

# **ECE Learning Circuits**

## **Design Document**

**Group 22: codyr2, ishag2, neelmp2**

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**TA: Prashant Shankar**

**Team #22**

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# 1. Introduction

## 1.1 Objective

With the variety of subdisciplines of engineering available, many high school students around the world who want to pursue a STEM major have difficulty choosing the right subdiscipline for them. A factor that contributes to this difficult choice is that many high school curricula do not offer classes specifically designed to teach engineering topics and these schools are limited in their curricula on how much material they are able to teach. This limited exposure to available curricula can result in uncomfortable major selections by students. In addition, younger students, such as the ones at the elementary and middle school level complain about subjects like math and science, and argue with teachers about why they need to study them. It is important that an effort is made to provide students, at any grade level, an exposure to engineering as it can help them to better appreciate the material they are taught in school. It can also guide them to choose the viable path to enter the STEM field.

Our purpose is to solve the two cases that are described above: to assist high school students in choosing a STEM major that aligns with their interests, and to introduce younger children to engineering topics. We propose ECE Learning Circuits. Our circuits will help high school students in choosing an engineering major by providing them with enough background in electrical and computer engineering. In the future, this product can be improved to include more engineering disciplines and topics. Our circuits will also give early exposure to younger children to help them realize the importance of learning math and science and their applications to the real world outside of the textbook. We plan to construct a series of circuits that teach electrical and computer engineering topics to students of all ages. The circuit design is broken down into a beginner stage, intermediate stage, and an advanced stage.

The beginner circuit will teach students about all the logic gates (AND, OR, XOR, NOT, NAND, NOR, and XNOR). Refer to figure 4 for a detailed block description of our beginner circuit. The intermediate circuit will teach students about sensor instrumentation and will allow students to build a circuit involving the use of the piezoelectric sensor. This will allow the students to not just learn what a sensor is and how they work, but also understand how to build a circuit to make use of the sensors. Refer to figure 5 for a detailed block description of our intermediate circuit. The advanced circuit will teach students about designing a RF transmitter. Refer to figure 6 for a detailed block description of our advanced circuit. Lastly, we will help the students in getting more hands on experience with the circuit design process by allowing them to solder circuit elements, like resistors, capacitors and diodes, onto a printed circuit board as part of the beginner and the intermediate circuits.

## 1.2 Background

The learner circuits that exist in the market are snap circuits. These are circuits someone can self build onto a protoboard. The wiring on protoboards is temporary which means that they are useful in teaching students how to debug circuits but they have their limitations such as messy wiring and connection problems. Our solution is different compared to these types of circuitry learning products as we plan to have students develop the beginner and intermediate circuits onto a printed circuit board and the advanced circuit on a protoboard. The circuit on the protoboard will help students gain experience in debugging. The circuits on PCBs will allow for a clear display of the elements and will help students to understand and keep track of how each element in the circuit operates; it will also be useful in teaching them soldering.

Furthermore, colleges have introductory engineering courses in which they help undeclared engineering majors get a better idea of what specific engineering field to focus in. However, even after taking these courses, there is still a high amount of engineering orientated students who are unsure about which major is right for them. The Colorado State University led a research study where they concluded, "18% of incoming engineering students are undeclared. In an introductory 100-level class, of the 52 students in the class, 4% were enrolled in a specific engineering major and 69% were Open Option (undeclared) engineering students" [1]. Our solution will help these students at many different universities get an earlier experience in electrical and computer engineering topics at the high school and earlier grade level. This will avoid them having to wait to learn engineering topics until college and help lower the chance that a student will drop out, should they choose to select electrical or computer engineering as their major. For example, our circuit will not be a course that a student would have to be signed up for. This will allow our users to interact with the circuits mobily in order to to learn engineering topics while studying at the secondary education level.

### 1.3 Visual Aid

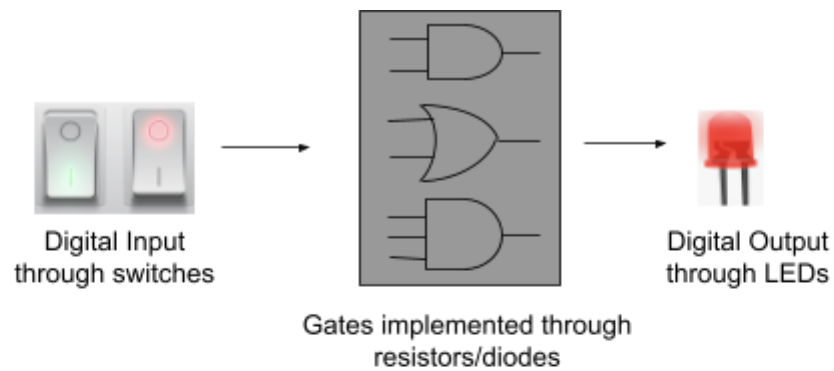


Fig. 1. Beginner Circuit - Logic Gates [2][3]

