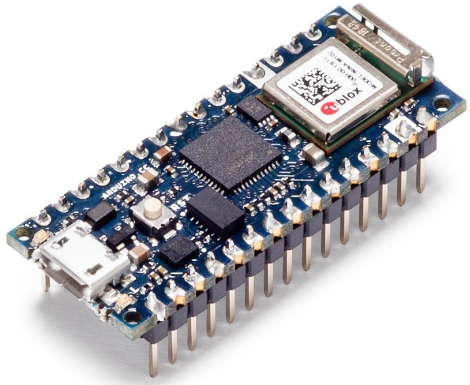


Figure 4-2: Arduino Nano 33 IoT with headers
Retrieved from [32]

For this project, I am writing a library for making digital instruments that can detect if institutions still exist. This is accomplished by connecting the microcontroller to the internet, and making it ping the Wikipedia website with a certain periodicity, in order to download and check the first sentence of the first paragraph of the entry. As an example of the library, I am using the National Rifle Association, which sadly still exists.

The [33, Open Drawing Machine] is a collaborative project with Gaurav Patekar for the research group Future Sketches at MIT Media Lab. It is a low cost open source machine, consisting of an Arduino microcontroller and hardware for drawing computationally. We have done the research together, Gaurav designed and 3D printed the hardware, and I have packaged the results as a still unfinished openFrameworks addon.

Currently the Open Drawing Machine can receive drawing commands from a com-

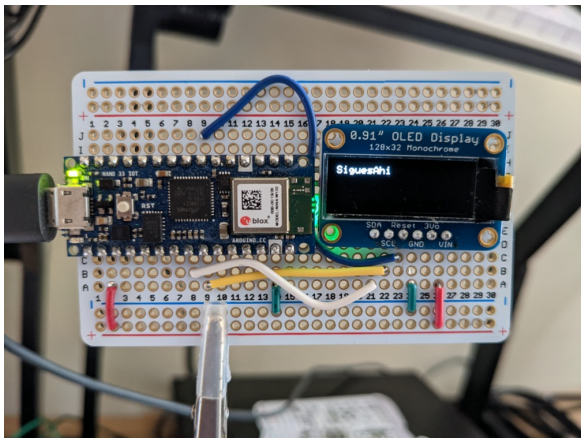


Figure 4-3: SiguesAhi project
Picture by myself

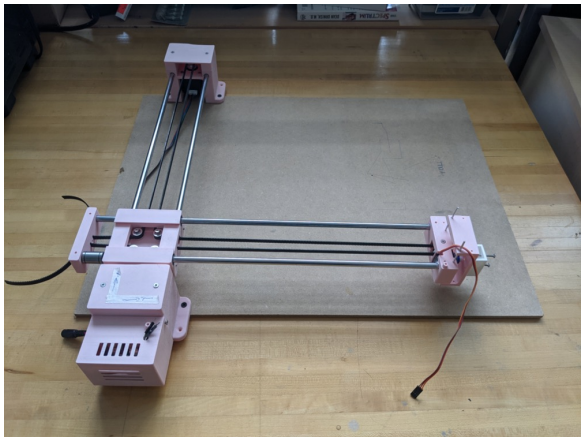


Figure 4-4: Open Drawing Machine project
Picture by myself

puter through a serial port, and the next step of this project is being able to receive commands from other computers through networks and the internet. This comes from the last project I will mention that I worked on while at MIT Media Lab, which is Introduction to computer networks for artists [34], a collection of tutorials for remote peer-to-peer collaboration between artists. This project is inspired by the amazing research on remote collaboration, sensors, peer-to-peer protocols, by friend Lisa Jamhoury, including the app Kinectron.

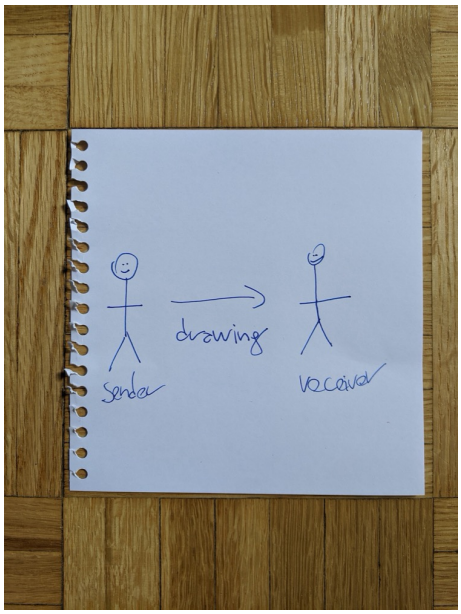


Figure 4-5: Introduction to computer networks for artists project
Picture by myself

4.4 Computational media arts instruments

There is a rich ecosystem of personal computers, operating systems and software for making art, and it is common nowadays for artists to rely on their computer for making all of their art, on the go, wherever they are. In the 1990s, musicians stopped having to rely on analog hardware, and started replacing their tools for recording and mixing with software on their computers.

Apart from the proliferation of laptop computers and software for arts, I will share my research in devices that I like to call computational media arts instruments. They are computational because they are digital and crunch numbers, and they are instruments that allow us to process different media in creative ways.

I will focus on the instruments that can be programmed, and that promote open source hardware or software. Many of these instruments often sit at my desk for inspiration, or I spend hours playing with them for my art and learning from them and the communities around them.

The tables 4.1 and 4.2 are respectively summaries of techniques and influences of the instruments that I reference in this section.

Company	Instrument	Year	Basis	Software
Bastl Instruments	Illuminati	2019	MCU	None
Bastl Instruments	Kastle Drum	2020	MCU	Arduino, C++
Bastl Instruments	Kastle v1.5	2017	MCU	Arduino, C++
Bastl Instruments	OMSynth	2016	IC	None
Bastl Instruments	microGranny 2	2016	MCU	Arduino, C++
Bastl Instruments	Servo	2016	MCU	Arduino, C
Critter & Guitari	Organelle	2016	Linux	Pure Data
Critter & Guitari	EYESY	2020	Linux	Python, Pygame
monome	aleph	2013	Linux	C
monome	norns	2018	Linux	Lua, SuperCollider
Shbobo	Shnth	2013	MCU	Shlisp
Shbobo	Shtar	2017	MCU	Shlisp

Table 4.1: Technical details of media arts instruments

Company	Instrument	Influence
Bastl Instruments	Illuminati	Output with LEDs
Bastl Instruments	Kastle series	Use of breadboard and jumper wires
Bastl Instruments	OMSynth	Distribution as tutorials + parts kit
Bastl Instruments	microGranny 2	Arduino as basis for instrument
Bastl Instruments	Servo	Output with servo motor
Critter & Guitari	Organelle	Computer for sound
Critter & Guitari	EYESY	Output with screen
monome	aleph, norns	Computer for sound
Shbobo	Shnth, Shtar	Input with multiple gestures

Table 4.2: Influence of media arts instruments

4.4.1 Bastl Instruments

Bastl Instruments is a Czech company of multimedia instruments, which has had a huge impact and influence on my research and practice. When I first started researching the Eurorack format some years ago, I visited the shop Control in Brooklyn, NY, and some modules by Bastl stood out to me, because of their wooden panels and interaction with classic physical computing educational materials, such as motors and solenoids, which was an inspiration for me to include servo motors as an output in Tiny Trainable Instruments.

Figure 4-6: Bastl Instruments Servo module
Retrieved from [35]

Another inspiration comes from their microgranny 2 granular sampler which is made with an Atmega microcontroller and its firmware is open source and available as a repository on their GitHub account, along with many other of their instruments.

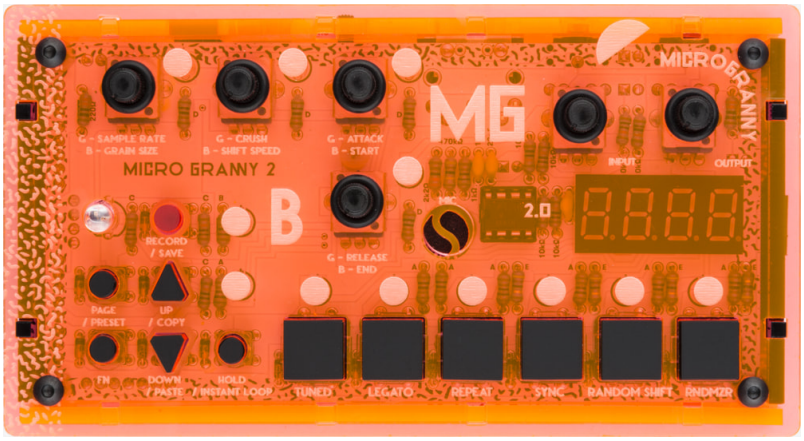


Figure 4-7: Bastl Instruments microGranny 2
Retrieved from [35]

Their Kastle synthesizers are also based on microcontrollers, and feature a patchbay for making connections with jumper wires, the same used for prototyping in electronic breadboards, which influenced me to make the Tiny Trainable Instruments built with breadboards and jumper wires, instead of custom printed circuit boards. Also, the Kastle synths are forgiving instruments, their inputs and outputs are robust enough to allow for mistakes in connections, in an electrical and mechanical way, which I think is perfect for safe experimentation. It would be a bummer if the instrument

was easy to break, or if it demanded a huge effort in understanding electronics for using it.

Figure 4-8: Bastl Instruments Kastle v1.5
Retrieved from [35]

As of writing, two different units are in production, both retailing for around 100.00 USD: the Kastle v1.5 melodic / drone synthesizer, and the Kastle Drum, for rhythm. The only difference between these synthesizers is the firmware and the labels on the faceplate. The community is encouraged to write new firmware to modify their behavior.

Figure 4-9: Bastl Instruments Kastle Drum
Retrieved from [35]

Another instrument I want to highlight is the Illuminati, currently discontinued, a device that uses different inputs (audio, control voltage, MIDI messages) to control the light intensity of connected USB lamps, which influenced the conception of Tiny

Trainable Instruments as multimedia arts instruments, not only focusing on audio and music, but also printed text, light, and screen output.

