NESLA Coil

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1. Introduction

1.1 Objective

In an effort to develop efficient methods of wireless power transmission, Nikola Tesla invented the Tesla Coil, a high voltage resonant transformer circuit that emits electromagnetic energy into the air. Although the Tesla Coil is not successful in achieving its intent to wirelessly transmit power, its lightning discharge effects provide a source of mesmerizing entertainment to observers. In recent years, engineers have redesigned the coil using solid state devices and signal processing techniques in order to use Tesla Coils to create a new form of novelty lightning music. Using the electrical breakdown phenomenon of air as a means of creating sound as opposed to traditional methods imposes limitations on the resolutions of sound the coil can emit. Coincidentally, these shortcomings are parallel to the producible sets of sounds that can be synthesized under the hardware constraints of the Nintendo Entertainment System, thus the Tesla Coil can be transformed into a clever accessory to the NES. Our objective is to extend the Nintendo Entertainment System's Audio Processing Unit's functionality beyond its designed limits, so that the NES' audio sub-systems are fully compatible with a musical solid-state Tesla Coil.

1.2 Background

The evolution of video game soundtracks are an auditory reflection of the overall advancement in developing microprocessor architectures and fabrication techniques over the past three decades. A revolution beginning with the release of 8-bit masterpieces like *Super Mario Bros.* and *The Legend of Zelda* on the Nintendo Entertainment System has made video game music an iconic, well appreciated, cultural symbol in the digital era. The computer hardware limitations of the 1980s meant that the NES could only synthesize a limited number sounds composed of basic geometric waveforms, musical compositions that reflect these limitations have been termed "Chiptunes." Viewing the NES, not as a video game console, but rather as an instrument that produces chiptunes.

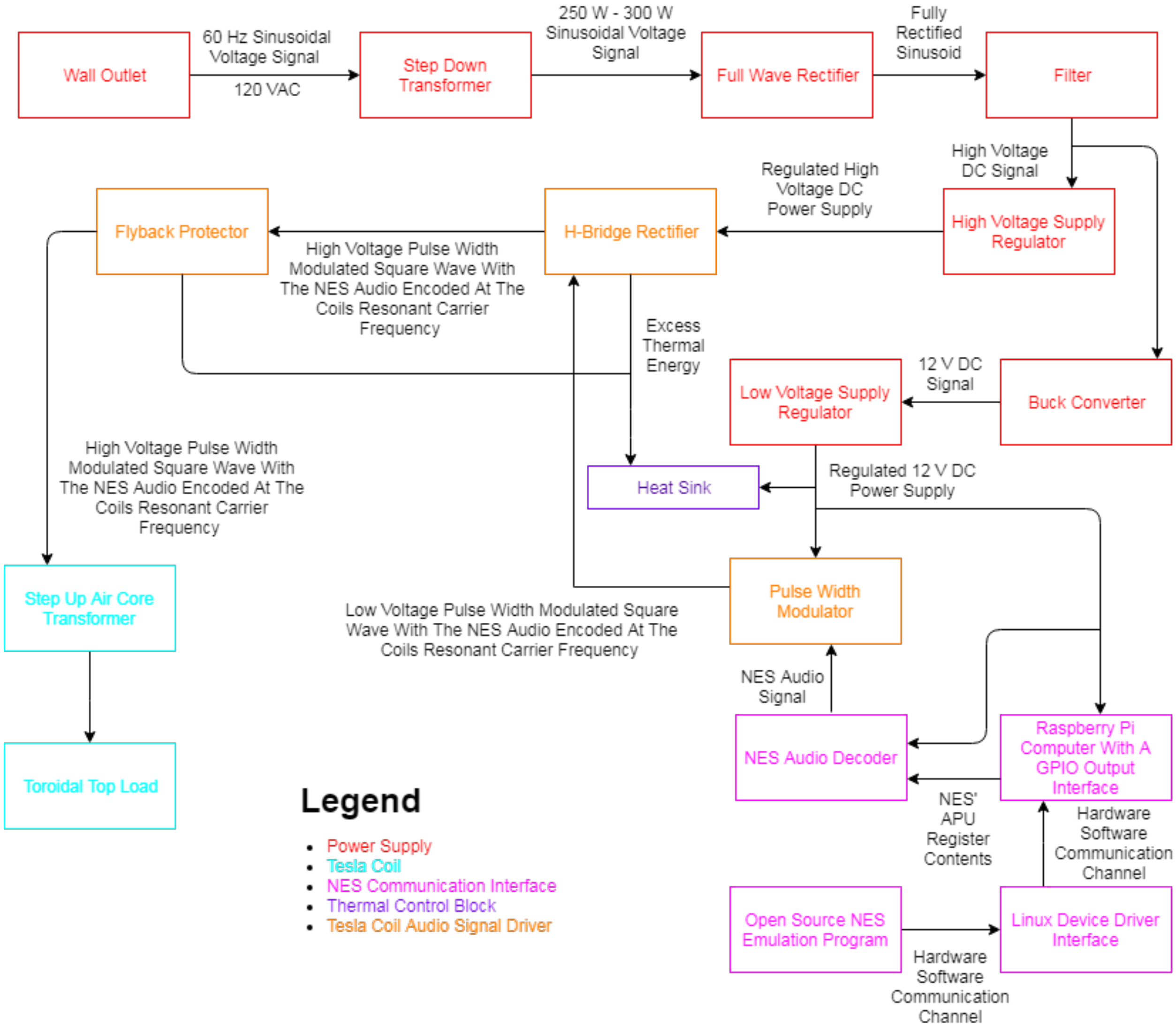
Because the NES revived the gaming world after the crash of the 80s, it became a cultural icon that signified the rebirth of video games. Because of this many people have created passion project devoted to the gaming system that started it all. In a way our project strives to do the same. By taking the classic sounds of the NES and transforming them into arcs in the air, we can create something unique that still make the NES the focus of the project. People will hear their favorite Super Mario songs, but through electricity itself. This is a way to praise the NES for its revolutionary impact on the gaming world, but acknowledge it through an ECE perspective. It shows that engineering can still be used as an art form to express one's own love for something. When people see the arcs of lightning, it will give them a new appreciation for something that they already knew about, the NES.