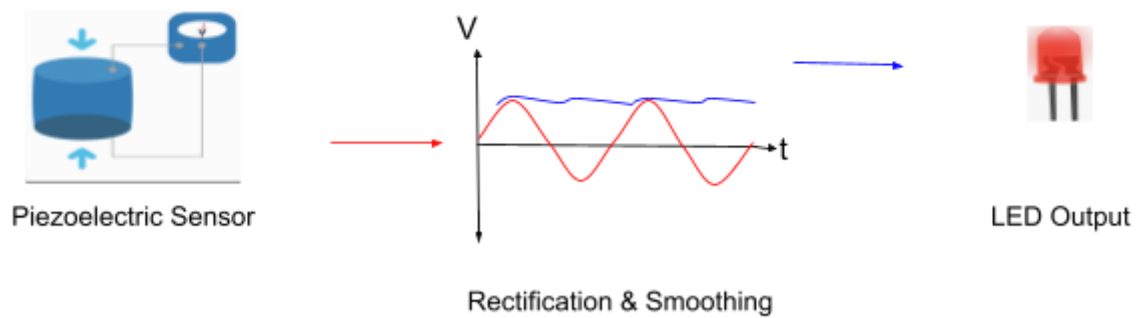


Fig. 2. Intermediate Circuit - Sensors [3][4]

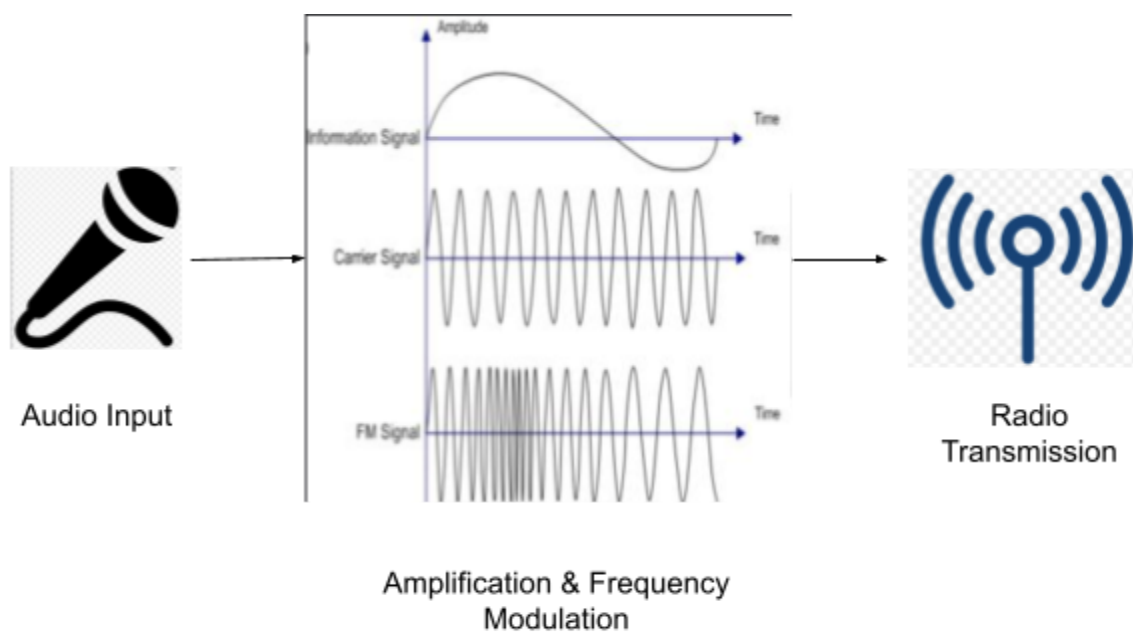


Fig. 3. Advanced Circuit - FM Transmitter [5][6]

## 1.4 High-Level Requirements

1. The beginner circuit must include all seven logic gates and each gate should output the correct boolean computation based on the user input.
2. The intermediate circuit must turn on an LED when the piezoelectric sensor detects pressure between 500-700 psi.
3. In the advanced circuit (RF circuit), the impedance of the antenna that transmits the radio wave must match with the characteristic impedance of  $50\Omega \pm 5\%$  for minimum power loss.

