ECE LEARNING CIRCUITS

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Abstract

ECE Learning Circuits teach high school students various topics that are taught in Electrical and Computer Engineering. We designed, built, and tested three circuits that serve this purpose. The circuits increase in difficulty as they move from one circuit design and implementation to the next. The beginner circuit teaches students about all the 7 logic gates and their circuit design and construction. The intermediate circuit teaches students about sensor implementation, with a focus on piezoelectric sensors. The advanced circuit teaches students about RF (radio-frequency) circuit design and how to reduce background noise through impedance matching. This learning kit includes a guide that explains all the aforementioned topics and provides a step by step tutorial to build each circuit. The guide assumes that the user does not have any prior knowledge about Electrical Engineering and is written in a manner that anyone can design, build and test the circuits without any assistance.

Contents

1. Introduction

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. This limited exposure to available curricula can result in uncomfortable major selections by students. It is important that an effort is made to provide students, at any grade level, an exposure to engineering as it can help them in choosing the right major and also, better appreciate the material they are taught in school.

Our purpose is 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 have constructed 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). 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. The advanced circuit will teach students about designing a Radio Frequency transmitter.

The learner circuits that exist in the market are snap circuits that can be self built onto a breadboard. Breadboards can be messy and hard to debug. Our solution first teaches students circuit design through a PCB because it is neater and easier to follow than a breadboard and also introduces them to soldering. The last circuit in our project teaches students how to build a circuit on a breadboard which is messier and harder to debug but an important part of circuit design. Therefore, our project covers all the important introductory aspects of circuit design and can help students decide if Electrical Engineering is a good fit for them.

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, if 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.

1.1 High Level Requirements

1. The beginner circuit must include all seven logic gates and each gate will output the correct boolean computation based on the user input.

2. The intermediate circuit must turn OFF an always ON 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

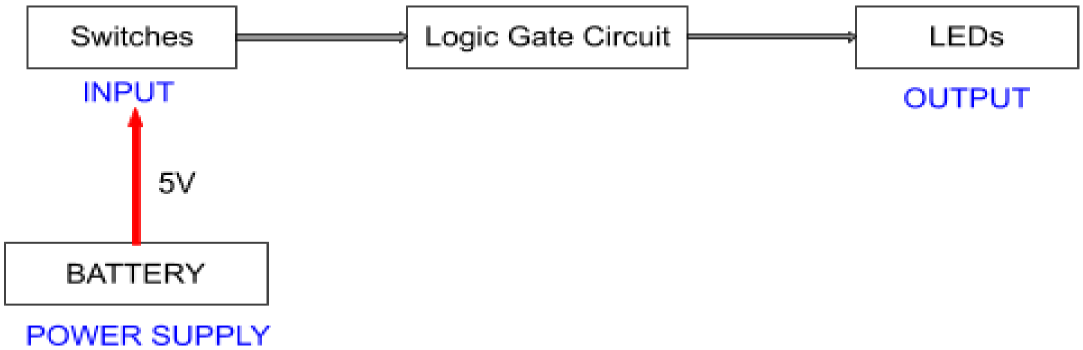


Fig. 1. Beginner Circuit Block Diagram.

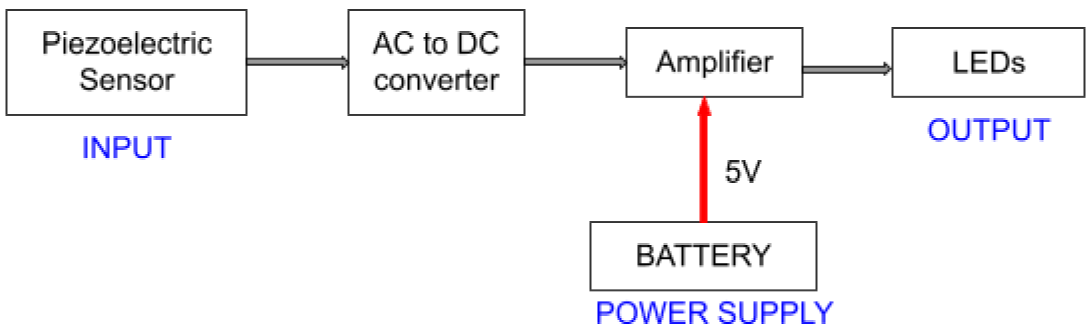


Fig. 2. Intermediate Circuit Block Diagram.

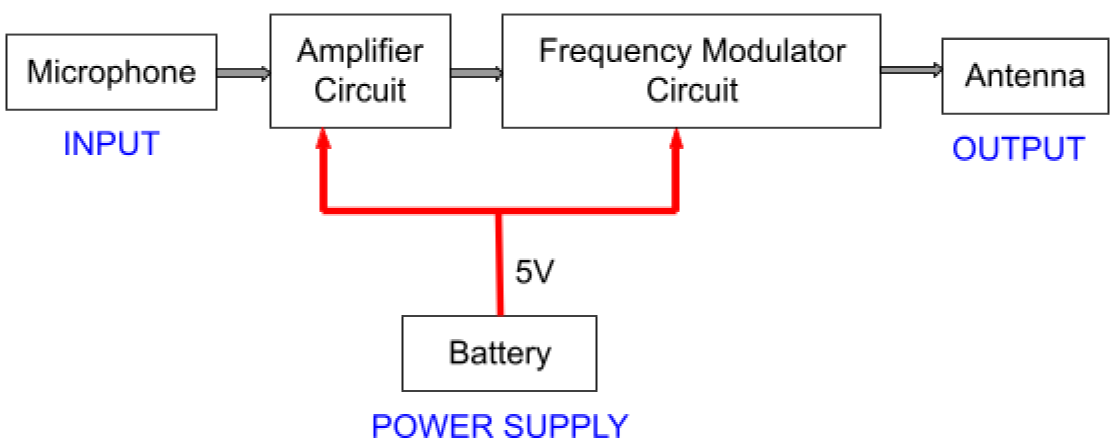
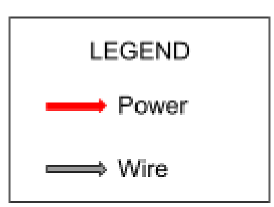


Fig. 3. Advanced Circuit Block Diagram.



2.2 Block Descriptions

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 will 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 will store energy and generate the carrier wave.