Figure 4-10: Bastl Instruments Illuminati
Retrieved from [35]

The final instrument from this company that I want to highlight is the OMSynth, one of many collaborations with Casper Electronics. This device is an educational and maker circuit development tool for creating synthesizers. It includes basic fundamental blocks, such as battery power, audio input and output, potentiometers for attenuating and boosting signals, and a suite of parts kits for building devices including sequencers, oscillators, and samplers, on the included breadboard. Its release as a kit was also a direct influence in the release of Tiny Trainable Instruments as a kit with instructions.

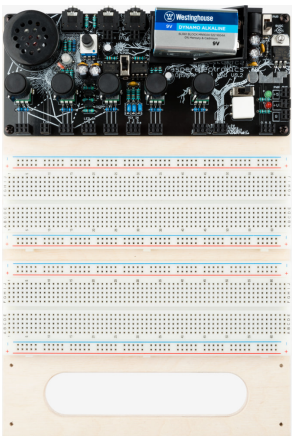


Figure 4-11: Bastl Instruments OMSynth
Retrieved from [35]

Many BASTL standalone instruments are 200.00 USD or less, which is a huge contrast to the 1960s, when a Moog analog system II cost 6,200.00 USD, which was enough to buy a small house [36]. Also, many of their instruments are sold as kits for building and soldering them yourself, for the cheaper cost and the added educational aspect of having hands-on experience.

4.4.2 Critter & Guitari

Critter & Guitari is an American company based in Brooklyn NY, which has released in the past computational microcontroller-based audiovisual instruments, from which my favorite is the Kaleidoloop, currently discontinued. It is a sampler with an internal mic and speaker, that allows you to record audio and then control its output with 2 knobs for volume and playback rate. It is designed to be portable for doing field recordings, and it was an influence on the design of the Tiny Trainable Instruments library, which allows the construction of standalone instruments, that with a USB power bank or a battery, you can take for a walk or place anywhere you want.

Figure 4-12: Critter & Guitari Kaleidoloop
Retrieved from [37]

In 2015, Critter & Guitari released the Organelle, a sound computer with the Linux operating system installed, and the software Pure Data as the programmable interface between the hardware and the sound engine. Every sound you can do on an Organelle

you could do on your laptop using Pure Data too, and you could build your own interface to interact with the sound.

Figure 4-13: Critter & Guitari Organelle M
Retrieved from [38]

ETC and EYESY computers for visuals, scriptable, Linux operating system + Python / pygame environment or openFrameworks.

Figure 4-14: Critter & Guitari EYESY
Retrieved from [38]

They can run on power supplies, and are also portable by the use of batteries.

4.4.3 monome

Aleph: earlier sound computer.

Norns: sound computer, currently on its second iteration, with expanded hard drive. Also there is a DIY version which is cheaper and runs on a Raspberry Pi. Norns is a

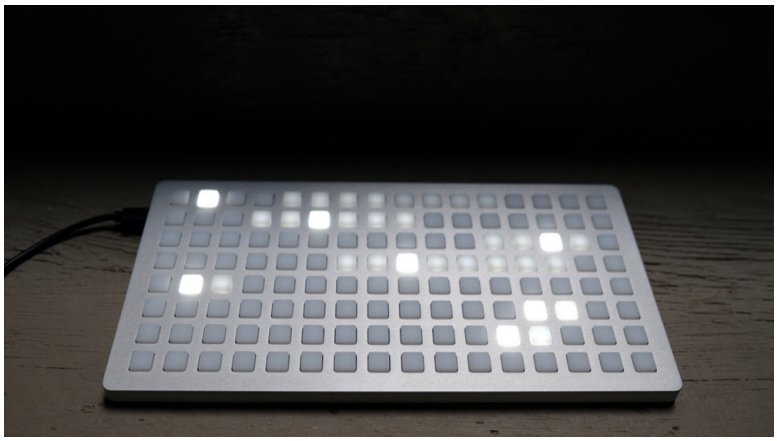


Figure 4-15: monome grid
Retrieved from [39]

Linux machine, running SuperCollider for the sound engine, and Lua scripts. It has spawned a community that continually releases new scripts and software updates.

Figure 4-16: monome aleph
Retrieved from [39]

4.4.4 Shbobo

In my first semester I was introduced by classmate Will Freudenheim to the Shbobo synthesizers by Peter Blasser. Peter Blasser has released several collections / companies of musical instruments, the most famous one being Ciat-Lonbarde.

Both run on microcontrollers, and they use a new proposed language called Shlisp,

Figure 4-17: monome norns
Retrieved from [39]

Figure 4-18: Shbobo Shnth
Retrieved from [40]

based on Lisp, and also they can be programmed using the Fish IDE.

As of 2021, their firmware and editor became open source, and it is available at `https://github.com/pblasser/shbobo`.

COMMENT ON OPEN SOURCE: something being open source doesn't necessarily mean it is accessible to a wider audience. Is one of the goals of your work to create instruments that are accessible to a wider audience?

They promote computer-centric approaches to making sound, such as the use of integers and metaphors of finite state machines, and also allow for different ways of

Figure 4-19: Shbobo Shtar
Retrieved from [40]

playing and sensing, such as the use of antennas for detecting hand distance, a microphone for detecting speech and whistling, and wooden bars with piezos for detecting pressure.

TODO: write how this inspired the new interactions i am inventing or appropriating for Tiny Trainable Instruments, such as a drum machine you can talk to, Alexa spinoff.

4.5 Education

This thesis is inspired by the work of the research group Lifelong Kindergarten at MIT Media Lab, led by professor Mitchel Resnick. In the book with the same title, he builds on Seymour Papert's work, and proposes that educational projects should have "Low floor, wide walls, high ceilings", and that learners thrive when they engage in the 4 Ps: "Peers, projects, passion, play".

In terms of peers, I have been lucky to have been supported by the MIT UROP office and MIT Media Lab, and had the opportunity to work with MIT undergrad researchers Peter Tone and Maxwell Wang. Also, this project was taught in collaborative workshops where people could discuss their ideas with their peers.

In terms of projects, this thesis includes the release of a software library, so that people can make the software their own, and spin-off their own projects. It is also open source so that people can learn from my mistakes and also fork to adapt to their

needs.

In terms of passion, this thesis is

In terms of play, this thesis project is not about correct answers, or even excellent classification with ML, it's all about finding innovative ways to interact with multimedia material, celebrate the small victories and the big glitches, and iterate over and over again.

4.6 Creative ML

COMMENT: what is the main argument of the whole piece and how does each independent part connect to that? you should start with a story from previous experiences that is particularly relevant as to why you were inspired to do this work. think "papert and the gears"

While being a graduate student and research resident at NYU ITP I saw how quick things changed in terms of ML. I saw how the project deeplearn.js allowed for people to train and deploy ML on their browsers, and how this library was acquired by Google and repurposed as TensorFlow.js, a JavaScript version of their ML framework TensorFlow.

In turn, at NYU ITP a team of artists and programmers built the library and community of ml5.js, with the 5 being an homage to p5.js. Technically, ml5.js is a wrapper for TensorFlow.js, in the same spirit that p5.js is a wrapper for HTML5 elements such as the canvas.

The last spark that led me to this thesis was the release of 2 libraries for ML on the Arduino platform: The currently beta version Arduino KNN, which allows for on-device training and resembles my earlier studies with Wekinator, in a more portable

Figure 4-20: Sam Lavigne, Training Poses, 2018
Retrieved from [41]

and private way, no data leaves the microcontroller, and the whole neural network can be wiped with one click of a button.

At a more complex level, I am also working with the TensorFlow Lite Micro, which I learned from Arduino blogs, and which currently is supported by the hardware Arduino Nano 33 BLE Sense.

COMMENT TO THE ABOVE PARAGRAPH: you may not even need to include the specific details here, but just highlight in larger overviews the types of projects you've worked on or the educational fields that influence your work

In late 2020 and early 2021 I completed the just released series of 3 courses of the TinyML Professional Certificate by Harvard at the online platform edx.org

Newer books and references that this thesis was inspired by include the books "You Look Like a Thing and I Love You: How Artificial Intelligence Works and Why It's Making the World a Weirder Place" by Janelle Shane (2019), and the book "Making Pictures with Generative Adversarial Networks" by Casey Reas (2019).

Also Yining Shi created a new class at NYU ITP in 2020, at the intersection of ML and physical computing.

4.7 Digital rights

ML algorithms need data to be trained on. I think it's a human right to not be surveilled, and I hope my thesis can put a positive spin on the gathering of data, by letting users perform auto surveillance, like the Ai Weiwei piece WeiweiCam, a 2021 project where the artist installed cameras for self surveillance as a protest against the Chinese government.

A huge inspiration for my thesis has been the Guardian Project by the Electronic Frontier Foundation, and the research and activism work by Sasha Sasha Costanza-Chock.

4.8 Digital rights

Electronic Frontier Foundation

Edward Snowden

Design Justice Network

4.9 Opera of the Future projects

During the development of this thesis, I have been fortunate to collaborate on different capacities with other thesis projects by classmates at Opera of the Future, which has directly inspired my work.

4.9.1 Squishies, by Hannah Lienhard

Squishies is Hannah Lienhard's Master's thesis, and consists of novel squishable interfaces for musical expression. We shared discussions about low-level sound design, code reusability, sound art education, and digital instruments. We were part of a Master's thesis working group, facilitated by Roya Moussapour with two other Media Lab classmates, where we workshopped drafts of our thesis. This practice and feedback has been critical in shaping the language and discourse of this thesis document.

4.9.2 Fluid Music, by Charles Holbrow

Fluid Music is Charles Holbrow's PhD thesis. It is a library for library design, documentation for contributors. The design of the interface, documentation, and scope of the thesis were a direct influence on the documentation and API coding style of this project.

TODO: mention the impact of the documentary Coded Bias, and how these researchers impacted my desire to make my thesis. Also mention how right before pandemic I had started a pottery class, with the intention of making clay-based instruments for thesis, as a metaphor of making code and hardware and software feel fluid and not static, I want to empower people to program, in particular ML because of its dangerous implementations by oppressive governments and corporations, and in particular for arts, for making artists dream come true.