## 2. Design

### 2.1 Block Diagram

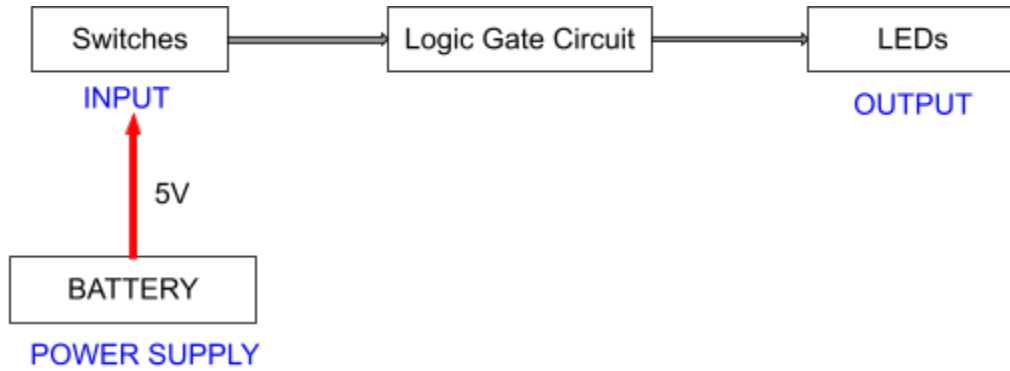


Fig. 4. Modular Design of Beginner Circuit

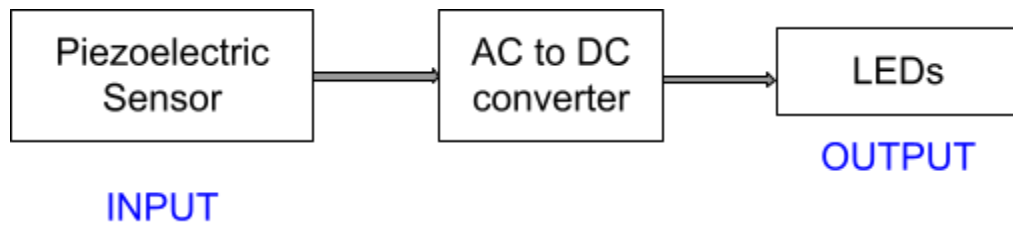


Fig. 5. Modular Design of Intermediate Circuit

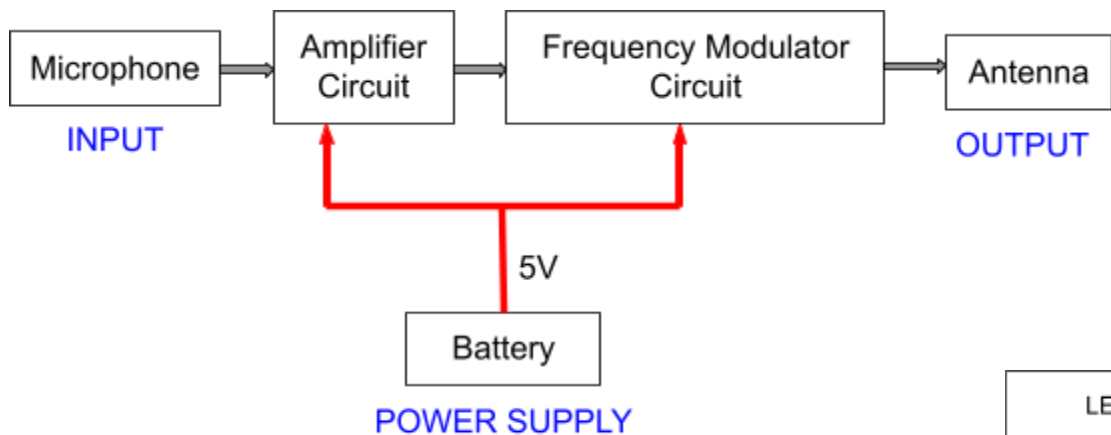
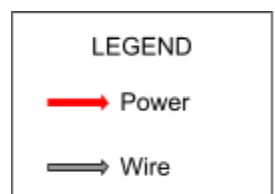


Fig. 6. Modular Design of Advanced Circuit



In the beginner circuit, the switches will receive the input from the 5 [V] battery. The logic gate circuit will contain seven logic gates implemented using resistors and diodes. A schematic representation of this idea is illustrated in Figure 7. The LEDs should display the logic gate output. Following the design of the beginner circuit, the intermediate circuit will consist of the piezoelectric sensor which outputs variable AC voltage when it detects a change in pressure. Our sensor circuit must smoothly convert the AC voltage to DC. With correct detection of change in pressure in the environment, the output of this circuit will be an LED output. A schematic representation of this idea is illustrated in figure 8. In the advanced circuit, the microphone will receive the audio input, the amplifier circuit will amplify it since the input is generally weak, the frequency modulator circuit will generate the carrier wave and combine the message and the carrier wave and the antenna will transmit the modulated carrier wave. A schematic representation of this idea is illustrated in figure 9.

## 2.2 Block Requirements

### 2.2.1 Power Supply

A continuous supply of 5[V] through a battery is crucial to the functioning of all the three circuits: beginner, intermediate and advanced. The battery should be able to supply power for at least two hours which will be plenty of time to experiment and work with each circuit. In the beginners circuit, we need to supply power to the switches for them to send a high/low signal to the logic gate circuit. In the intermediate and advanced circuits, we need a voltage supply to bias the BJTs to set their DC operating points. In the advanced circuit, we also need to supply power to the tank circuit that would store energy and generate the carrier wave.