2.2.2 Beginner Circuit

In the beginner circuit, the switches receive the input from the 5 [V] battery. The logic gate circuit contains seven logic gates implemented using resistors, diodes and BJTs. We had an option of using TTL chips for implementing the seven logic gates, but we figured that the students will learn more by building circuits that can perform these operations. This is because TTL chips would only teach them about the logic gates' truth table. The LEDs display the logic gate output.

Switches: The switches in the beginners circuit will have a binary input: 0, or low, is inputted by connecting the input to GND and 1 is inputted by connecting the input to V_{DD} which is equal to 5 [V].

Logic Gate Circuit: This circuit is the main component of the beginners circuit. It is 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.

LED: The LED lights up if the logic gate circuit's output is 1 or turns off if its output is 0.

2.2.3 Intermediate Circuit

The intermediate circuit consists of the piezoelectric sensor which outputs a variable AC voltage when it detects a change in pressure. Piezoelectric sensors produce an AC voltage at a very high frequency. To be able to see the LED flicker, we need to convert the AC signal to DC. This is done by AC to DC converter. The magnitude of the voltage generated by the sensor is too weak to turn ON/OFF an LED and needs to be amplified. The amplifier circuit performs a DC amplification on the AC to DC converter's DC output. This amplified voltage turns an always ON LED, OFF.

Piezoelectric Sensor: This sensor senses the pressure applied to it and produces an analog voltage with magnitude in the range of 1-2 [V].

AC to DC converter: The AC to DC converter takes the piezoelectric sensor's input and performs a full wave rectification with smoothing on it to hold the signal at a constant value. This is illustrated in Figure 4. Its output is a DC voltage in the range of 1-2 [V].

Amplifier Circuit: The amplifier circuit performs a DC amplification on the AC to DC converter's DC output of 1-2 [V] to 2-4 [V].

LEDs: The LED is connected to the amplifier circuit. If the students build the AC to DC converter and amplifier circuit correctly, the LED will turn OFF when pressure is applied to the sensor.

2.2.4 Advanced Circuit

In the advanced circuit, the microphone receives the audio input when the user taps or speaks into it and the microphone generates an AC voltage. This voltage generated is too weak so the amplifier circuit performs AC amplification on it. The sound wave has a frequency of about 20 Hz - 20 kHz which is too low for transmission; a signal with a frequency this low gets distorted in transmission. Therefore, it needs to be encoded onto a high frequency carrier wave. The frequency modulator circuit performs this task. The antenna finally transmits the frequency modulated signal.

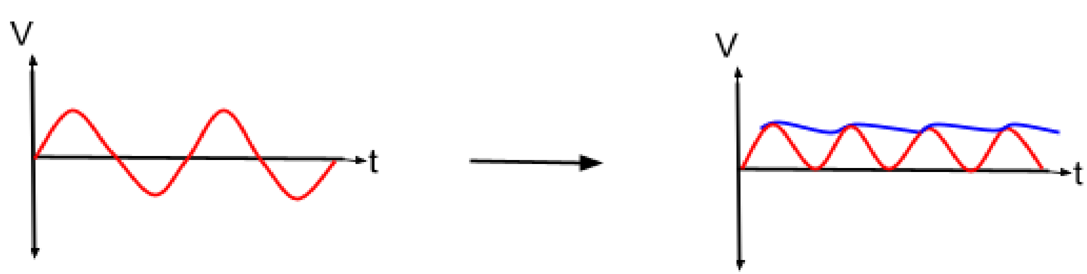


Fig. 4. Rectification and Smoothing.

Microphone: The microphone takes an audio input and generates a corresponding AC voltage with magnitude in range 2.5 - 3 [V].

Amplifier Circuit: This amplifier circuit performs AC amplification on the output of the microphone by a gain value of 110.

Frequency Modulator Circuit: The tank circuit (parallel combination of an inductor and capacitor) in this block generates the carrier wave with a frequency in the range of 88MHz - 108 MHz. The value of the frequency of the carrier wave is given by Equation (1) A BJT modulates the carrier wave according to the amplified audio signal received from the amplifier circuit. Figure 5 illustrates the graphs of the carrier waves and how its frequency is modified according to the signal wave.

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

where *f* is the frequency, *L* is the inductance and *C* is the capacitance.

Antenna: The antenna converts the carrier signal to radio waves and transmits it.

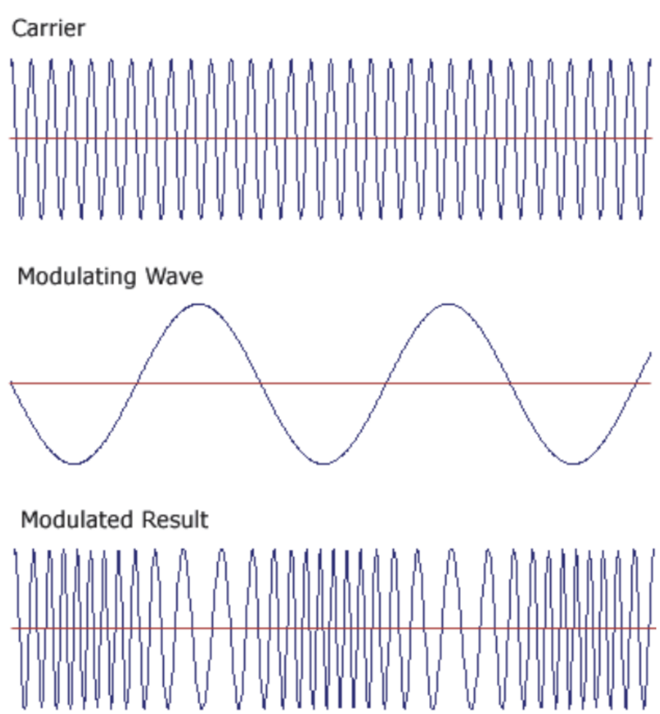


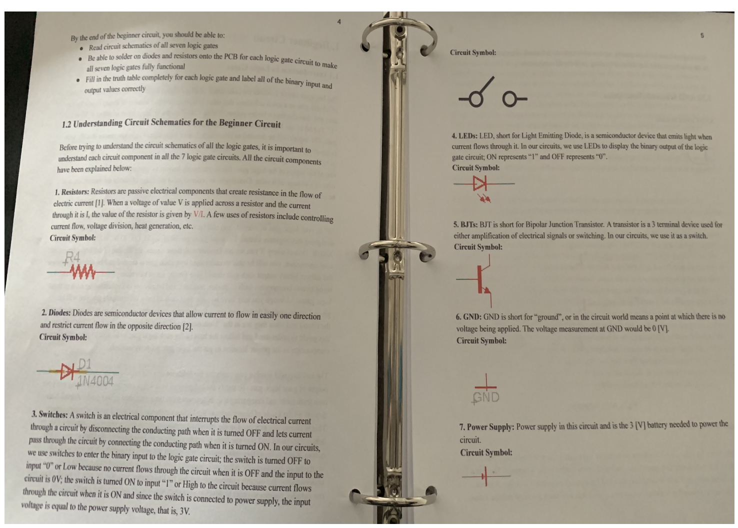
Fig. 5. Carrier Wave Influenced by Frequency Modulation.