Chapter 5

Project evaluation

Yeah you wanted a hit
but tell me
where's the point in it?

You Wanted a Hit
LCD Soundsystem, 2010

5.1 Digital release

This thesis project lives on 2 different repositories, hostd on GitHub, to foster collaboration via issues and pull requests, and also with frequent updates, to show people the whole process behind this thesis project.

The main repository contains this thesis document, Jupyter notebooks for machine learning, documentation for beginners and educators, and auxiliary shell scripts. It is hosted at `https://github.com/montoyamoraga/tiny-trainable-instruments`.

The auxiliary repository contains the Arduino library, including its source code and

examples. It is hosted at `https://github.com/montoyamoraga/TinyTrainable`.

5.2 Workshop

Figure 5-1: Workshop packages
Picture by myself

For user testing and sharing this thesis, some workshops were conducted during TODO, with support from a grant at CAMIT for teaching the workshops in English in USA, and in Chile in Spanish, remotely over teleconferencing software and after being approved by the MIT COUHES TODO explain.

The workshop instructions are documented on the docs/ folder of the repository available at `https://github.com/montoyamoraga/tiny-trainable-instruments`

Each workshop consists of 2 sessions of 2 hours each, spread over 2 consecutive days.

In the first session we will first help people with installation of the software, and then move on to start wiring the materials on the electronic breadboard material. We will concentrate on the simpler examples with color input. We will also collect data of gesture and speech to create custom databases and use them to train other slow machine learning models that will keep on running on the student's workshops after the workshop is over.

In the second session we will use the result of the trained models to create more advanced instruments that react to gesture and speech. We will also show the participants the other

I applied to and was awarded a grant by the Council for the arts at MIT (CAMIT), which consisted of 2,000.00 USD to buy materials to teach the Tiny Trainable Instruments workshop to 20 people, during June 2021.

I taught this workshop 3 times, 2 of them were in English for people based in the USA, and 1 time in Spanish for people based in Chile, with a total of 20 kits being delivered.

Figure 5-2: Workshop flyer cover in English
Graphics by Renata Gaui

The multimedia aspect of this project was featured, in particular the ability to use different inputs, including color, gesture and speech, to control different outputs, including serial messages, sound, and motor movement.

Figure 5-3: Workshop flyer cover in Spanish
Graphics by Renata Gaui

5.3 Multimedia documentation

TODO: upload a collection of examples made by people who came to the workshops, featuring the software library and what they learned.

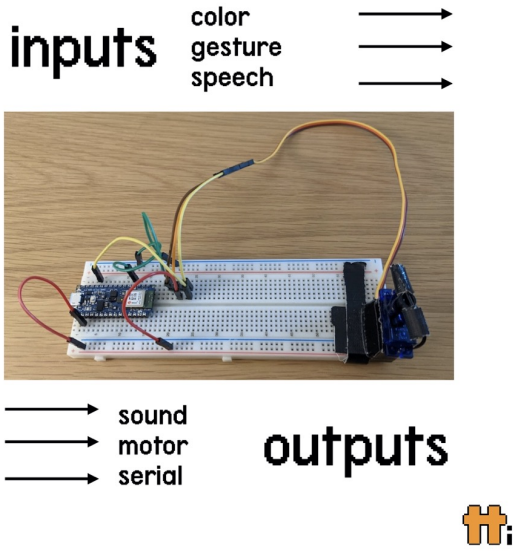


Figure 5-4: Workshop multimedia output in English
By Renata Gaui

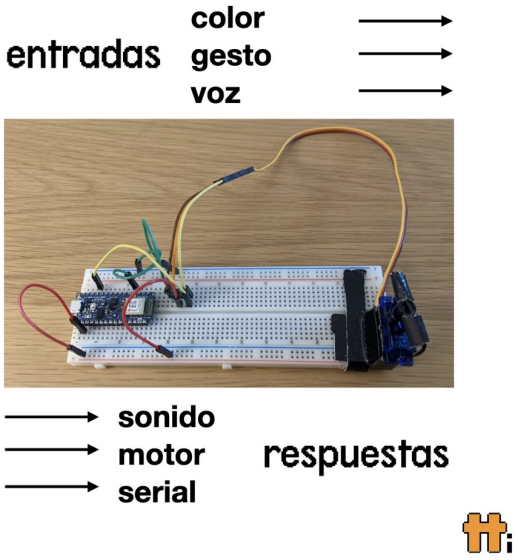


Figure 5-5: Workshop multimedia output in Spanish
By Renata Gaui

Chapter 6

Conclusions and future work

Don't get any big ideas
they're not gonna happen

Nude
Radiohead, 2007

In this thesis I have presented all the stages of the design and development of new standalone multimedia instruments using machine learning and microcontrollers, with a strong focus on AI ethics. The project includes software examples, hardware suggestions, educational material, and strategies for ethical off-cloud machine learning and creation of custom artisanal databases.

This thesis is also the basis for further research, including the creation of subsequent multimedia instruments and software libraries, the writing of new courses and educational units at the intersection of arts, physical computing, interaction design, and computational ethics.

6.1 Contributions

Concrete contributions:

1. Publishing TinyTrainable, a software library for machine learning with microcontrollers for multimedia art.
2. Design, writing, and teaching a 4-hour workshop for beginners, enthusiasts, and artists to teach with the software library.
3. Publishing code and tutorials for creating custom databases for gesture and speech.
4. Publishing custom-trained machine learning models for gesture and speech recognition.
5. Publishing code and tutorials for training machine learning algorithms on the cloud and on personal computers for privacy and agency.
6. Publishing other related software libraries, such as MaquinitasParams for communication with other instruments, and MaquinitasRitmos for rhythmic data.

Abstract contributions:

1. Demonstrating how a broader range of people can use machine learning to support their creative expression.

6.2 Lessons learned

1. Writing software for artists is hard.
2. Writing software libraries for other artists is even harder.

3. Collaboration with other people is essential to write code and educational material.

4. Documentation of all design decisions is key to explaining why and how everything works.

5. Navigating licenses and copyright is hard.

6.3 Future work

6.3.1 Hardware for new instruments

This thesis relies on an Arduino microcontroller because of their open source nature, commercial availability, software and community support, and detailed documentation.

In particular I picked the Arduino Nano 33 BLE Sense, because of two main reasons at the time this project started in late 2020: it is the only Arduino supported by TensorFlow Lite for microcontrollers and featured in the HarvardX certificate on Tiny Machine Learning, and also because of its convenience of having embedded sensors, which makes it simpler and cheaper to acquire data for live interaction and for building custom databases, eliminating barriers to instrument makers and prototypers.

Microcontrollers come and go. Most probably this board will be discontinued, but the strategies and software can be forked and adapted to other microcontrollers and software architectures. I am particularly looking ing this thesis project to other open source microcontrollers, including other Arduino boards, PJRC Teensy and Adafruit Circuit Playground, which would enable the adoption of other software stacks, such as Python instead of C++, and also to other communities building multimedia instruments and experiences.

In terms of the outputs of the Tiny Trainable Instruments, I focused on creating many parallel multimedia approaches, including making sounds with piezo buzzers and MIDI, manipulating light with LEDs, creating movement and rhythm with servo motors, and printing text with thermal printers and screens. This is to appeal to a larger audience of artists and learners, interested in different mediums, and I hope this thesis project inspires more complex artworks and interactive experiences that this library currently allows, and that people can contribute back to the library to share these new capabilities with everyone.

The Tiny Trainable Instruments are built with prototyping electronic breadboards, to make explicit their open-endedness, and to promote experimentation and lower barriers. A further iteration of this project would include the creation of custom printed circuit boards with fixed wiring, and also enclosures and packaging.

6.3.2 Software for new instruments

This thesis has been published as an open source software library for Arduino. It promotes modularity and adaptability, where a Tiny Trainable Instrument can be any combination of the multiple inputs and outputs.

The file structure of the source code and the software dependencies of this library were also built with flexibility in mind, to encourage the remix and adaptation of this library to future projects.

A challenging aspect of this project is the breadth of the disciplines combined, and its novel application of machine learning in microcontrollers. As discussed in previous chapters, there is a trend and new wave of builders and makers creating standalone multimedia instruments, based on open operating systems like Linux, and/or different microcontrollers.

Despite the existence of artists and makers building standalone computational in-

struments, these skills are still hard to acquire. Additionally, the principles of this project, including being as cheap as possible, and as open as possible, are designed to encourage experimentation and hacking, but also can pose additional challenges. I hope this project encourages people to learn how to make instruments, and also engages in discourse about the creation of new curricula for the next generation of instrument makers and artists.

Another challenging aspect of writing software for multimedia instruments is its licensing, both choosing a license and also respecting and understanding the license of other code and resources we are using. The dependencies of this software are mostly other libraries by Arduino, Google, Adafruit, and with different licenses including public domain, MIT, and Apache. I hope this document helps to navigate these legal complexities and that this project helps artists and enthusiasts to navigate this landscape and overcome these barriers.

6.3.3 Educational impact

This project was built to inspire and celebrate a new generation of coursework, workshops, and books, in the disciplines of ethical machine learning and microcontroller-based instruments.

I hope that this thesis project is adopted by educators, to introduce students to machine learning, physical computing, media arts, and computational ethics. It would be amazing if aspects of Tiny Trainable Instruments could be incorporated into existing music, arts, sculpture, and computer science curricula, to create a new wave of instrument makers and media artists.

Appendix A

Context

You might have to think of
how you got started
sitting in your little room

Little Room
The White Stripes, 2001

Since joining MIT in summer 2019, I didn't leave the U.S.A., and it's the longest stretch I have had of not visiting my home country Chile. This thesis in particular was written between November 2020 and August 2021, mostly in Boston, MA, U.S.A., while on a F-1 visa.

A.1 Language

My native language is Spanish, and this thesis was written in English, using the metric system, and the Gregorian year-month-day format.

I tried to avoid violent language, including some widespread conventions of computer

science which I hope become obsolete, such as executing a file, or screenshot, instead of running a file or screen capture.