TABLE I  
R&V OF POWER SUPPLY

Requirement	Verification
1. Battery must supply $5 \pm 4\%$ [V] to all three of the circuits.	<ol style="list-style-type: none"> <li>1. Connect batteries for each circuit with an oscilloscope</li> <li>2. Verify that the voltage measurements read from the battery source are in the range of 4.8 - 5.2 [V] for all three of the circuits.</li> </ol>



### 2.2.2 Beginner Circuit

Switches: The switches in the beginners circuit will have two distinct inputs: logic low (0) will be denoted as connecting the switch to ground (0 [V]), and logic high (1) will be denoted as connecting the switch to the battery (5 [V]).

TABLE II  
R&V OF SWITCHES

Requirement	Verification
<ol style="list-style-type: none"><li>1. Two switches will be needed for the computation of each logic gate in the beginner circuit.</li><li>2. The switches should be debounced to eliminate the circuit from reading multiple switch triggers at once.</li></ol>	<ol style="list-style-type: none"><li>1. Connect the input to a signal generator to derive a DC voltage of 0V for Low and 5V for High.</li><li>2. Connect the output to an oscilloscope to read the voltages for each of the inputs.</li><li>3. Verify that the voltage matches each of the inputs made (ground = logic zero, <math>V_{cc} = 5 [V]</math> = logic high) .</li><li>4. Make sure that two pins are connected as inputs to each logic gate input.</li><li>5. Observe the LEDs for propagation delay such that the correct output of the logic computation is always displayed. A square wave can be generated on the oscilloscope to verify the correct outputs across time.</li></ol>

Logic Gate Circuit: This circuit is the main component of the beginners circuit. This will be implemented using resistors and diodes. If the students solder the components correctly, the correct output of the logic gate computation will be displayed on the LEDs.

TABLE III  
R&V OF LOGIC GATE CIRCUIT

Requirement	Verification
1. The correct output for each of the logic gates should be created using series and parallel combinations of resistors and diodes.	<ol style="list-style-type: none"> <li>1. Connect the input to a signal generator to derive a DC voltage of 0[V] for low and 5V for high.</li> <li>2. Compare the output displayed on the oscilloscope with the truth table of the respective logic gates.</li> </ol>

LED: The LED must light up if the logic gate circuit's output is 1 or turn off if its output is 0.

TABLE IV  
R&V OF LED

Requirement	Verification
1. One single LED is required in order to showcase the final output of the logical computation for each logic gate.	<ol style="list-style-type: none"> <li>1. Hook up the pins of an ammeter on each side of the LED to measure the current flowing across the LED</li> <li>2. Verify that the value of the current is <math>20 \text{ mA} \pm 50\%</math></li> <li>3. The LED will read a value of logic high when the value of the current is within this value range mentioned in step two.</li> <li>4. The LED will read a value of logic low when the value is below 20 mA.</li> </ol>

### 2.2.3 Intermediate Circuit

Piezoelectric Sensor: This sensor should sense the pressure applied to it and produce an analog voltage that will be used to light an LED.

TABLE V  
R&V OF PIEZOELECTRIC SENSOR

Requirement	Verification
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1. The sensor should generate an AC voltage with an amplitude of 2-3 [V] in response to applied pressure of 500-700 psi.	1. Connect the output pins to an oscilloscope 2. Verify that a voltage in the range of 2-3 [V] is generated.
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AC to DC converter: Piezoelectric sensors produce an AC voltage at a very high frequency. To be able to see the LED light up, we need to convert the signal to DC. The AC to DC converter should take the piezoelectric sensor's input and do a full wave rectification with smoothing on it to hold the input signal at a constant value. This means that the AC voltage will have a constant amplitude of approximately 2-3 [V] after passing through this converter.

TABLE VI  
R&V OF AC TO DC CONVERTER CIRCUIT

Requirement	Verification
1. A diode-capacitor network should convert the AC output of the sensor with the amplitude in the range of 2-3 [V] to a DC voltage of 2-3 [V].	1. Connect the input to a signal generator to derive an AC voltage. 2. Connect input and output to an oscilloscope. Check that the output DC voltage is maintained constant at the amplitude value of the input AC voltage.

LEDs: The LED is connected to the amplifier circuit. If the students build the AC to DC converter and amplifier circuit correctly, the LED should light up when pressure is applied to the sensor and should stay lit until the sensor is vibrating.

TABLE VII  
R&V OF LED

Requirement	Verification
1. One single LED is required in order to showcase the final output of the sensor after ADC conversion and amplification.	1. Verify that the LED turns on when pressure is applied to the sensor and the LED stays on for 4-5 seconds without fluctuating.

## 2.2.4 Advanced Circuit

Microphone: The microphone should take a sound input that would be converted into an electrical signal that would modulate the frequency of the carrier radio wave.

TABLE VIII  
R&V OF MICROPHONE

Requirement	Verification
1. A microphone should take the audio input of 50 - 65 decibels and generate an AC voltage of amplitude 2.5-3 [V].	1. Connect the output of the microphone to the oscilloscope to check that an analog voltage is generated.