2.3 Guide

The guide is what completes our project design. Its purpose is to satisfy three requirements and clarify what the user will be doing for designing and testing of each circuit. First, the guide will allow the user to obtain more useful information about each circuit. For example, if the user is unsure about how a BJT works, they can read more information on the behavior of the BJT in this guide. This will allow the user to avoid making assumptions and allow them to finish the design of the circuit on their own. Second, the guide will allow the user to verify their circuits. For example, there will be many times where they will be either soldering a component onto a PCB or making a wired connection on the breadboard. The guide will provide pictures to allow the user to check if their design is correct or not. Lastly, the guide will be providing tutorials on how to build and test their circuit. This will give the user a way to follow a procedure on how to build a circuit from start to finish and a procedure on how to test that their circuit is behaving correctly.

2.3.1 Beginner Circuit Guide

Introduction: The introduction provides the reader with a brief overview of what to expect in the circuit design and a description on what the circuit teaches. It also provides an objective subsection, highlighting the objectives of the circuit. The user will be able to understand all of the objectives after reading through the guide and implementing the circuit. Lastly, the introduction provides all the circuit symbols that are used in the schematics that the student will learn before building the circuits. Refer to Figure 6 for a screenshot of what the introduction looks like for the beginner circuit.



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By the end of the beginner circuit, you should be able to:

- Read circuit schematics of all seven logic gates
- Be able to solder on diodes and resistors onto the PCB for each logic gate circuit to make all seven logic gates fully functional
- Fill in the truth table completely for each logic gate and label all of the binary input and output values correctly

1.2 Understanding Circuit Schematics for the Beginner Circuit

Before trying to understand the circuit schematics of all the logic gates, it is important to understand each circuit component in all the 7 logic gate circuits. All the circuit components have been explained below:

1. Resistors: Resistors are passive electrical components that create resistance in the flow of electric current [1]. When a voltage of value V is applied across a resistor and the current through it is I, the value of the resistor is given by V/I. A few uses of resistors include controlling current flow, voltage division, heat generation, etc.
Circuit Symbol:

R4

2. Diodes: Diodes are semiconductor devices that allow current to flow in easily one direction and restrict current flow in the opposite direction [2].
Circuit Symbol:

D1
1N4004

3. Switches: A switch is an electrical component that interrupts the flow of electrical current through a circuit by disconnecting the conducting path when it is turned OFF and lets current pass through the circuit by connecting the conducting path when it is turned ON. In our circuits, we use switches to enter the binary input to the logic gate circuit; the switch is turned OFF to input "0" or Low because no current flows through the circuit when it is OFF and the input to the circuit is 0V; the switch is turned ON to input "1" or High to the circuit because current flows through the circuit when it is ON and since the switch is connected to power supply, the input voltage is equal to the power supply voltage, that is, 3V.

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Circuit Symbol:

4. LEDs: LED, short for Light Emitting Diode, is a semiconductor device that emits light when current flows through it. In our circuits, we use LEDs to display the binary output of the logic gate circuit; ON represents "1" and OFF represents "0".
Circuit Symbol:

5. BJTs: BJT is short for Bipolar Junction Transistor. A transistor is a 3 terminal device used for either amplification of electrical signals or switching. In our circuits, we use it as a switch.
Circuit Symbol:

6. GND: GND is short for "ground", or in the circuit world means a point at which there is no voltage being applied. The voltage measurement at GND would be 0 [V].
Circuit Symbol:

GND

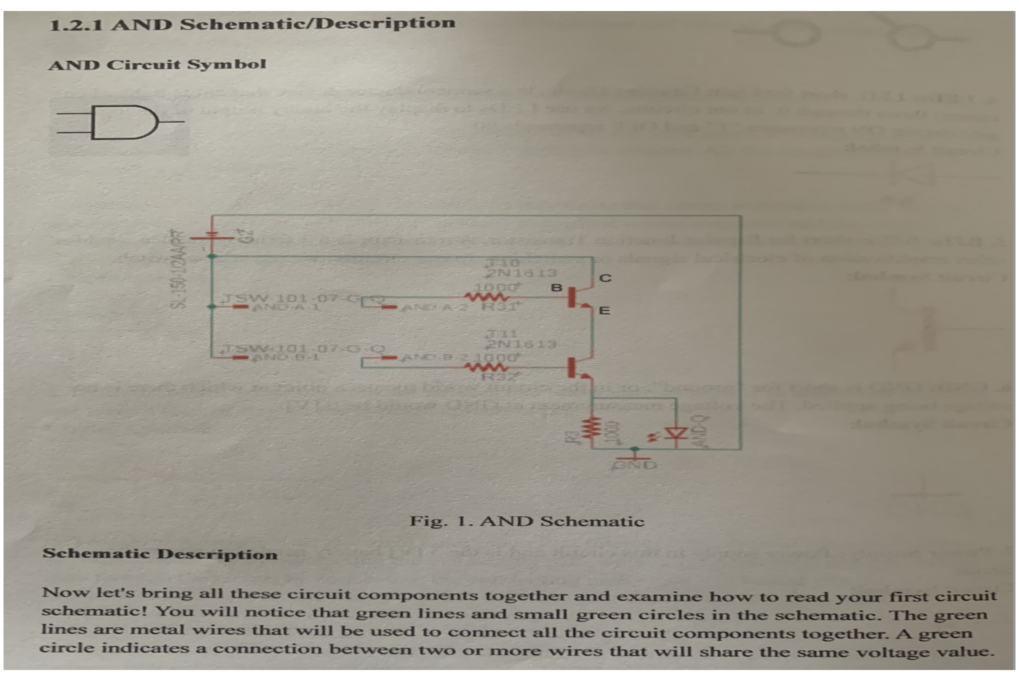
7. Power Supply: Power supply in this circuit and is the 3 [V] battery needed to power the circuit.
Circuit Symbol:

Fig. 6. Beginner Circuit Guide - Introduction.