A.2 Software

This thesis document was written using LaTeX and the Microsoft Visual Studio Code editor, and then exported to the PDF format.

The TinyTrainable library was written in C++, and packaged as an Arduino library, relying on open source library dependencies by Adafruit, Arduino, and Google.

The auxiliary code is a mix of Python scripts, Jupyter Python notebooks, and shell scripts.

The documentation was written using Markdown.

The workshops were taught using the videoconferencing software Zoom, and organized via Google Forms.

A.3 Hardware

This project was written on a 2017 Macbook Air 13-inch, running the macOS 10.15.7 Catalina operating system.

The software library and the software examples were written to be deployed on the Arduino Nano 33BLESense microcontroller.

A.4 Collaborators

Priscilla Capistrano is the senior administrative assistant in the Opera of the Future research group and made sure that everything worked.

Peter Tone is a MIT undergraduate student, who was a researcher, designer, programmer, and tester of the TinyTrainable Arduino library, as part of the MIT UROP program.

Maxwell Wang is a MIT undergraduate student who was a documentation writer, and hardware and software tester, as part of the MIT UROP program.

Roy Macdonald solved my most difficult programming questions, and helped to implement the solutions.

The Council for the Arts at MIT provided the generous funding of the workshop materials.

Renata Gaui designed and created the flyers for the workshops.

Bernardita Moraga packaged and distributed the materials for the workshop in Chile.

Appendix B

Scripts

By pressing down a special key
it plays a little melody

Pocket calculator
Kraftwerk, 1981

For this thesis I developed some scripts which are included in this repository on the scripts/ folder.

I included comments and variables with the hope of making them readable and useful for other people, and also published them on a standalone repository with a MIT License at `https://github.com/montoyamoraga/scripts`.

B.1 Formatting code with clang-format

clang-format is a command line tool for formatting code. This script was written to auto format the code from the Arduino/C++ library TinyTrainable.

```
echo "formatting with clang"
find "$PWD/../TinyTrainable/src" "$PWD/../TinyTrainable/examples" -iname
    "*.cpp" -o -iname "*.h" -o -iname "*.ino" | while read f
do
  clang-format -i "$f"
  echo "formatted $f"
done
```

B.2 Converting formats with ffmpeg

ffmpeg is a command line tool for converting audiovisual files between formats. This script was written to convert audio files from .mp3 to .ogg format for training a database for speech recognition.

```
# clear command line
"clear"

# directory name
DIR_MEDIA="media"

# extension of original files
EXT_ORIGINAL="mp3"

# extension of desired files
EXT_DESIRED="ogg"

# announce start running script
echo "start running " $PWD/$0

# check if files/ exists
```

```
if [ -d "$DIR_MEDIA" ];

# if files/ exists then
then

  echo "success, $DIR_MEDIA/ exists"

  # check if there are .mp3 files in files/
  if [ -f $DIR_MEDIA/*.$EXT_ORIGINAL ];

    # if there are files with $EXTENSION in directory
    then

      echo "success, there are matching $EXT_ORIGINAL files"

      # iterate over every matching file in directory
      for i in $DIR_MEDIA/*.$EXT_ORIGINAL;

        # pipe the filename into cut
        # -d is delimiter of '.'
        # -f is the field number, indexed in 1
        # it retrieves the filename without the extension
        do name=`echo "$i" | cut -d'.' -f1`

        echo convert "$i" $EXT_ORIGINAL to $EXT_DESIRED

        # ffmpeg conversion
        ffmpeg -i "$i" "${name}.$EXT_DESIRED"

        echo converted "$i" to $EXT_DESIRED

        # delete original file
```

```
        rm "$i"

        echo deleted "$i"

      # finish iteration
      done

    # if there are no matching files in directory
    else
      echo "fail, no $EXT_ORIGINAL files in $DIR_MEDIA/"

  # end of if statement for matching files
  fi

# if directory does not exist
else
  echo "fail, $DIR_MEDIA/ does not exist"

# end of if statement for existence of directory
fi

# announce finished running script
echo "finished running " $PWD/$0
```

B.3 Deleting metadata with exiftool

exiftool is a command line tool for reading and writing metadata from files. This script was written to delete metadata from images, like GPS coordinates added by modern smartphones, only keeping the actual image.

```
# clear command line
"clear"

# directory name
# DIR_MEDIA="media"
DIR_MEDIA="$PWD/../thesis/images"

# extension of files
EXT_ORIGINAL="jpg"

# announce start running script
echo "start running " $PWD/$0

echo "looking for files with extension $EXT_ORIGINAL in $DIR_MEDIA/"

# check if directory exists
if [ -d "$DIR_MEDIA/" ];

# if directory exists then
then

  # announce directory exists
  echo "success, $DIR_MEDIA/ exists"

  find "$DIR_MEDIA" -iname "*.$EXT_ORIGINAL" | while read f
    do
      exiftool -all= -overwrite_original "$f"
      echo "formatted $f"
    done

else
  # announce directory does not exist
```

```
  echo "fail, $DIR_MEDIA/ does not exist"

# end of if statement for existence of directory
fi

# announce finished running script
echo "finished running " $PWD/$0
```

B.4 Converting formats with pandoc

pandoc is a command line tool for converting between formats. This script was written to convert from .tex files to .docx files, so that each chapter of this thesis document could be uploaded to Google Docs for feedback from the committee.

```
echo "pandoc latex to docx"

cd "$PWD/../thesis"

# iterate through all .tex files in thesis/
find "$PWD" -iname "*.tex" | while read f
do
  # retrieve basename
  base=$(basename "$f" .tex)
  # delete original docx file
  rm -f "$PWD/docx/$base.docx"
  # create new docx file with pandoc
  pandoc -s -o "$PWD/docx/$base.docx" "$f"
done

# do all the files manually, and with bibliography
```

```
pandoc -o "$PWD/docx/aaron-thesis.docx" "$PWD/chap1.tex" "$PWD/chap2.tex"
    "$PWD/chap3.tex" "$PWD/chap4.tex" "$PWD/chap5.tex" "$PWD/chap6.tex"
    "$PWD/appa.tex" "$PWD/appb.tex" "$PWD/appc.tex" "$PWD/appd.tex"
    "$PWD/appe.tex" --bibliography "$PWD/main.bib"
```

Appendix C

Documentation

Now you play the synthesizer
don't be lazy now
make it hiss like rattlesnakes

'81 How to Play the Synthesizer
The Magnetic Fields, 2017

For this thesis I wrote the following documentation, included at the docs/ folder of the repository, and also included here.

Bill of materials

Notes about the microcontroller

This project is based on the microcontroller `Arduino Nano 33 BLE Sense`. Please don't confuse it with the similarly named `Arduino Nano 33 BLE`! It is recommended to get the one ***with headers***, so you can immediately start using it on a breadboard without needing to solder the headers on it.

Minimum materials

This is the list of minimum required materials for Tiny Trainable Instruments

Item	Quantity	Cost (USD)	Retailer	Comment
Arduino Nano 33 BLE Sense with headers	1	33.40	Arduino	Microcontroller
Breadboard	1	5.95	Adafruit	Prototyping
Jumper wires	1	3.95	Adafruit	Connections
Micro USB cable	1	2.95	Adafruit	Power

Sound and movement outputs

These are the recommended materials for starters, and are taught in the workshop.

Item	Quantity	Cost (USD)	Retailer	Comment
Piezo buzzer	1	1.50	Adafruit	Output sound
Micro servo	1	5.95	Adafruit	Output movement

Additional outputs

These additional outputs include more expensive or more complex materials, and they are recommended for more advanced users. They are not covered on the beginner workshop, but are supported by the Tiny Trainable Instruments project and software library.

Item	Quantity	Cost (USD)	Retailer	Comment
LED	1	6.95	Adafruit	Output light
MIDI DIN	1	1.75	Adafruit	Output MIDI data
Thermal printer	1	61.95	Adafruit	Output printed text
128x32 OLED screen	1	12.50	Adafruit	Output screen

Installation

This guide includes information as of June 2021, and we will explicitly include the software versions we are using.

We advise to install the same versions we are using, and if there is any issue with the library or related software, please us know via email or an issue the repository.

For additional documentation, please visit the official Arduino docs website at docs.arduino.cc, and in particular the documentation of the Arduino Nano 33 BLE Sense microcontroller at docs.arduino.cc/hardware/nano-33-ble-sense.

Arduino IDE

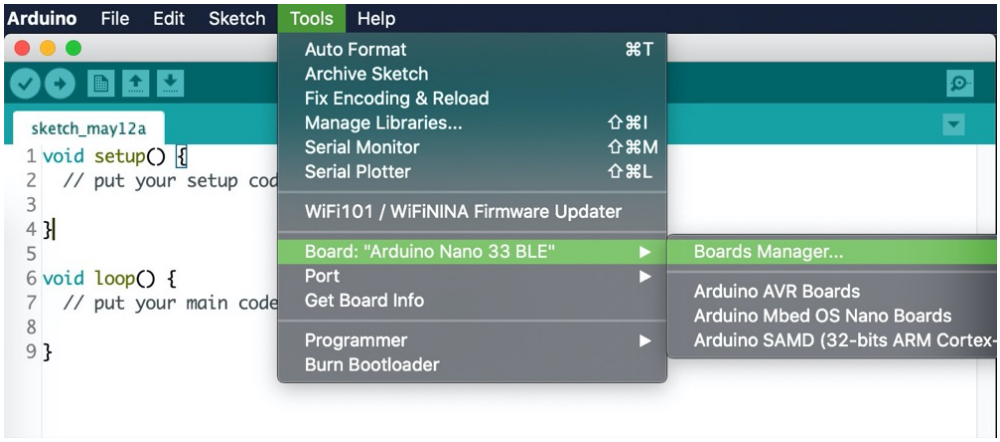
Download and install the Arduino IDE, available at https://www.arduino.cc/en/software. Select the stable release corresponding to your computer's operating system.

As of June 2021, we are using Arduino IDE 1.8.15.