Amplifier Circuit: The output of the microphone is generally weak and needs to be amplified before it can be used. This amplifier circuit should amplify the output of the microphone by at least a gain value of 110.

TABLE IX  
R&V OF AMPLIFIER CIRCUIT

Requirement	Verification
1. The BJT amplifier circuit needs to increase the AC voltage generated by the microphone and amplify this voltage using a gain value of at least $110 \pm 5\%$ .	1. Connect input and output to the oscilloscope to check that 2.5-3 [V] is amplified to 5-6 [V].

Frequency Modulator Circuit: This circuit should generate the carrier signal that will be transmitted. This circuit should also modulate the frequency of the carrier wave according to the frequency of the message signal received from the amplifier circuit which is proportional to the sound input.

TABLE X  
R&V OF FREQUENCY MODULATOR CIRCUIT

Requirement	Verification
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<ol style="list-style-type: none"> <li>1) A tank circuit made of inductor and capacitor should generate an AC current</li> <li>2) BJT should combine the message and carrier waves</li> </ol>	<ol style="list-style-type: none"> <li>1) Connect the output of the tank circuit to the oscilloscope to</li> <li>2) Check that the output is generating the correct carrier wave with a frequency of 75 - 100 MHz.</li> <li>3) Connect the input of the FM circuit, tank circuit and the output of the BJT to the oscilloscope</li> <li>4) Check that the BJT is correctly modulating the modulated carrier wave</li> </ol>
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Antenna: The antenna should convert the carrier signal to radio wave and transmit it.

TABLE XI  
R&V OF ANTENNA

Requirement	Verification
<ol style="list-style-type: none"> <li>1. The antenna should be impedance matched at <math>50\Omega \pm 5\%</math></li> <li>2. The angle for the antenna should be vertically upwards when trying to hear the sound inputted into the microphone.</li> <li>3. The wire of the antenna needs to be at least 75 cm in length for operation at a 100 MHz frequency.</li> </ol>	<ol style="list-style-type: none"> <li>1. Divide the voltage with the current at the output of the antenna using an oscilloscope measurement</li> <li>2. Verify that the impedance is correctly matched at <math>50\Omega \pm 5\%</math></li> <li>3. Check to see that the audio that is imputed is correctly transmitted and the audio is clear with the excess noise removed</li> <li>4. Tune the receiver to a frequency near 100 MHz with a lot of static. Place it 10 ft away. Then verify that you can hear the audio from the input clearly.</li> </ol>