Schematic Descriptions: After the student learns about the circuit symbols that appear in the circuit schematic, they will be ready to move on to interpreting the schematics. In the beginner circuit, the student will find the schematics for the AND, OR, XOR, NOT, NAND, NOR, and XNOR logic gates. Under each schematic, there is a detailed description about how the circuit components have been chosen and placed, methods of how to keep track of voltage and currents through the circuit, and lastly, questions along the way to test the students' understanding. Solutions to these questions are answered in the Appendix of the guide. Refer to Figure 7 for an example of the AND logic gate schematic and description. All of the logic gate schematics can also be found in Appendix A of this document.

Building Tutorial: Once the students are familiar with the circuit schematic and can read it throughout form input to output, they will be ready to construct the circuit. The building tutorial asks the user to refer to the Appendix of the guide for a soldering tutorial in which they learn about how to solder components onto a PCB. They will then follow the tutorial to solder on resistors and diodes in the correct places on the circuits in order to finish the PCB design of each logic gate.

Truth Table Worksheet: A truth table, or a table that keeps record of the binary inputs and outputs of each logic gate is provided. This allows the user to record their outputs for each of their logic gates after they finish soldering on their components using the building tutorial. The student will be able to verify their answers with the correct truth table solutions that are provided in the guide's Appendix. Truth tables' answers are in Appendix B of this document



1.2.1 AND Schematic/Description

AND Circuit Symbol

Fig. 1. AND Schematic

Schematic Description

Now let's bring all these circuit components together and examine how to read your first circuit schematic! You will notice that green lines and small green circles in the schematic. The green lines are metal wires that will be used to connect all the circuit components together. A green circle indicates a connection between two or more wires that will share the same voltage value.

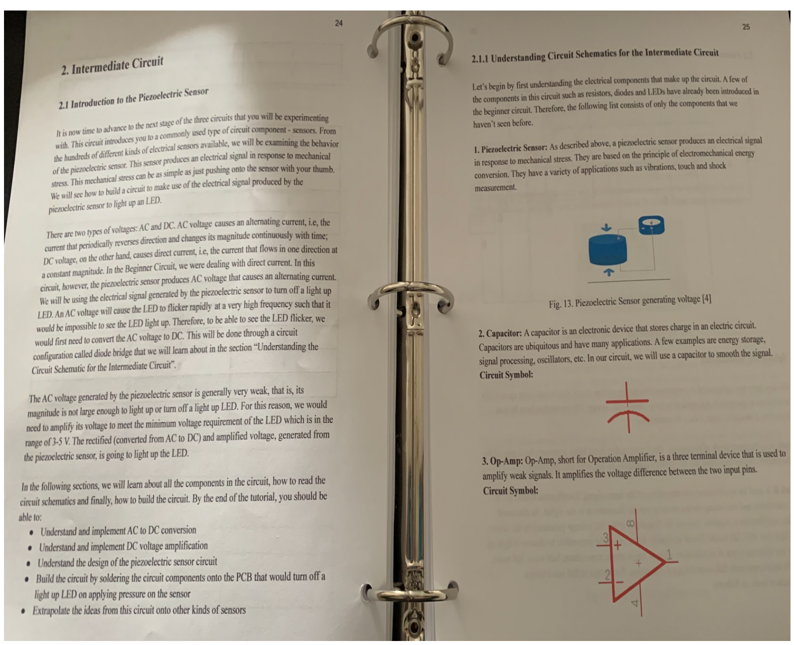
Fig. 7. Beginner Circuit Guide - Schematic Description.

2.3.2 Intermediate Circuit Guide

Introduction: The introduction of the intermediate circuit guide is written in the same style as the beginner circuit guide. Through this section, the user will be able to obtain an overview of the intermediate circuit and learn the objectives. The circuit symbol descriptions have also been updated with the new circuit symbols that the reader will see in the intermediate schematic. Refer to Figure 8 for a screenshot of what the introduction looks like for the intermediate circuit.

Schematic Description: After the student learns about the circuit symbols that appear in the circuit schematic, they will be ready to move onto interpreting the schematic. In the intermediate circuit, there is a circuit schematic for the piezoelectric sensor. The circuit has been divided into blocks unlike the beginner circuits' schematics. This is because the circuit schematic is larger compared to the beginner circuit. The schematic is broken down into subcomponents and the purpose of each subcomponent is explained. This block style description is illustrated in Figure 9. The intermediate circuit schematic can also be found in Appendix A of this document.

Building Tutorial: The building tutorial has not been changed for this section. The student will continue to refer to the soldering tutorial in the appendix to be able to solder the right components onto the PCB. The only change now is that the user will be completing the circuit using new circuit components such as the capacitor.



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2. Intermediate Circuit

2.1 Introduction to the Piezoelectric Sensor

It is now time to advance to the next stage of the three circuits that you will be experimenting with. This circuit introduces you to a commonly used type of circuit component - sensors. From the hundreds of different kinds of electrical sensors available, we will be examining the behavior of the piezoelectric sensor. This sensor produces an electrical signal in response to mechanical stress. This mechanical stress can be as simple as just pushing onto the sensor with your thumb. We will see how to build a circuit to make use of the electrical signal produced by the piezoelectric sensor to light up an LED.

There are two types of voltages: AC and DC. AC voltage causes an alternating current, i.e, the current that periodically reverses direction and changes its magnitude continuously with time; DC voltage, on the other hand, causes direct current, i.e, the current that flows in one direction at a constant magnitude. In the Beginner Circuit, we were dealing with direct current. In this circuit, however, the piezoelectric sensor produces AC voltage that causes an alternating current. We will be using the electrical signal generated by the piezoelectric sensor to turn off a light up LED. An AC voltage will cause the LED to flicker rapidly at a very high frequency such that it would be impossible to see the LED light up. Therefore, to be able to see the LED flicker, we would first need to convert the AC voltage to DC. This will be done through a circuit configuration called diode bridge that we will learn about in the section "Understanding the Circuit Schematic for the Intermediate Circuit".

The AC voltage generated by the piezoelectric sensor is generally very weak, that is, its magnitude is not large enough to light up or turn off a light up LED. For this reason, we would need to amplify its voltage to meet the minimum voltage requirement of the LED which is in the range of 3-5 V. The rectified (converted from AC to DC) and amplified voltage, generated from the piezoelectric sensor, is going to light up the LED.