1.3 High Level Requirements

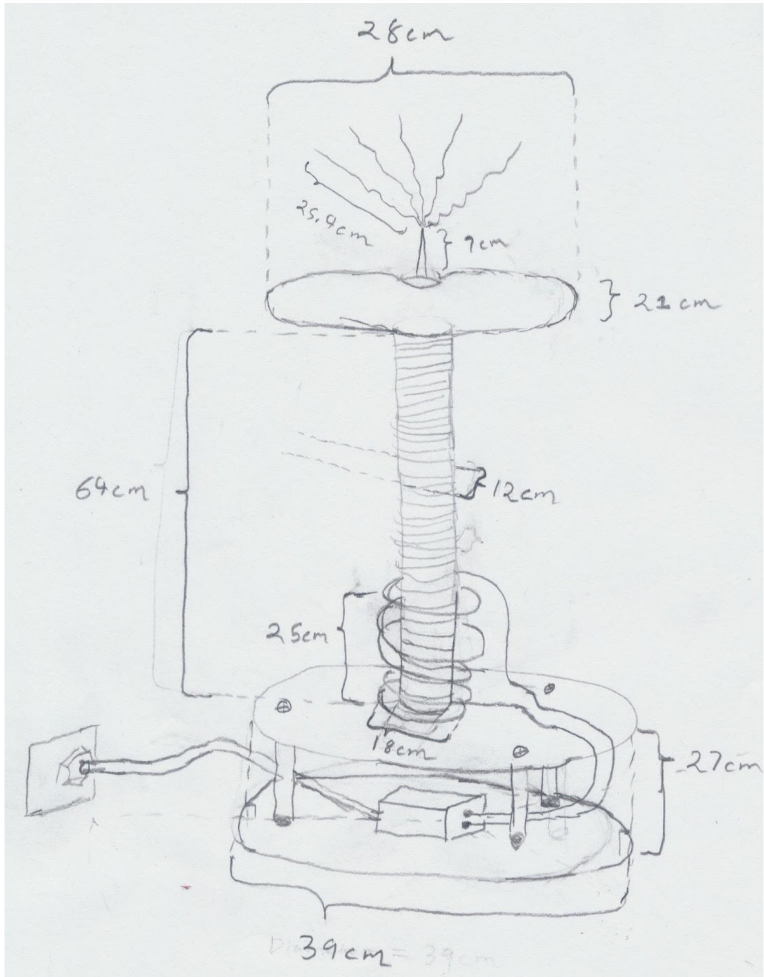
- The Tesla Coil's toroidal top load should be able to emit sparks between 8 to 10 inches in length.
- The Tesla Coil's electrical discharge should be able to emit sound waves that cover the entire set of audio waveforms from the Pulse 1, Pulse 2, Triangle and Noise channels on the Nintendo Entertainment System's APU.
- The Tesla Coil's audio modulation inputs should be designed in such a way that they natively interface with the NES APU. Meaning that as far as the NES APU is concerned, the Tesla Coil outputting the sound is equivalent to the standard Television Diaphragm speaker it was originally designed for.