## 2.3 Schematics

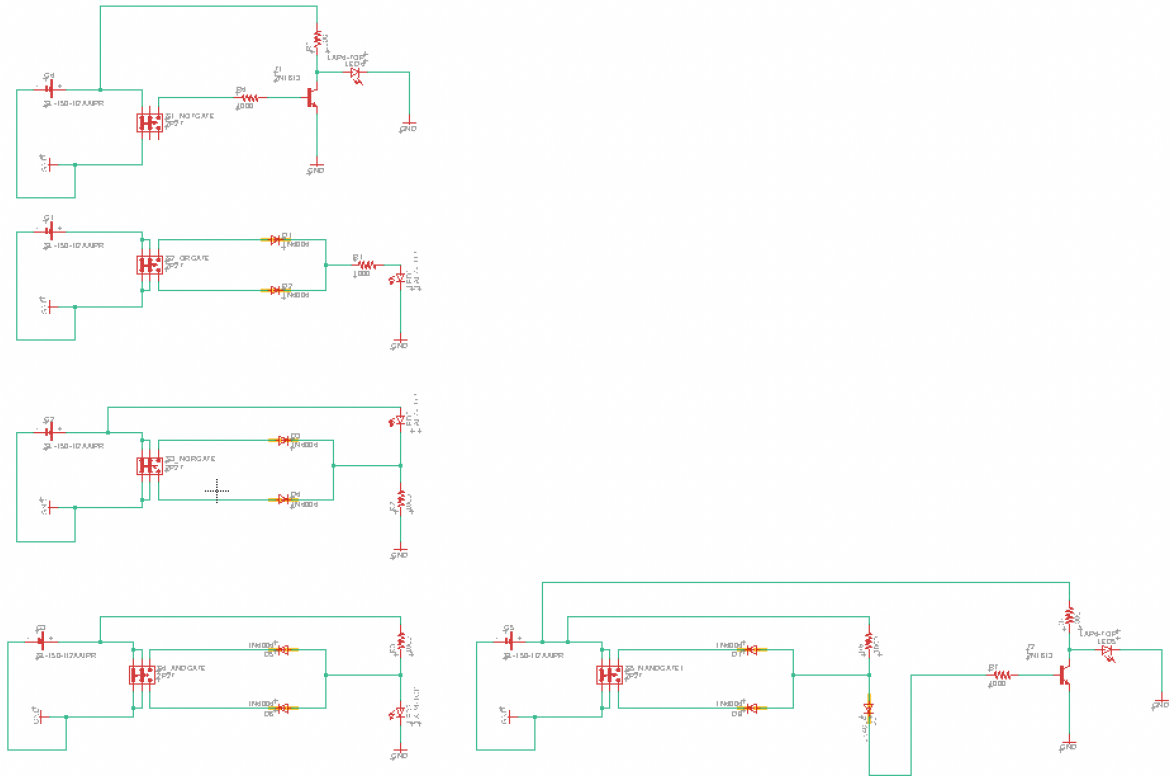


Fig. 7. Beginner Circuit Schematic

Figure 7 illustrates the design we have for the diode-resistor network for the development of the logic gates: AND, OR, and NOR. One LED located at the output of the circuit is used to display the answer for these two-input logic gates. Diodes are used to limit the current flow throughout the circuit which is dependent on the user input for the switches. The switch is shown in the figure to be connected to the battery on one side and ground on the other side. The user will select the desired input of logic high or logic low using the switch.

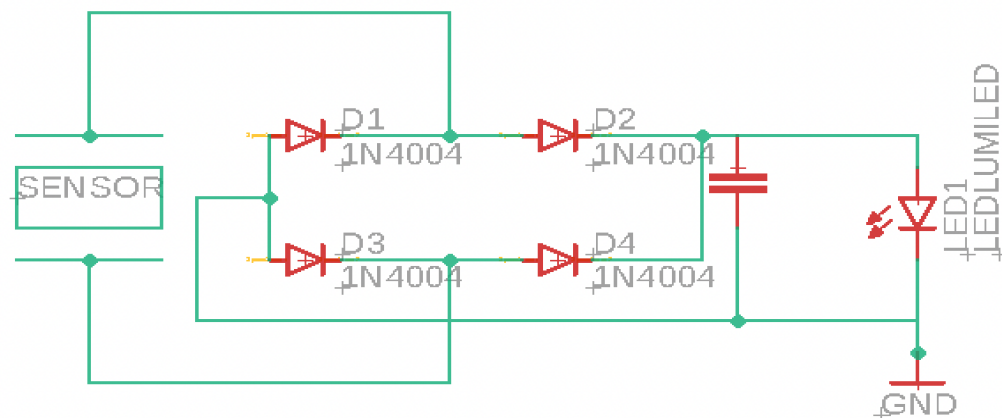


Fig. 8. Intermediate Circuit Schematic

Figure 8 displays our schematic for the intermediate (sensor) circuit. The piezoelectric sensor in the circuit takes the pressure input and converts it to AC Voltage. This voltage signal is passed to the diode bridge for AC to DC conversion. The capacitor at the end of the diode bridge smooths the output signal. The rectified and smoothed output signal lights up the LED.

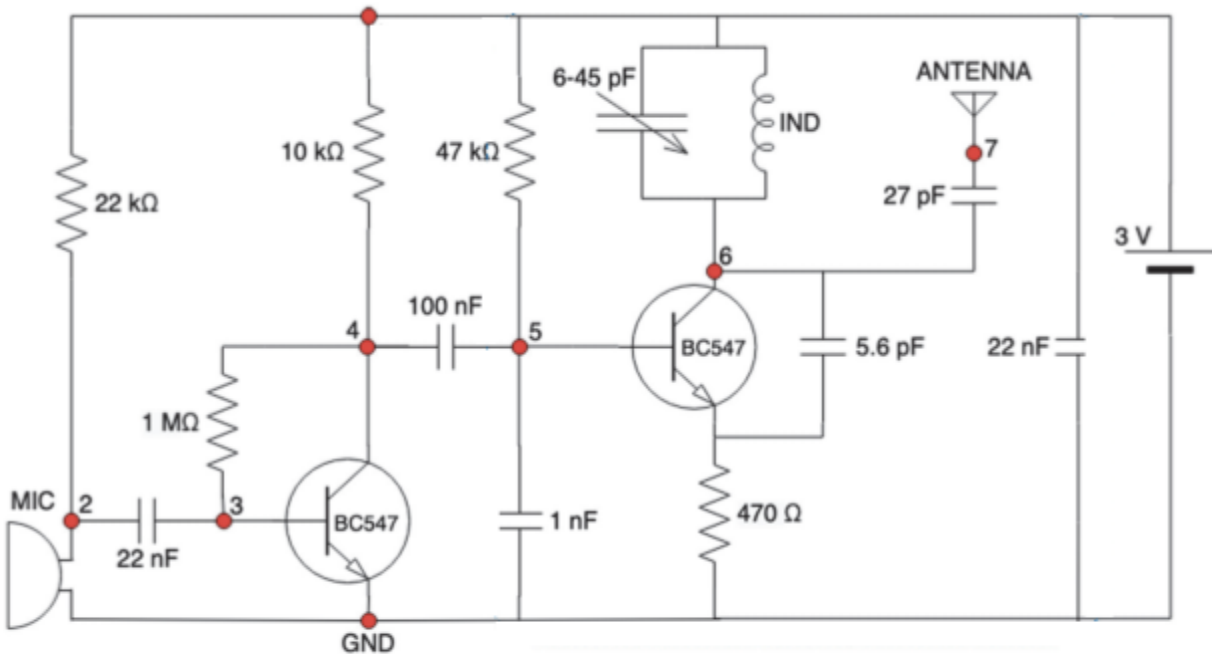


Fig. 9. Advanced Circuit Schematic [7]