In the following sections, we will learn about all the components in the circuit, how to read the circuit schematics and finally, how to build the circuit. By the end of the tutorial, you should be able to:

- Understand and implement AC to DC conversion
- Understand and implement DC voltage amplification
- Understand the design of the piezoelectric sensor circuit
- Build the circuit by soldering the circuit components onto the PCB that would turn off a light up LED on applying pressure on the sensor
- Extrapolate the ideas from this circuit onto other kinds of sensors

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2.1.1 Understanding Circuit Schematics for the Intermediate Circuit

Let's begin by first understanding the electrical components that make up the circuit. A few of the components in this circuit such as resistors, diodes and LEDs have already been introduced in the beginner circuit. Therefore, the following list consists of only the components that we haven't seen before.

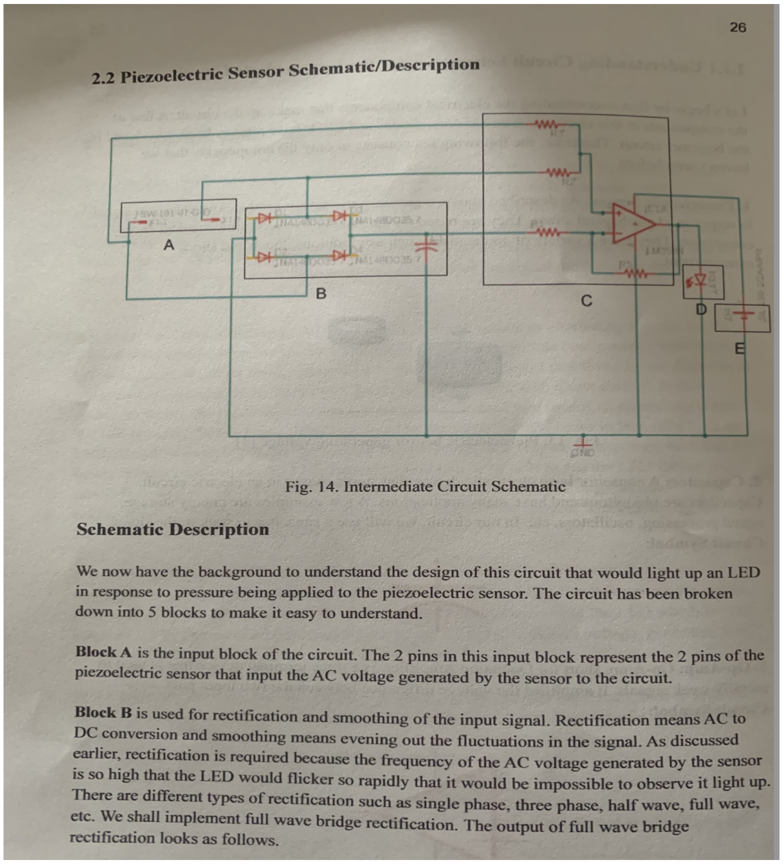
1. Piezoelectric Sensor: As described above, a piezoelectric sensor produces an electrical signal in response to mechanical stress. They are based on the principle of electromechanical energy conversion. They have a variety of applications such as vibrations, touch and shock measurement.

Fig. 13. Piezoelectric Sensor generating voltage [4]

2. Capacitor: A capacitor is an electronic device that stores charge in an electric circuit. Capacitors are ubiquitous and have many applications. A few examples are energy storage, signal processing, oscillators, etc. In our circuit, we will use a capacitor to smooth the signal.
Circuit Symbol:

3. Op-Amp: Op-Amp, short for Operation Amplifier, is a three terminal device that is used to amplify weak signals. It amplifies the voltage difference between the two input pins.
Circuit Symbol:

Fig. 8. Intermediate Circuit - Introduction.



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2.2 Piezoelectric Sensor Schematic/Description

Fig. 14. Intermediate Circuit Schematic

Schematic Description

We now have the background to understand the design of this circuit that would light up an LED in response to pressure being applied to the piezoelectric sensor. The circuit has been broken down into 5 blocks to make it easy to understand.

Block A is the input block of the circuit. The 2 pins in this input block represent the 2 pins of the piezoelectric sensor that input the AC voltage generated by the sensor to the circuit.

Block B is used for rectification and smoothing of the input signal. Rectification means AC to DC conversion and smoothing means evening out the fluctuations in the signal. As discussed earlier, rectification is required because the frequency of the AC voltage generated by the sensor is so high that the LED would flicker so rapidly that it would be impossible to observe it light up. There are different types of rectification such as single phase, three phase, half wave, full wave, etc. We shall implement full wave bridge rectification. The output of full wave bridge rectification looks as follows.

Fig. 9. Intermediate Circuit - Schematic Description.

2.3.3 Advanced Circuit Guide

Introduction: The introduction of the advanced circuit guide is written in the same style as the beginner and intermediate circuit guide. Not much is changed except now, the user will be able to obtain an overview of the advanced circuit and as well learn the objectives. The circuit symbol descriptions have also been updated with the new circuit symbols that the reader will see in the advanced schematic. Refer to Figure 10 for a screenshot of what the introduction looks like for the intermediate circuit.

Schematic Description: After the student learns about the circuit symbols that appear in the circuit schematic, they will be ready to move onto interpreting the schematic. The advanced circuit involves understanding a large scale circuit schematic which initially looks intimidating. This will not be the case as we are going to describe the circuit again in a block style description such that the student will know exactly what each block of the circuit is responsible for as they prepare to build the circuit on the breadboard piece by piece. Refer to Figure 11 for a screenshot of what the advanced circuit schematic description looks like.

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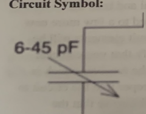
- Be able to verify that your audio input into the microphone can be picked up by your radio at the proper frequency range of 80 MHz - 100 MHz.
- Gain knowledge to attempt trying to find a solution to reduce the extra background noise from the radio due to the antenna not operating at the same frequency of the receiver

3.1.1 Understanding Circuit Schematics for the Intermediate Circuit

Let's begin by first understanding the electrical components that make up the circuit. A few of the components in this circuit such as resistors, diodes and BJTs have already been introduced in the beginner and intermediate circuits. Therefore, the following list consists of only the components that we haven't seen before.