Arduino Mbed OS Nano boards

After installing the Arduino IDE, we need to install the core and necessary libraries for the Arduino Nano 33 BLE Sense microcontroller. Open the Arduino IDE and navigate on the menu to the `Boards Manager`:

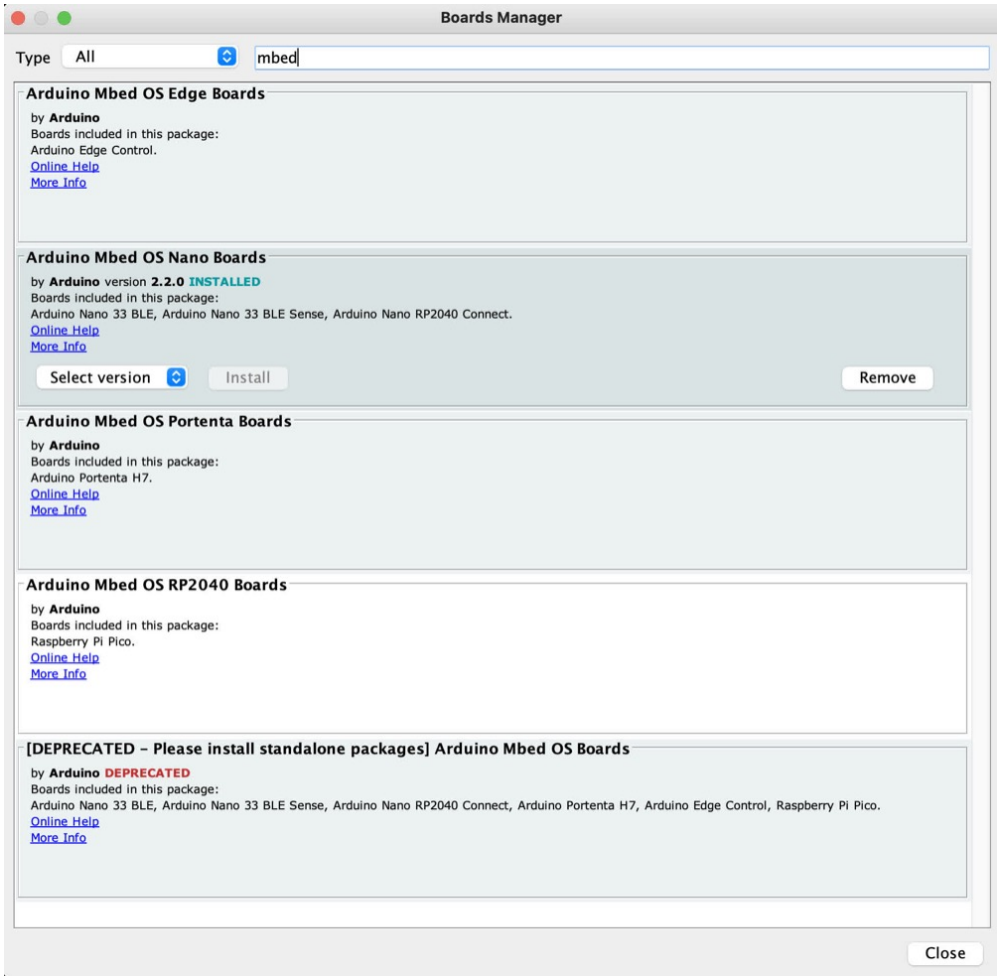
```
Tools > Board: "<board_name>" > Boards Manager...
```



Use the search bar to find the option `Arduino Mbed OS Nano Boards` and install it, this might take a while.

Please note that if you look for "Mbed", several different options will appear, be careful with the similar named one called `Arduino Mbed OS Boards` which is deprecated and we should not install.

As of June 2021, we are using version 2.2.0.



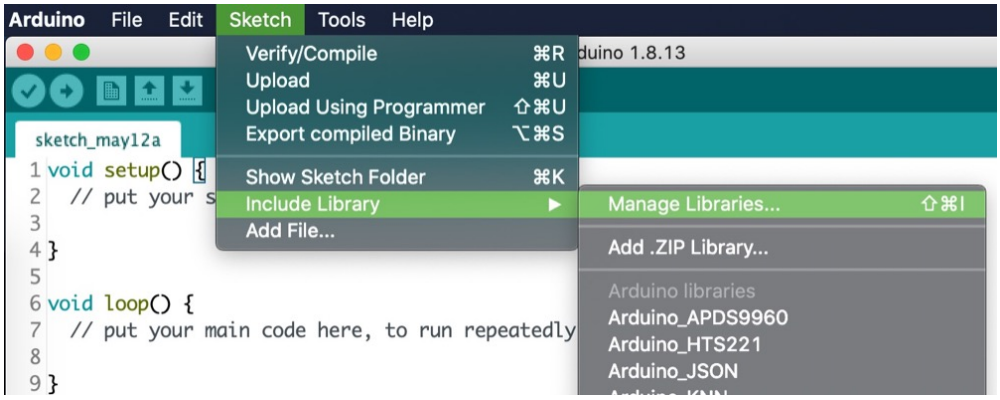
After the installation is complete, we can select the board we are going to work with (Arduino Nano 33 BLE), from the `Tools` menu:

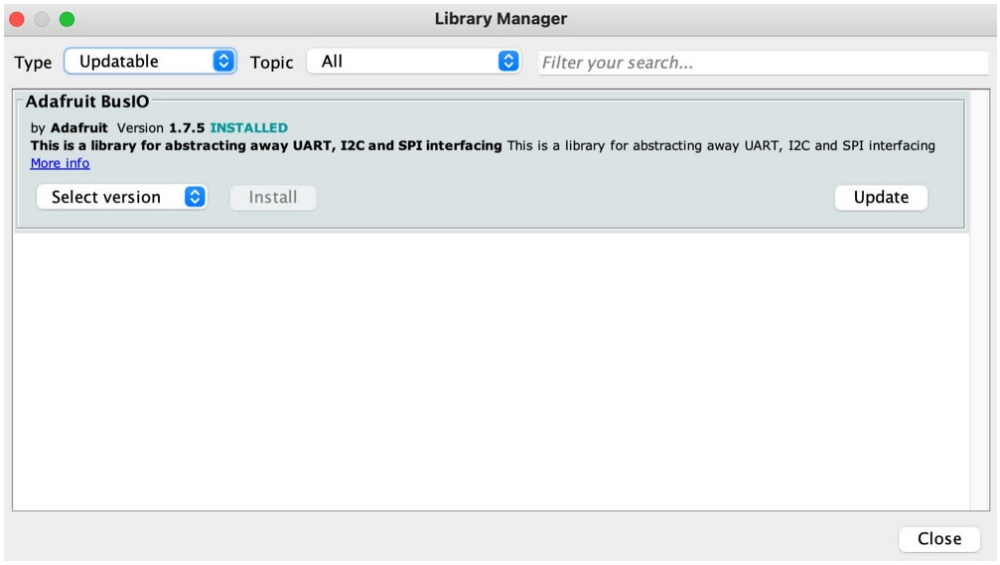
```
Tools > Board: "<board_name>" > Arduino Mbed OS Nano Boards > Arduino Nano 33 BLE
```

Please note that this option is valid for both Arduino Nano 33 BLE, and for the board we are using, the Arduino Nano 33 BLE Sense.

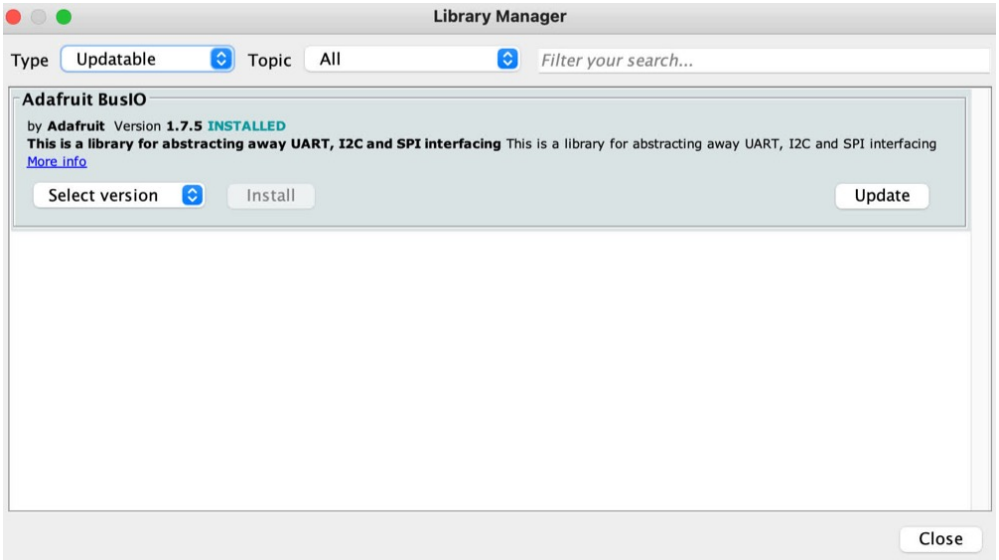
Arduino libraries

Before installing the TinyTrainable library for this project, please first update all your installed libraries. On the Arduino IDE, navigate on the menu to `Tools > Manage Libraries... >`, and then on the `Type` dropdown menu select `Updatable`.



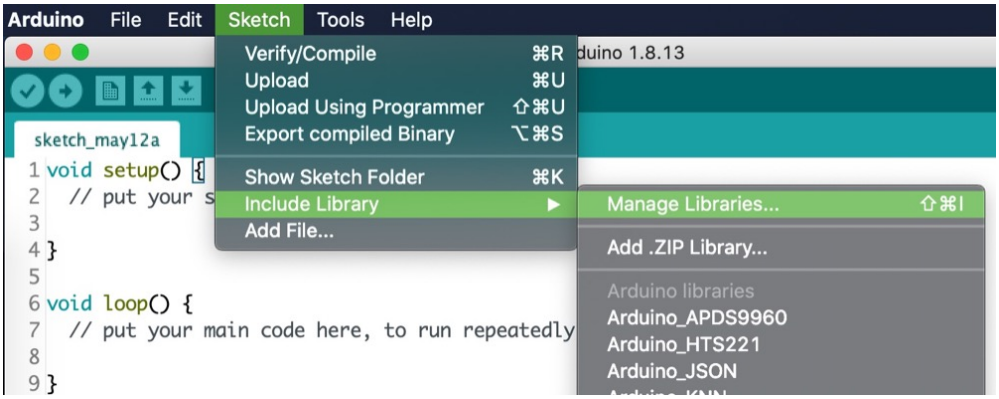


To update each outdated library to their latest version, hover on top of each library, and click on the button `Update`. For this example we are showing the updating of the library Adafruit BusIO, which is installed on my computer, but most probably is not on yours, and you don't need it for this project either.