Figure 9 shows the schematic for the advanced (RF) circuit. The microphone takes the audio input and passes it to the BJT where it gets amplified. The LC circuit generates the carrier wave at the desired frequency fixed by the user by changing the capacitance of the variable capacitor. The second BJT modulated the frequency of the carrier wave with respect to the frequency of the amplified signal received from the first BJT. This frequency modulated carrier wave is transmitted through the antenna.

## 2.4 Tolerance Analysis

The critical part of our design for the completion of our project is transmission of the radio wave through the antenna. To transmit the frequency modulated carrier wave generated by the tank circuit (LC circuit), the length of the antenna needs to be matched with the the wavelength of the carrier signal as follows:

$$L = \frac{\lambda}{4} \quad (1)$$

where  $L$  is the length of the antenna and  $\lambda$  is the wavelength of the signal.

Also,

$$\lambda = \frac{c}{\nu} \quad (2)$$

where  $c$  is the speed of light ( $3 * 10^8$  m/s) and  $\nu$  is the frequency of the carrier signal. Combining (1) and (2):

$$L = \frac{c}{4\nu} \quad (3)$$

A mismatch in the wavelength of the signal and the length of the antenna causes noise in the output signal and reduces the bandwidth of the antenna. The FM receiver can cover signals with frequencies in the range 64 - 108 MHz. Since we are transmitting a wave with frequencies in the range of 75 - 100 MHz, to be able to receive the signal at the FM receiver, the error percentage in the length of the antenna can be calculated using (3) as follows:

$$\begin{aligned} \Delta L &= \frac{\frac{3*10^8}{4*108*10^6} - \frac{3*10^8}{4*100*10^6}}{\frac{3*10^8}{4*100*10^6}} * 100 \% \\ &= 7.4 \% \end{aligned}$$

Therefore, an acceptable error in the length of the antenna would be  $\pm 7.4\%$ .

## 3. Cost and Schedule

### 3.1 Cost Analysis

#### 3.1.1 Labor

For each partner:

Hourly salary = \$32/hour

Total number of hours = 10 hours/week \* 8 weeks



Total salary for each partner =  $32 \times 10 \times 80 = \$25,600$

Total salary for all partners =  $3 \times 25600 = \$76,800$

### 3.1.2 Parts

TABLE XII  
COST ANALYSIS OF PARTS

Part	Quantity	Vendor	Cost per unit	Total Cost
Breadboards	1	Sparkfun	\$9.95	\$9.95
Battery Pack	1	Amazon	\$5.99	\$5.99
Battery Holder	3	Sparkfun	\$1.5	\$4.5
Toggle Switches	15	Sparkfun	\$1.95	\$29.25
Resistor Kit	1	Sparkfun	\$7.95	\$7.95
Capacitor Kit	1	Sparkfun	\$7.95	\$7.95
Diodes - 1N4148	10	Sparkfun	\$0.15	\$1.50
BJT -BC337	5	Sparkfun	\$0.50	\$2.50
LED Bag	1	Sparkfun	\$9.95	\$9.95
Inductor - 39 nH	1	Sparkfun	\$0.56	\$0.56
Variable capacitor - 6-25 pF	1	Mouser	\$3.59	\$3.59
Microphone	1	Sparkfun	\$0.95	\$0.95
<b>Total</b>				<b>\$84.64</b>

### 3.1.3 Grand Total

Grand Total = Cost of Parts + Labor = \$ 76,886.64

## 3.2 Schedule

TABLE XIII  
WEEKLY SCHEDULE

<b>Week</b>	<b>Cody</b>	<b>Isha</b>	<b>Neel</b>
<b>03/08/21</b>	Begin designing the beginner circuit. Focus on board layout of PCB	Begin designing the beginner circuit. Focus on board layout of PCB	Begin designing the beginner circuit. Focus on schematics of beginner circuit
<b>03/15/21</b>	Finalize the board layout of the beginner circuit with proper dimension	Finalize the board layout of the beginner circuit and verify dimensions and all connection made	Have our TA check the Eagle design of the beginner circuit and submit order for first round PCBway (this thursday)
<b>03/22/21</b>	Begin designing the intermediate circuit. Focus on board layout of PCB	Begin designing the intermediate circuit. Focus on schematics of beginner circuit	Begin designing the intermediate circuit. Focus on the board layout of PCB. Possibly check with TA if finished. If possible have design ready for the second round PCBway (this thursday) otherwise wait until the final round
<b>03/29/21</b>	Begin designing the advanced circuit. Refer back to talks with Prof. Goddard throughout the semester. Begin amplifier circuit	Begin designing the advanced circuit. Start verifying that the amplifier circuit increases the amplitude of the audio input	Begin designing the advanced circuit on a protoboard and test impedance matches that were calculated to verify clear audio output of the transmitter circuit
<b>04/05/21</b>	Finalize the component layout for all blocks of the advanced circuit on the protoboard	Perform final verification of each block and make sure that the amplifier and frequency modulation circuits work	Make sure to submit an order for the third round PCBway this Thursday if not done in the second round Perform testing along with Isha and verify that the correct percentage of noise is