1. Variable Capacitor: Similar to the capacitor in the intermediate circuit, this capacitor is an electronic device that stores charge in an electric circuit. Capacitors are ubiquitous and have many applications. The only difference now is that a variable capacitor allows us to change the amount of capacitance in the circuit from 6 pF to 45 pF. This is done by using a screwdriver to tune and adjust the value of the capacitance in the circuit. The purpose of this capacitor is to allow the user to adjust the capacitance and thus the frequency of the circuit to help the transmitter to have the same frequency as the receiver.
Circuit Symbol:



2. Inductor: This is a new circuit element that you have not seen before. An inductor is responsible for producing voltage when there is a change in current flowing across it. Like a capacitor it behaves similarly as a storage device and stores energy rather than charge. In reality, the inductor is simply a coil of wire wounded together. The purpose of the inductor is to allow the generation of a radio wave which is necessary for the connection between the transmitter and receiver to occur. Without the inductor in the circuit, the FM transmitter would not work.
Circuit Symbol:

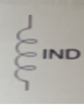


Fig. 10. Advanced Circuit - Introduction.

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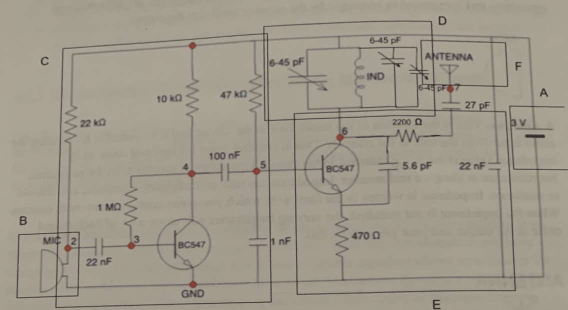


Fig. 21. Revised FM Transmitter Circuit

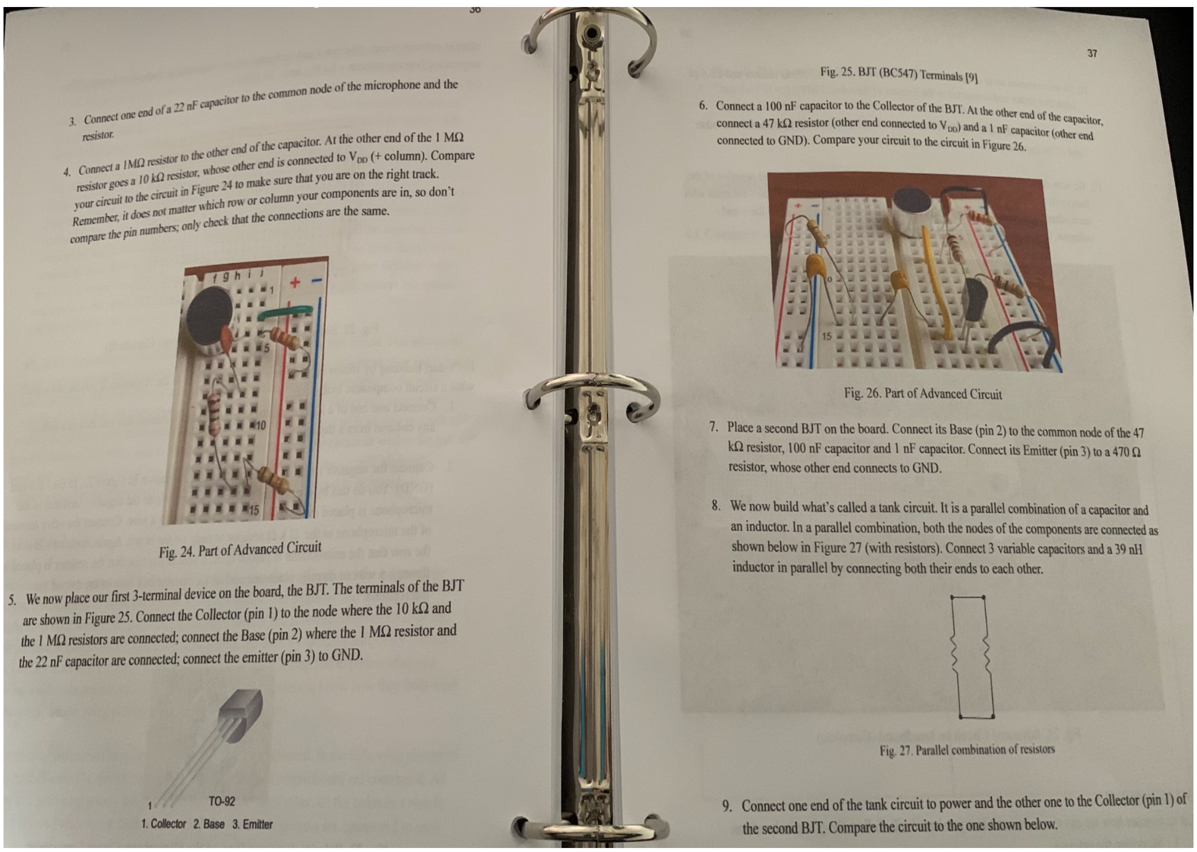
Now we will take a look at how to interpret the final schematic in this guide. The FM transmitter schematic looks more messy than any of the schematics you have seen so far in the guide, but do not worry. You will be able to use all of the knowledge you have learned so far to be able to understand this schematic as well. Figure 8 shows the original schematic that is created by professor Goddard and has the noisy output at the radio. Figure 9 shows our solution to his circuit and what we will be teaching you as the user about how to fix professor Goddard's circuit. For the schematic description, we will be constantly referring to figure 9 as figure 8 only serves the purpose of illustrating what changes were made to professor Goddard's FM transmitter circuit.

Refer to the letters A-F that are referenced throughout the advanced circuit in figure 9. Each letter corresponds to a block in the circuit that contributes to the overall design.

Block A is the location of the battery in the circuit. This circuit uses a battery of 3 [V] in order to power the circuit and allow all the circuit elements to work with each other to produce the output at the receiver/radio.

Fig. 11. Advanced Circuit - Schematic Description.

Building Tutorial: The building tutorial is different for the advanced circuit compared to the other two circuits. This is because this circuit is not built on a PCB, but rather on the protoboard. Students will follow the building tutorial and learn how to wire circuit components together in parallel or series configurations of a large scale schematic. The building tutorial has step by step procedures on how to wire the components together and pictures to allow the students to verify that they have built each block of the circuit carefully before they move onto the next. Refer to Figure 12 for an illustration on how the building tutorial was written.



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3. Connect one end of a 22 nF capacitor to the common node of the microphone and the resistor.