2. Design

2.1 Block Diagram



2.2 Physical Design



Above is a sketch with approximate dimension which reflects what the NESLA coil should look like once it is finished and operational. Note that auxiliary dashed lines were added to convey orientation in space, and three-dimensional axis that measurements were made along. All components other than the coil itself sit below two 39 cm diameter wooden disks which are separated from one another using three 27 cm wooden rods placed 120 degrees apart from one another near the perimeter of the disks. The rods should be orthogonal to both wooden disks. The top surface of the upper disk has support for the primary and secondary coils to stand orthogonal to the surface. The coil 64cm in height will be wrapped around PVC pipe which has a diameter of 12 cm. The top toroidal load interconnects with the wiring of the secondary coil and has a 7 cm high needle to concentrate the electric field lines, yielding the point in which the electric discharge is emitted.

2.2 NES Communication Interface

The overall data communication module will serve as the interface of the NES sound data to the output to the Tesla coil. Data will come in from an .nsf file, which could be the music file for any arbitrary game, and exit the data communication module as a digital signal that will enter PWM module that controls the power and frequency of the Tesla coil.

2.2.1 NES emulator

The NES emulator on the computer will read a .nsf (NES sound format) and output the data to the Raspberry Pi. Since there are no pins directly usable on the computer, the data must be fed to the Raspberry Pi.

Requirement: The emulation tool will read .nsf files and communicate to the Raspberry Pi.

2.2.2 Linux Device Driver Interface

Stable version of the Linux kernel on a computer that will be able to run the NES emulation software. This will serve as the operating system that controls USB port that connects to the Raspberry Pi to output the NES emulator data.

Requirement: Able to run the NES simulation software.

Requirement: Must be a stable build of Linux that is compatible with Raspberry Pi's architecture.

Requirement: Must be able to support the use of software to set pin outputs on the Raspberry Pi's GPIO output interface.

2.2.3 Raspberry Pi with A GPIO Output Interface

The Raspberry Pi serves as the middle ground between the data of the computer and the output pins that feed into our custom digital circuit. The Raspberry Pi will be programmed to read the data from the computer and output the data in the format required on the GPIO.

Requirement: This module will successfully read data from the computer. The emulator should be able to set arbitrary pin voltages on the GPIO.

Requirement: Translate the data into digital signals and output them on the GPIO pins to be read by IC circuit.

2.2.4 NES Audio Decoder

The decoder takes the digital signal from the raspberry pi GPIO pins and outputs an audio signal that will go to the PWM module.

This is a digital circuit that will run at around 1.789773MHz (NTSC) or 1.662607MHz PAL [2]. There are 23 registers in the APU of the NES. Using the output of each register on the GPIO module, the digital circuit will determine the frequency and amplitude of the different sound channels. Once the sound data is decoded, it will superimpose the signals together and output it to the PWM module.

Requirement: Perform at around 1.66MHZ to 1.78MHz

Requirement: Accurately translate the APU's digital register data into an analog voltage signal representing the corresponding sound.

Requirement: Able to superimpose the resulting decoded sound signals requested by all of the APU's output channels and send the superposition to the PWM module

2.3 Power Supply

This section of the design deals with making the AC wave from the wall come in and turning it into a DC voltage that we can deal with. By doing this we then have the ability to power our many circuit parts, along with create the high voltage that we need in order to run the coil as a sufficient power and voltage.