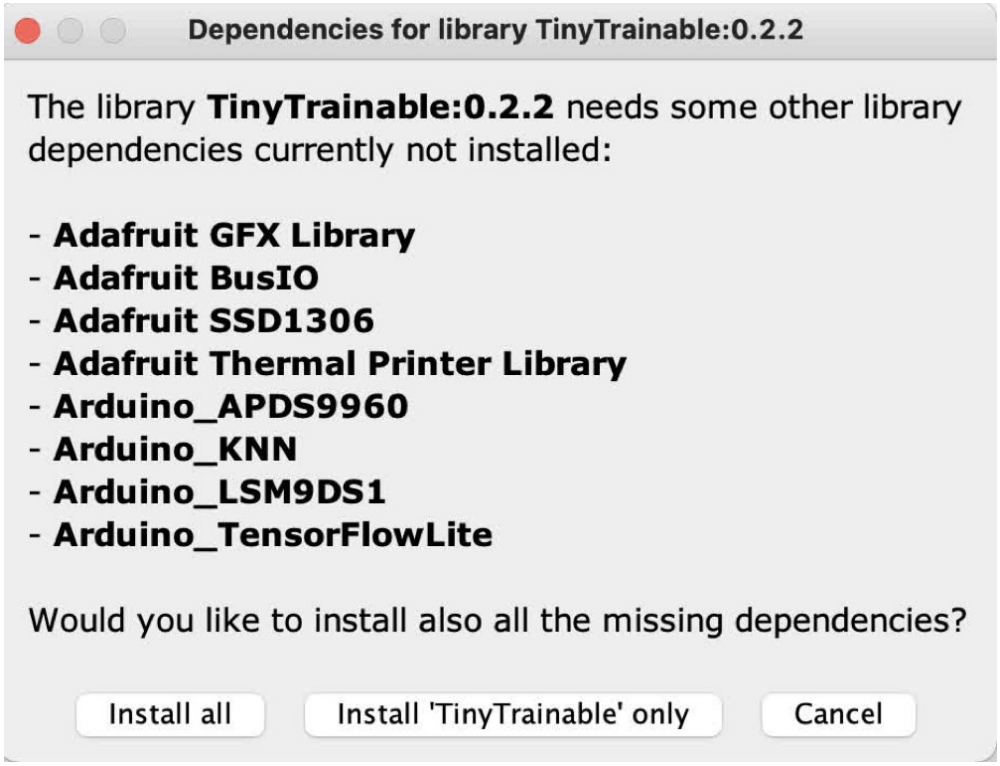


Please repeat this process until there are no updatable libraries left.

Next we will install all the libraries needed for this project. On the Arduino IDE, navigate on the menu to `Tools > Manage Libraries... >`



Go to the search bar of the Libraries Manager and type `TinyTrainable`. This installation will give you the option to also install its dependencies, select `Install all` to download them.



As of June 2021, the latest version 0.2.2 of the TinyTrainable library has these dependencies:

Libraries for using the embedded sensors of our microcontroller:

- `Arduino_APDS9960`: color, proximity
- `Arduino_LSM9DS1` acceleration, magnetic field, gyroscope orientation

Libraries for machine learning:

- `Arduino_KNN`: k-nearest neighbor algorithm.
- `Arduino_TensorFlowLite`: microcontroller version of the TensorFlow machine learning library. Please download the latest non-precompiled version.

Libraries for multimedia output:

- `Adafruit GFX Library`: for output with screen.
- `Adafruit SSD1306`: for output with screen.
- `Adafruit Thermal Printer Library`: for output with thermal printer.
- `Servo`: for output with servo motors.

Python for machine learning

For input-color, you only need Arduino libraries.

For input-gesture and speech, you either need to install specific Python libraries on your computer, or use the free Google Colab service, because we will create databases and train algorithms on a computer.

For beginners, we suggest using Google Colab, because it will be an easier installation, and the algorithms will run faster.

If you decide to run the algorithms on your machine, you will need Python, TensorFlow and Jupyter.

These are the versions we will be using, as of June 2021:

- Python 3.8.6
- TensorFlow 2.3.2
- Jupyter Lab 3.0.5

Your computer might have Python already installed, but it might be one that is not compatible with the TensorFlow version we are using, so we suggest using a Python version manager, like the tool pyenv https://github.com/pyenv/pyenv.

After installing pyenv, open the terminal and go to this repository. If you dont know how to download a repository to your machine, follow this tutorial about cloning repositories from GitHub.

```
cd tiny-trainable-instruments/
```

Check that pyenv is able to read the .python-version file

```
pyenv versions
```

You should see a list, with the version we are using and an asterisk, to highlight that this is the Python version we will use. If there is no asterisk and it says that the required version of Python is not installed, use the command:

```
pyenv install <python version number>
```

If you are using an old version of pyenv, there's a chance that the install won't work; copy the entire command pyenv gives you (including the &&'s) and enter it into the terminal. Then once pyenv is updated, try the above command again.

Now that you have the correct version of Python, create a virtual environment (which we will name env) using the Python package venv. Most dependency problems can be solved by using a virtualenv; we can’t support issues not

using a virtualenv due to the huge variety of system configurations. On your terminal type:

```
python -m venv env
```

Activate the virtual environment with this command, which you will use every time you want to enter the venv:

```
source env/bin/activate
```

Now your terminal should have every new line starting with (env). Your command prompt should look something like this:

../docs/images/1-arduino-boards-manager

The pip of your Python virtual environment might need updating; you can update to the latest version with the command

```
pip install --upgrade pip
```

Then use pip to install the Jupyter packages, along with their dependencies:

```
pip install -r requirements.txt
```

Now you can run the Jupyter Lab tool with `jupyter-lab`. This will open a tab on your browser to navigate through the files in your computer and allow you run code and read the documentation.

The code for input-gesture and input-speech is written using Jupyter notebooks, which have the extension .ipynb, and are located on the folder `instruments/`. The documentation is written in several Markdown files with extension .md. These files are on the folder `docs/`, which includes an index on README.md.

If you double click on a Markdown file, it will open an Editor window with the Markdown code. To view the rendered text you can right click and select "Open with Markdown Preview". If you have internet connection, it might be more convenient to access the online documentation on the online repository.

To close the Jupyter notebook server, press `ctrl+c` in the terminal (even on OSX; it's not `cmd`) and confirm with `y`.

To exit the virtual environment once you're done, use the command `deactivate`. Note that the command `jupyter-lab` will not work until you reactive the virtual environment.

Wiring

Conventions

Wires:

- Red = 3.3 V power from Arduino
- Green = Ground from Arduino

Breadboard

Breadboards are built so that within each of the rows, the 5 tie points in the columns labelled `a–e` are electrically connected inside the board and act as a single electrical node, and same with `f–j`.

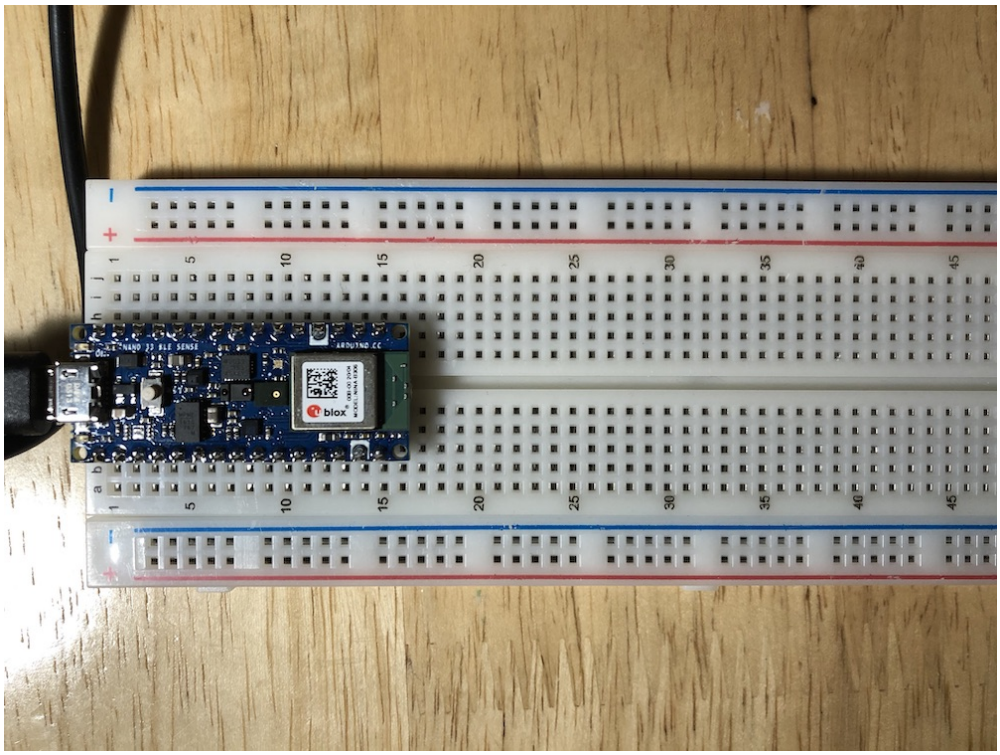
In addition, there are 2 columns to each side of the breadboard, where each column is one electrical node. Conventionally, we connect the positive voltage to the column labelled `+`, and the ground to the column labelled `–`.