4. Connect a 1MΩ resistor to the other end of the capacitor. At the other end of the 1 MΩ resistor goes a 10 kΩ resistor, whose other end is connected to V_{DD} (+ column). Compare your circuit to the circuit in Figure 24 to make sure that you are on the right track. Remember, it does not matter which row or column your components are in, so don't compare the pin numbers; only check that the connections are the same.

Fig. 24. Part of Advanced Circuit

5. We now place our first 3-terminal device on the board, the BJT. The terminals of the BJT are shown in Figure 25. Connect the Collector (pin 1) to the node where the 10 kΩ and the 1 MΩ resistors are connected; connect the Base (pin 2) where the 1 MΩ resistor and the 22 nF capacitor are connected; connect the emitter (pin 3) to GND.

TO-92
1. Collector 2. Base 3. Emitter

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Fig. 25. BJT (BC547) Terminals [9]

6. Connect a 100 nF capacitor to the Collector of the BJT. At the other end of the capacitor, connect a 47 kΩ resistor (other end connected to V_{DD}) and a 1 nF capacitor (other end connected to GND). Compare your circuit to the circuit in Figure 26.

Fig. 26. Part of Advanced Circuit

7. Place a second BJT on the board. Connect its Base (pin 2) to the common node of the 47 kΩ resistor, 100 nF capacitor and 1 nF capacitor. Connect its Emitter (pin 3) to a 470 Ω resistor, whose other end connects to GND.

8. We now build what's called a tank circuit. It is a parallel combination of a capacitor and an inductor. In a parallel combination, both the nodes of the components are connected as shown below in Figure 27 (with resistors). Connect 3 variable capacitors and a 39 nH inductor in parallel by connecting both their ends to each other.

Fig. 27. Parallel combination of resistors

9. Connect one end of the tank circuit to power and the other one to the Collector (pin 1) of the second BJT. Compare the circuit to the one shown below.

Fig. 12. Advanced Circuit - Schematic Description.

3. Verification

3.1 Beginner Circuit

To verify all the seven logic gate circuits in the beginner circuit, we inputted 0 through GND and 1 through V_{DD} and compared the output of the LED (1 when ON, 0 when OFF) with the respective logic gate's truth table. We want to use switches for inputting 0 and 1 because they will make the circuit easier to use for the students. We did not have switches at the time of testing and we assumed that the switches would input 0 for OFF and 1 for ON much like directly connecting the input to GND and V_{DD}. We tested the circuits again with switches and found that OFF behaved as an open circuit since the switches were not connected to GND in any way. Therefore, the circuits did not behave as expected and we had to make some adjustments in the circuit designs like changing resistor values and adding BJTs. We were finally able to make the seven circuits work with pushbutton switches and verified using the aforementioned method of inputting binary data through GND and V_{DD} and noting the output through LED.

3.2 Intermediate Circuit

We first verified the output of the piezoelectric sensor by tapping it and plotting the voltage generated using an oscilloscope as described in the Requirement and Verification table in the Appendix C. The plot generated is shown in Figure 13.

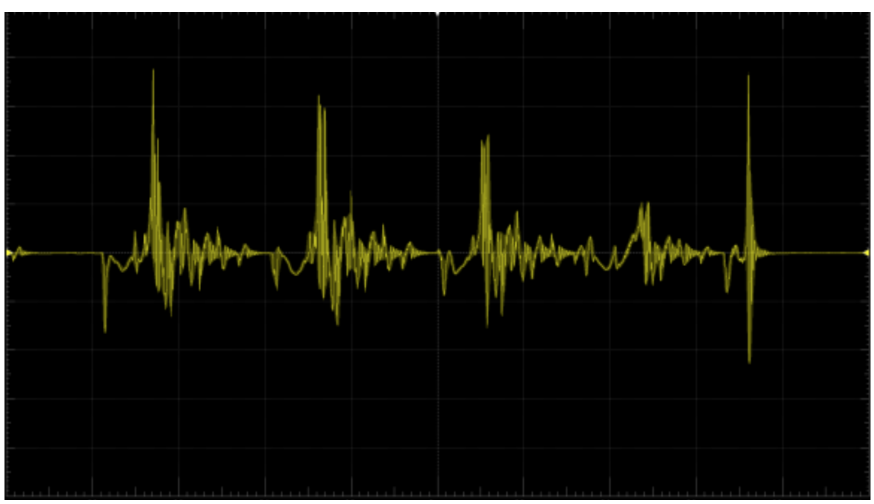

Fig. 13. Voltage generated by a piezoelectric sensor.

Next, we verified the functioning of the AC to DC converter circuit by passing the voltage generated by the sensor through it and plotting it on the oscilloscope. The plot generated is shown in Figure 14.

Finally, we verified the output of the DC amplifier circuit by passing the output of the AC to DC converter through it and observing its output through the LED. The output turned an always ON LED OFF and therefore, that meant that our circuit was working.

3.3 Advanced Circuit

Since the advanced circuit had already been tested by Professor Goddard [2] and he knew that the circuit only required impedance matching, we did not have to go through each verification step described in the Requirement and Verification table (given in Appendix C). We directly built the circuit on a breadboard and started verifying if the impedance was matched. We tried different values of resistors - 0 Ω, 1 kΩ, 2.2 kΩ, 3.3 kΩ, 4.7 kΩ, 10 kΩ to adjust the real part of the impedance and different comnfigurations of three variable capacitors (6 - 45pF) - 3 in series, 3 in parallel, 2 in series and 1 in parallel and 2 in parallel and 1 in series as well as tuned each variable capacitor to adjust the imaginary part of the impedance. We found that 2.2 kΩ or 3.3 kΩ resistors and capacitors all in parallel produced the best output by checking the sound quality at the FM receiver. The final setup that produced the best results is shown in Figure 15.

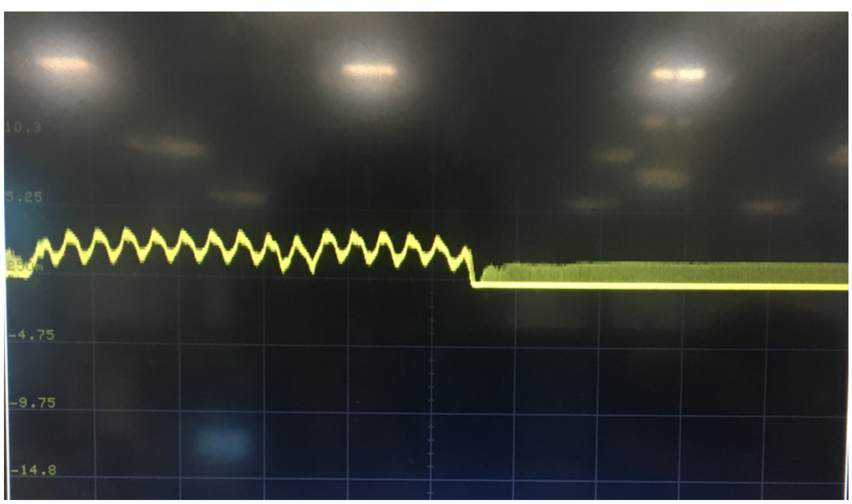

Fig. 14. AC to DC converter circuit output.