2.3.1 Step Transformer circuit

We will use a transformer to step down the total wattage of the 120VAC sinusoid coming from the wall outlet to the required amount needed for our project which we expect to be between within 250 W - 300 W. We will implement this component by making an iron core transformer ourselves or purchasing a pre-made one. The transformer will have multiple secondary windings so that we will have a range of wattages to power our circuitry. This will allow us to filter our transformer outputs in parallel. We need to partition the wattage across the output windings such that large amounts of power can be delivered to the Tesla Coil's driver, and small amounts of power can be delivered to the circuitry that processes the audio components.

Requirements: The flux into our iron transformer core will never saturate

Requirements: WE use enough wires in our circuit to avoid skin depth problems with our current

2.3.2 Full wave rectifier

This circuit's design is to take a wall AC outlet and fully rectify it. The output of this module should be the absolute value of a sine wave. This full wave rectifier will probably use 4 diodes in the common fashion.

Requirement: It must be able to handle 250 watts of power.

Requirement: This circuit must have some form of surge protection to make sure that no one will get hurt if something breaks in the circuit.

Requirement: This circuit must have sufficient cooling in order to make sure the parts being used do not break down over time.

2.3.3 Filter

This block will focus on using some form of a filter to make our now fully rectified wave into a more DC-like output. What we want ideally is a wave with very little ripple. In order to do this, we must design a filter that works well but doesn't use massive capacitors and inductors.

Requirements: Must have minimal ripple. (1-3% ripple)

Requirement: The passives of the circuit cannot be massive.

2.3.4 Low Voltage Supply Voltage Regulator

This circuit should be able to maintain a steady 12V DC voltage signal independent of the loading conditions on the circuits output terminal. It is important to design the low voltage supply regulator separately from the high voltage supply regulator, as different design considerations need to be made. . This circuit must keep our voltages fairly constant for the low voltage version because we are using these voltages to power the digital logic devices that decode the NES game data into observable sound.

Requirements: The Low Voltage Supply Regulator should maintain a 12V DC signal and vary less than 10% as we vary the load impedance over one to two orders of magnitude.

Requirements: The Low Voltage Supply Regulator should be able to supply enough power to the digital logic components such that they operate as expected.

2.3.5 High Voltage Supply Regulator

This circuit should be able to maintain a steady high voltage signal between 100V - 300V DC and this desired output signal should be independent of the loading conditions on the circuits output terminal. This circuit must keep our voltages steady as we change impedances as the output terminals from this voltage regulator will serve as the high voltage DC line supply that is required by the H-Bridge component. The voltage level must always stay within the operating conditions specified by the datasheets of the power MOSFETs used in the H-Bridge. If the expected voltage signal were to move outside the datasheet defined operational boundaries of the power MOSFETS we have the possibility of burning them, which may produce a fire and will completely ruin the project.

Requirement: The High Voltage Regulator's input must be able to handle the power that we desire to supply it, and it should vary less than 10% as we vary the load impedance over one to two orders of magnitude.

Requirement: Must be able to handle large spikes in voltage without exceeding its own current and voltage ratings.

2.3.6 Buck Converter

The buck converter circuit will be used help power our logic in the circuit we build. It will take the high-voltage DC that we created earlier and step it down to a voltage applicable to the circuit components. This will be somewhere in the range of 5-12 volts.

Requirement: This circuit must make sure that the voltage it outputs is a clean DC signal with minimal ripple.

2.4 Tesla Coil Audio Signal Driver

2.4.1 H Bridge Rectifier

The H Bridge Rectifier topologically consists of 4 high power MOSFETs in a Wheatstone bridge configuration symmetric about the primary side of the Tesla Coil's step up transformer. A square wave rated within 10-15% of the Tesla Coil's resonant frequency is continuously applied to the MOSFET gate terminals. The frequent on/off application of gate voltage rapidly switches the voltage source driving the Tesla Coil between the regulated high voltage DC power supply and ground. The gate signal is pulse width modulated, such that it encodes the NES audio signal but is carried at the resonant frequency. Applying the square waveforms to the gates at the resonant frequency of the coil is what creates the electrical discharge from the top load. Encoding the sound through pulse width modulation specifies the resulting sound we observe.

Requirements: The MOSFETs must be able to handle the high DC voltages being placed between their drain and source terminals without the occurrence of junction breakdown.