			eliminated at the output of the antenna
<b>04/12/21</b>	Final verification and building of the working advanced circuit onto the protoboard	Final verification and building of the working advanced circuit onto the protoboard	Final verification and building of the working advanced circuit onto the protoboard
<b>04/19/21</b>	Perform mock demo to TA and start preparing for the final presentation and the final paper	Perform mock demo to TA and start preparing for the final presentation and the final paper	Perform mock demo to TA and start preparing for the final presentation and the final paper
<b>04/26/21</b>	Prepare project for presentation	Prepare project for presentation	Prepare project for presentation
<b>05/03/21</b>	Work on final paper and give presentation	Work on final paper and give presentation	Work on final paper and give presentation

## 4. Ethics and Safety

While we may be designing circuits, the actual circuitry will be done for us by the ECE electronics shop based off of our eagle design that we send to them. However, some circuits will be implemented for testing on a protoboard. This leads to the first ethical code we must follow: “Avoid harm”. The ACM Code of Ethics states, “unjustified physical or mental injury, unjustified destruction or disclosure of information, and unjustified damage to property, reputation, and the environment”[8]. In order to maintain this code, we will be using an adequate power supply of no more than 5 [V] and making sure that proper connections are made such that we do not fry the board. This can lead to harm as the customers can touch the circuit board not knowing it is burning and can burn up. We will also examine the data sheets for all the circuit elements we use such as TTL chips to make sure that the correct data is transferred properly and right connections are made. An assistive guide for each circuit will be made as well covered in detail in this section. It will include methods for avoiding injuries such as when one solders components onto the circuit in order to create the final working circuit. Overall, along with making sure that the design is neat, following the assistive guide for each circuit, and making sure to not go over this power supply, there are no other areas in our design that may lead to harm.

For the advanced circuit, we will be working with an unfamiliar circuit as it is from a different owner. We must understand the circuit fully before we build and attach all the components of the Goddard circuit onto the protoboard. The circuit consists of using BJTs and capacitors, so we want to avoid supplying too much power to the circuit input which may cause the components to burn up. An injury that may result due to this would be a burned finger after careless contact with rearranging the circuit components. Another potential method that this causes is forgetting to unplug the power supply when moving around the circuit components on the breadboard. When building the advanced circuit, the user should unplug the power supply before rearranging the circuit components and coming into contact with them with their hands.

Lastly, we need to consider the safety for the public and or people who will be using our product. The ACM code of ethics continues to say, “ensure that the public good is the central concern during all professional computing work” [8]. This is important because we need to make sure that the users of our product, when building the circuits, are following correct procedures in the design process. To solve this and ensure the safety of the public, we will be creating a user guide that will illustrate and detail the procedure of making and testing the circuit from start to finish. The user guide will inform the user as well about safety hazards so that care is taken when making our learner circuits. We will be including a soldering tutorial in this guide. The soldering tutorial in the guide will outline a procedure showing where exactly each circuit component needs to be soldered in order for each circuit to work properly. It will also give cautions as to

how one should be careful when soldering components onto a PCB. The tutorial will indicate the high temperature of soldering which is capable of causing skin irritation and skin to be burned. The assistive guide is designed so that inexperienced people are able to follow the warnings and instructions for each circuit stage and stay safe when interfacing with the circuits.

Furthermore the guide will detail more on the user about how to build each of the three learner circuits. Without this guide, our product would be confusing to operate and can also create careless injuries where inexperienced people or young children may harm themselves by messing around with the electrical equipment surrounding them. The guide for the beginner circuit will introduce the user to the schematics that we used for each logic gate and teach them how to read each schematic design. This will be explained alongside teaching them how to solder the components in the right places and describing what purpose it was for placing that specific resistor or diode in that location. The guide for the intermediate and advanced circuits will be done in a similar manner where we first give the reader a clear understanding of the schematics. We will discuss what the purpose of each component is and record data from the circuit using electrical measuring equipment. For example, in the intermediate circuit, we will explain the behavior of the piezoelectric sensor and then have the student follow a tutorial on how to measure the output voltage of the sensor when pressure is applied using an oscilloscope. The guide will serve a purpose to allow our users to have a deeper understanding of each circuit and reduce the risk of injuries from uncautious mistakes by the user. We will design the tutorials with a clear process of the knowledge and steps needed to take to safely construct each circuit from start to finish.

## References

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