A full breadboard guide is available at https://learn.adafruit.com/breadboards-for-beginners/breadboards.

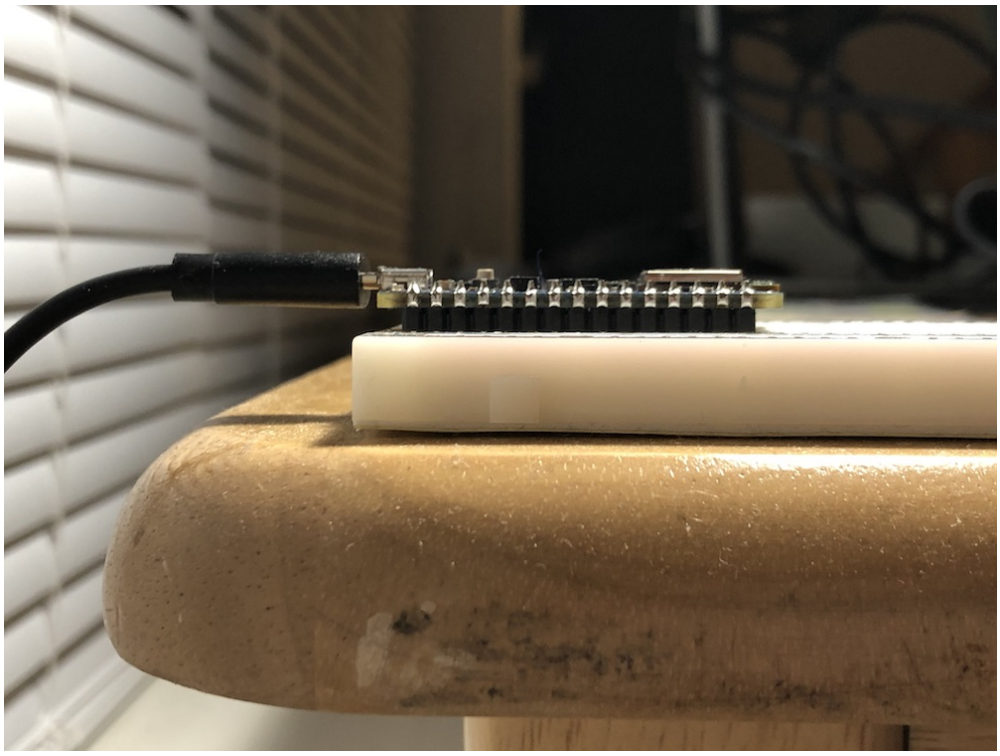
Arduino microcontroller

The Arduino Nano BLE 33 Sense we are using has 30 pins in total, 15 on each side. The official pinout is available at https://content.arduino.cc/assets/Pinout-NANOsense_latest.pdf.

We recommend placing the microcontroller at the top of the breadboard (C1 to C15 and G1 to G15) with the USB Micro port facing up.



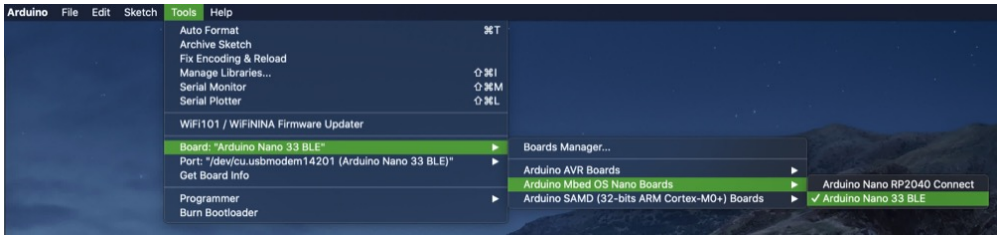
Note that the microcontroller should be flush with the breadboard; none of the headers should be visible.



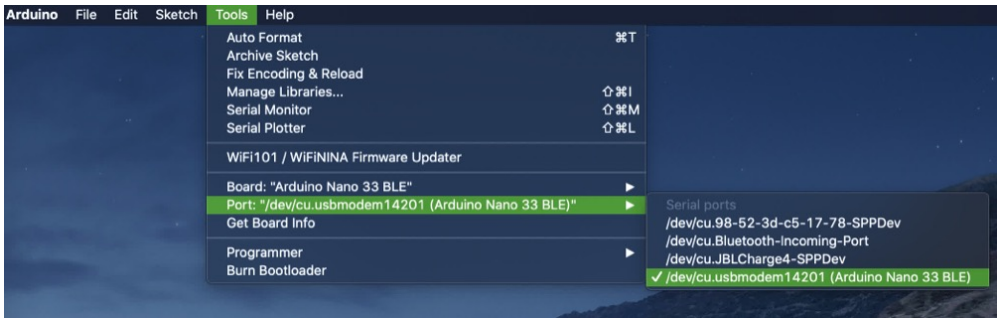
Your first example

Connect your Arduino microcontroller to your computer with the USB cable and open the Arduino IDE software.

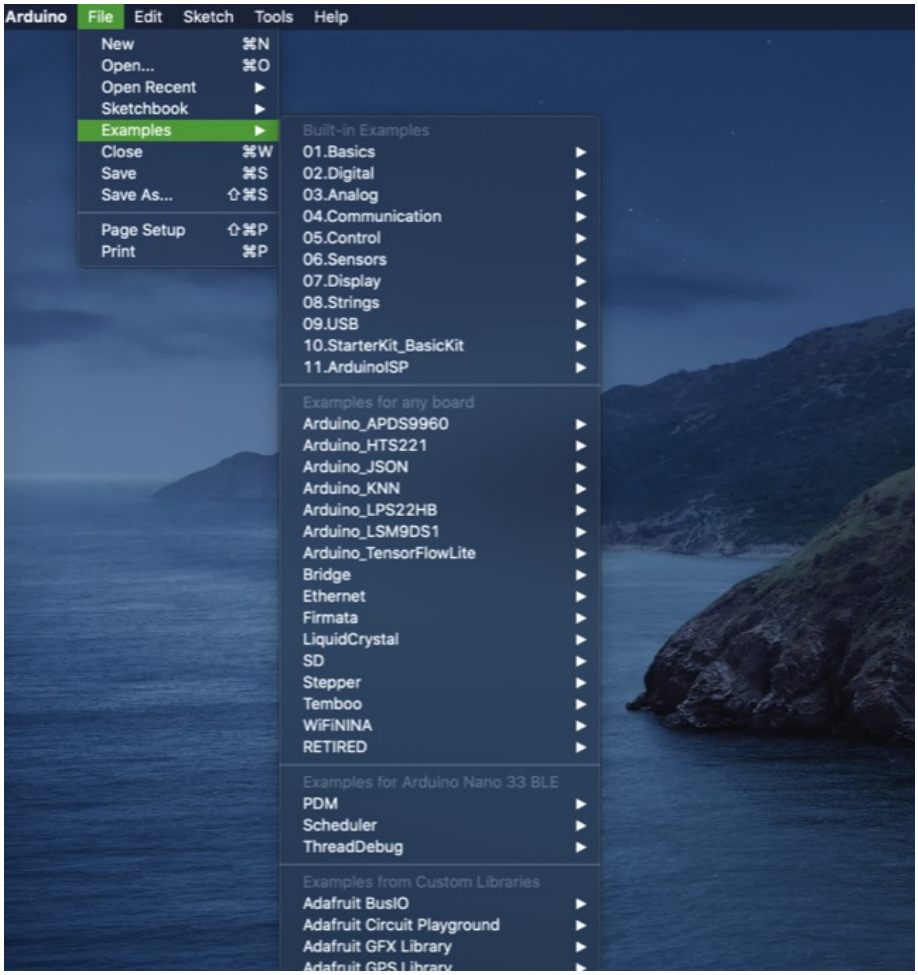
On the board, select the `Arduino Nano 33 BLE`.

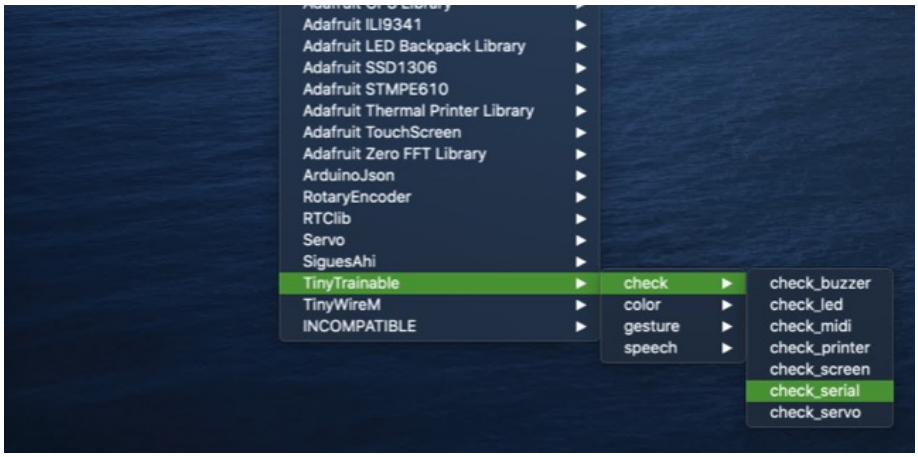


Then make sure yor port points to your Arduino, the number is irrelevant, and the actual text changes between computers.