Requirements: The MOSFETs must be able to carry out the switching behavior within 10-15% of the Tesla Coil's resonant frequency.

Requirements: The MOSFETs must be able to remain within their appropriate operating temperature ranges as specified by their datasheet.

2.4.2 Flyback Protector

A buffer circuit needs to be placed between the step up air transformer's primary winding and the output terminals of the H bridge rectifier. The reason a buffer is required is because the rapidly alternating high voltage waveform being fed into the air-core transformer from the output of the H bridge attempts to exhibit jump discontinuities at the points of switching. Since the amount of magnetic flux circulating in the transformer coils over time must be differentiable, it decreases smoothly with time. As a result, a large spike of current can be induced in the opposing direction potentially fry our H bridge. This phenomenon is called current flyback. By incorporating power diodes as a blockage mechanism against this hazardous flyback effect, we can protect our coil driver circuitry from the damaging effects.

Requirements: The diodes used to block backward current flow must be able to handle the reverse bias applied upon the frequent occurrence of current flyback without junction breakdown.

Requirements: The diodes must maintain temperatures that are within their appropriate ranges as indicated by their data sheets throughout the Tesla Coil's entire operating cycle.

2.4.3 Pulse Width Modulation circuit

This block uses the basic form of a Pulse Width Modulation (PWM) circuit. We will create a switching circuit with our DC voltage that we created earlier in order to switch at a frequency high enough to mask our music signal coming in from the other section of our project. We will use NMOS circuitry in order to create our carrier frequency. We will then power the gates by using our new audio signal coming from our NES in order to modulate this carrier wave so when it comes out of the Tesla coil, you will be able to hear the music.

Requirement: Be able to handle a high enough frequency to allow good sound definition from the PWM circuit.

2.5 Tesla Coil

2.5.1 Step Up Air Core Transformer

The air core transformer is responsible for creating the high voltage that produces the desired electrical discharge. A helical air core separates the primary and secondary transformer terminals. The secondary inductance in ratio to the primary inductance is set such that a voltage of several kilovolts in magnitude is induced in the secondary coil when it is magnetically coupled with a primary coil who's voltage is in the range of several hundreds of volts. We can achieve this by altering the shape and amount of turns composing the secondary. We also must pay attention to the distance between the concentric coils that make up the step up air core transformer.

Requirements: The transformer should have an air core and step up the secondary terminal's voltage one to two orders of magnitude above the primary terminal's voltage.

Requirements: The transformer should be helical and the length between the inner and outer radii of the concentric coils should be small enough such that the primary and secondary coils magnetically interact, but far enough such that the primary and secondary coils electrically interact.

2.5.2 Toroidal Top load

This part of the circuit acts as the Tesla Coil's capacitive load, and is driven by the high voltage secondary winding. We will place a 7 cm high needle at the center of the toroid such that the electric field lines at the needle's tip converge to a point. By adding this geometric feature to our top load, we can be almost certain that the expected electrical discharge that creates the arcing effects is emitted from the point of highest electric field concentration. The toroid and needle should be have aluminum covering its surface area.

Requirements: The Toroidal Top Load should function as a capacitor.

Requirements: The Toroidal Top Load should be the region of emission for the desired electrical discharge creating the arcs.

Requirements: The Toroidal Top Load's aluminum coating should not noticeably deteriorate as a result of the electrical discharge.

2.6 Thermal Control Block

2.6.1 Heat Sink

This component is primarily concerned with the thermal regulation of the H Bridge and the Flyback Protector. The heat sink functions by enclosing the heat producing devices, namely the power MOSFETs and diodes, and serves as a thermal energy deposit for the excess heat energy produced. A 12 V DC fan will be integrated into the heat sink, such that device cooling occurs through convective heat transfer.

Requirements: The heat sink must regulate device temperatures such that they stay within their appropriate ranges as indicated by their data sheets throughout the entire Tesla Coil operation cycle.

Requirements: The shape and material of the heat sink should accelerate the dissipation of undesired thermal energy.

Requirements: The heat sink should cover the devices we want to thermally regulate.

2.7 Risk Analysis

The block that would cause the most trouble for our group would be the coil itself. This is because we use very high voltages in our coil to produce arcs around the coil. This has the ability to cause some serious harm would anyone get close enough for the arcs to hit them. In order to counteract this possible event, we need to be very careful when testing this circuit. At the start we need to take every precaution in order to make sure that everyone around the project is safe. We understand that this specific project is going to be inherently more dangerous than most projects, but we hope that this added danger won't be enough to put anyone in harm's way. When we test this we plan to be very far away from the unit when we turn it on, and also be next to a switch to turn off all power going into the coil in case something isn't working correctly in the circuit.

A Tesla coil has enough voltage that if anyone were to actually touch it, it would deliver a potentially lethal shock. We do not take this precaution lightly and will make every effort to make sure this cannot happen. Under no circumstances will anyone be allowed near the Tesla coil during operation, and long after operation to make sure that the entire circuit is discharged correctly. We also understand that our coil can be scaled up to any amount of power, but we will be designing a coil that will be just large enough for us to create arcs that will allow us to hear the audio and no further. Any larger and we will only get larger arc lengths, which will make the coil more dangerous to others around it.

Another thing worth considering is the initial testing of the coil. This will arguably be the most dangerous part of the project. Because at this point it will be unknown if the circuit will work to its fullest potential we will need to make extra precautions to make sure that if something does go wrong there is zero possibility for someone to get hurt. We will isolate the coil from everything around and make sure to tell all others around us that we will be working with high voltages and arcs. We also will have a kill switch far away from the circuit itself to make sure that if something catastrophic does occur we can end the test immediately before things get too out of hand. If the coil does break it will be a massive setback for our design so getting it right will be critical to our success.

Aside from the dangers of the coil, the other block that with cause the most problems in terms of its complexity will be the PWM circuit that masks our audio signal into our carrier signal. This requires an H bridge circuit that will be switching at a high frequency. Because of this we will need to make sure that our copper wires will be able to handle the current being sent into it. The skin depth of copper at that frequency may force us to use multiple wires to carry our signals. We also need to worry about taking our 4 different audio channels that come from the NES and adding them together into audio signal to be sent into the PWM circuit. This may be problematic and require some added circuitry in order to make sure that the audio signal that comes out will be clean to the ears. This also requires us to make sure that the carrier frequency is fast enough to get the level of definition that we want out of our NES audio. This added added switching loss that may require us to have some form of cooling system in our circuit to make sure that the FETs do not burn up when they are switching. Not only that, but in order to get FETs that can switch relatively fast and can handle large amounts of current will be a potential problem. It's often hard to find FETs that can handle a lot of power but still have the ability to switch fast without extreme switching losses.

3. Safety and Ethics

There are several safety concerns with our project. The high power that our device uses can be potentially life threatening if the device is incorrectly implemented or lab safety procedures are not followed.

A transistor that is supplying too much power can easily overheat and burn a breadboard, in even a simple introductory circuit class such as ECE 110. As a high power device, the power supply circuit must be built in a safe such that the circuit itself does not overheat and cause damage to itself. All transistors must be rated and tested to be able to handle the voltages and currents required in the circuit design. The circuit itself will be designed to safely meet the power requirements of the device.

IEEE Code of Ethics, #1: “To hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices, and to disclose promptly factors that might endanger the public or environment” [1]. To ensure lab safety and the safety of our peers, we will ensure that our device safely is first simulated in SPICE before bringing the device for testing to the lab. We do not want any possible chances of causing harm to the others or the lab. We will also properly communicate to teaching assistants and teachers our intended usage of the lab and absorb potential feedback to ensure safety.

Due to our use of an NES emulator and Nintendo’s 8-bit sound format, we do not intend to commercialize our product in any form. We understand that this project if commercialized might have conflicts of interest with Nintendo. Adhering to the IEEE Code of Ethics, #2: “To avoid conflict of interest whenever possible, and to disclose them to affected parties when they do exists” [1], we will not try to commercialize or infringe on Nintendo’s rights in anyway. Our project is intended for our educational and creative purposes only.

4. References

[1] "IEEE IEEE Code of Ethics", *Ieee.org,* 2016. [Online]. Available: http://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed: Feb. 7, 2018].

[2] “APU,” *wiki.nesdev.com*, 24, Aug. 2017. [Online]. Available: https://wiki.nesdev.com/w/index.php/APU. [Accessed Feb. 7, 2018].