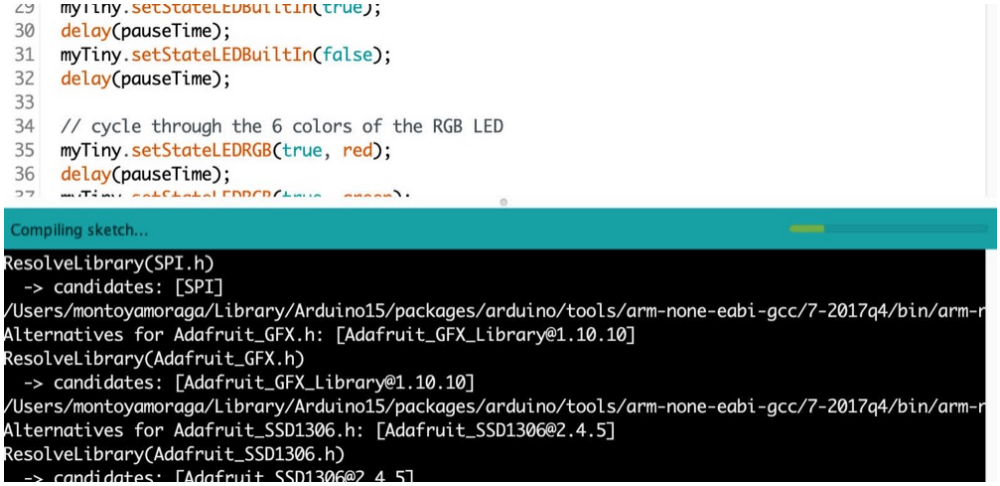


Now let's open the example `check_serial`, included with our TinyTrainable library.





Click on the arrow to the right for uploading the code, which will be shown on the bottom of the Arduino IDE, with the message `Compiling sketch`.



The compilation might take several minutes, and after it is done, the message will change to `Uploading...`

```
36  delay(pauseTime);
```

```
Uploading...
writeBuffer(scr_addr=0x34, dst_addr=0x1c000, size=0x1000)
[=======                  ] 25% (29/114 pages)write(addr=0x34,size=0x1000)
writeBuffer(scr_addr=0x34, dst_addr=0x1d000, size=0x1000)
[=======                  ] 26% (30/114 pages)write(addr=0x34,size=0x1000)
writeBuffer(scr_addr=0x34, dst_addr=0x1e000, size=0x1000)
[=======                  ] 27% (31/114 pages)write(addr=0x34,size=0x1000)
writeBuffer(scr_addr=0x34, dst_addr=0x1f000, size=0x1000)
[=======                  ] 28% (32/114 pages)write(addr=0x34,size=0x1000)
```

This process is shorter, and after it you will see the message `Done uploading`.

```
35  myTiny.setStateLEDRGB(true, red);
36  delay(pauseTime);
```

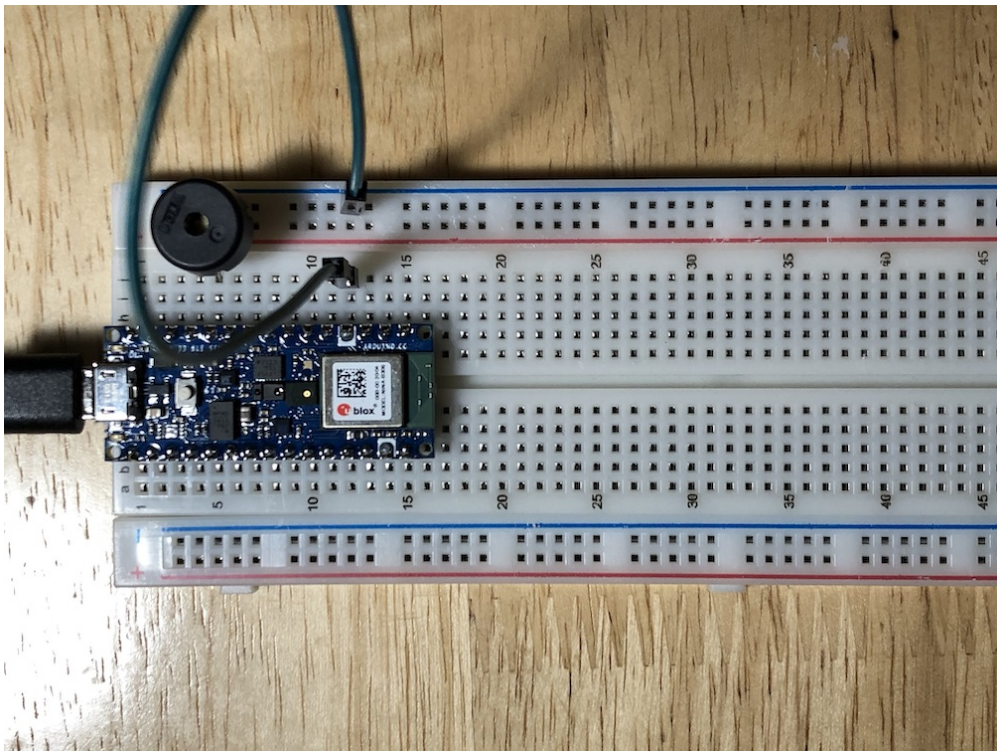
```
Done uploading.
[=========================  ] 94% (108/114 pages)write(addr=0x34,size=0x1000)
writeBuffer(scr_addr=0x34, dst_addr=0x6c000, size=0x1000)
[=========================  ] 95% (109/114 pages)write(addr=0x34,size=0x1000)
writeBuffer(scr_addr=0x34, dst_addr=0x6d000, size=0x1000)
[=========================  ] 96% (110/114 pages)write(addr=0x34,size=0x1000)
writeBuffer(scr_addr=0x34, dst_addr=0x6e000, size=0x1000)
[========================== ] 97% (111/114 pages)write(addr=0x34,size=0x1000)
writeBuffer(scr_addr=0x34, dst_addr=0x6f000, size=0x1000)
[========================== ] 98% (112/114 pages)write(addr=0x34,size=0x1000)
writeBuffer(scr_addr=0x34, dst_addr=0x70000, size=0x1000)
[========================== ] 99% (113/114 pages)write(addr=0x34,size=0x1000)
writeBuffer(scr_addr=0x34, dst_addr=0x71000, size=0x1000)
[==========================] 100% (114/114 pages)
Done in 18.200 seconds
reset()
```

On the upper right corner of the window, click on the magnifying glass icon for opening the `Serial monitor`. Make sure the settings on the bottom match the ones on your computer, and that's it!

You uploaded your first example to your Arduino, which is now busy sending the messages you seen on the screen, and also showing all the different lights it has :)

Ground

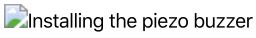
Notice that the 14th pin on the left side and the 12th pin on the right side are labelled with white paint; this marks ground, also identified on the pinout. Take a wire (preferably green by convention for ground) and connect it from I12 to anywhere on the top righthand negative rail (the upper 25 pins), like this:



Outputs

Buzzer

Next, connect one of the legs of the piezo buzzer to the node labelled D8 on the pinout (which should be row 5 on the breadboard). Connect the other leg to the ground rail. Your wiring should look like this:


Installing the piezo buzzer

Now you're good to go! Upload `check_buzzer` to the microcontroller, open the serial monitor (top right button in the Arduino IDE), and follow the instructions from there!

LED

MIDI

MIDI Din jack

5 pins, only 3 are used.

Printer

We are using a thermal printer from Adafruit.

https://www.adafruit.com/product/2753

It has 5 cables:

VH - red - connect to the power supply 5V - 9V DTR - yellow - connect to GND on the Arduino TX - green - data out of the printer RX - blue - data in to the printer GND - black - connect to GND on the Arduino

We use a power supply, whose ground is connected to the one on the Arduino.

The power supply is 9V, center positive. Here is one available:

https://www.adafruit.com/product/276

Serial

Use a micro USB cable to connect to a computer.

Servo

The servo we are using has three cables:

- Yellow: signal
- Orange: power
- Brown: ground

Contributing

Issues

If you find an error or have a comment, please start a discussion by submitting an issue on our repositories!

- https://github.com/montoyamoraga/tiny-trainable-instruments/issues
- https://github.com/montoyamoraga/TinyTrainable/issues

Pull requests

Here is a step by step guide to make pull requests to this repository.

- Create a free GitHub account
- Fork the repository
- Clone your new repository to your computer

```
git clone https://github.com/your_username/tiny-trainable-instruments.git
```

Optionally, you can also clone the submodules of this repository, with the command

```
git submodule update --init --recursive
```

- Change directory (cd) into the project folder

```
cd tiny-trainable-instruments
```

- Make your changes
- Stage and make a commit to your repository on your computer

```
git add .
```

```
git commit -m "your comment"
```

- Push your commit to your personal fork on GitHub

```
git push
```

- Open your repository online
- Open your pull request and wait for comments or approval

Contributing documentation

For more information about how to contribute documentation to an open source artistic project, we recommend looking at the documentation by the p5.js project, available at https://github.com/processing/p5.js/blob/main/contributor_docs/contributing_documentation.md

Adding submodules

If you think there are more repositories we should include as submodules for archival purposes, use the following command, replacing GITPATH with the location of the repository you want to include, and FOLDERPATH with the destination.

```
git submodule add GITPATH FOLDERPATH
```

Helper scripts

The helper scripts are located on the assets/ folder. To run them, cd to assets/ and then use the following commands

Compiling code

This script uses arduino-cli for checking the compilation of all examples of TinyTrainable.

```
sh compile-code.sh
```

Delete metadata

This script uses exiftool to delete the metadata of all pictures in docs/

```
sh delete-metadata.sh
```

Format code

This script uses clang-format to organize all the code in TinyTrainable

```
sh format-code.sh
```

Markdown to PDF

This script uses pandoc to convert the documentation from Markdown to PDF format.

```
sh markdown-to-pdf.sh
```

Appendix D

Open source contributions

Nos debemos tanta plata
Los unos a los otros
Me dan escalofríos

Viernes

Tus Amigos Nuevos, 2013

During this thesis I contributed the following pull requests to open source projects that are either direct dependencies or inspirations.

Author	Repository	Contribution
Adafruit	[42, Adafruit_SSD1306]	[43, Format binary numbers]
tinyMLx	[44, TinyMLx Arduino Library]	[45, Update architecture name]
Yining Shi	[46, ML for Physical Computing]	[47, Fixed some typos]

Table D.1: Pull requests to open source projects

Appendix E

Rules of thumb

Wishes on a wheel

How it's supposed to feel

Wishes

Beach House, 2012

During this thesis I have tried to follow these rules of thumb:

- Openly share small steps
- Learn by failing often
- Contribute back
- Use tools you like
- Cite other people
- Sleep as much as possible

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