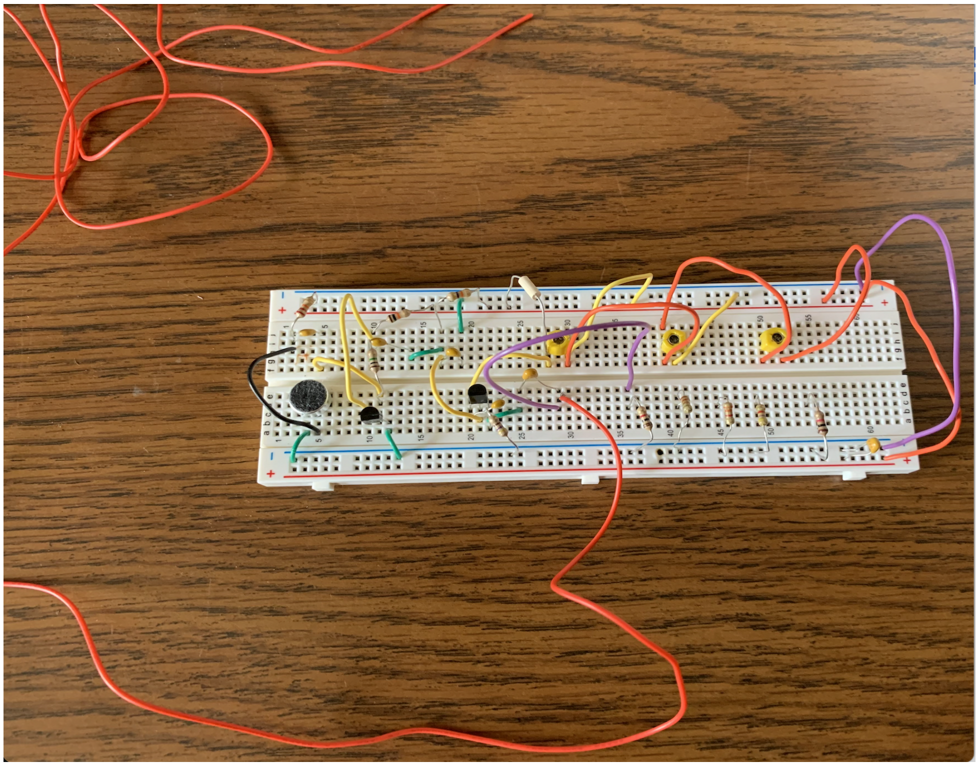

Fig. 15. Impedance matching the advanced circuit.

4. Cost

For each partner:

Hourly salary = $32/hour
Total number of hours = 10 hours/week * 8 weeks
Total salary for each partner = 32*10*80 = $25,600

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

TABLE I
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
Pushbutton Switches	20	Amazon	$1.95	$5.98
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
Total				**$61.37**

Grand Total = Cost of Parts + Labor = $ 76,861.37

5. Conclusion

5.1 Accomplishments

We have successfully built all the three parts, beginner, intermediate and advanced circuits, of our project, with a few changes from the initial design. We have also successfully designed an easy to follow guide. The guide is designed in such a way that the students learn about much more than just the three main topics (logic gates, sensors and FM transmitters) such as basics of circuit design, circuit components, soldering, circuit building on breadboard, etc. This Learning Kit will not only help students in deciding their major but will also help them in their introductory Electronics classes at college if they do decide to pursue Electrical Engineering.

5.2 Uncertainties

The advanced circuit of our project is prone to noise. Its output depends heavily on the environment, orientation of the antenna, FM receiver used and its orientation and even hand placement. Therefore, there is a small possibility that that circuit might not perform well, especially if the student is working on it on their own, without assistance. We have tried to do everything possible to make sure that a situation like this does not arise by reducing the noise as much as possible and also explaining the correct orientation of the antenna, FM receiver as well as hands, in the guide, with the help of pictures.

5.3 Ethics

As mentioned in the IEEE Code of Ethics, “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”[3], we have followed a procedure to obey ethical and safety measures when designing this project.

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. This will be described in the guide where the reader will consistently be told not to exceed this voltage. In addition to this safety measure, we also want to avoid burning injuries that can arise from working with soldering tools. This will be prevented as the guide will have a soldering tutorial that will explain what the user needs to do step by step when operating with the soldering equipment. Burning injuries will be reduced as the guide will repeatedly tell the user to not touch the heated portions of the soldering gun.

5.4 Broader Impact

Studies show that 50% of college students change their majors at least once. Changing major means wastage of time and money on the courses in your previous major. Since this Learning Kit would help students in selecting their college major and finding out if Electrical Engineering concepts seem interesting to them, we believe that the Kit has the potential of helping students save time and money at college by helping them make the right decision early on.

References

[1] Ashley Evanoski-Cole, Kimberly Catton P.E., Bert Vermeulen, Jamison Taylor Bair, and Thomas H. Bradley. "Confidence of Undecided First-Year Engineering Students in Choosing Their Major and Implications for Retention". *2017 ASEE Annual Conference & Exposition, Columbus, Ohio, 2017, June*. ASEE Conferences, 2017. https://www.jee.org/28067. [Accessed: 28-February-2021]

[2] L. L. Goddard, Y. M. Kang, S. J. McKeown, A. Haser, C. C. Johnson, and M. N. Wilson, *A Project-Based Exploration of Electrical and Computer Engineering*. Champaign, Illinois: Goddard Independent Publishing, 2020. [Online] Available: http://psl.mntl.illinois.edu/2020_09_22_Book.pdf. [Accessed: 18-February-2021]

[3] ACM Code 2018 Task Force. “ACM Code of Ethics and Professional Conduct.” *ACM*, Association for Computing Machinery, 22 June 2018 [Online], Available: www.acm.org/code-of-ethics. [Accessed: 16-February-2021]

Appendix A

Beginner Circuit Schematics

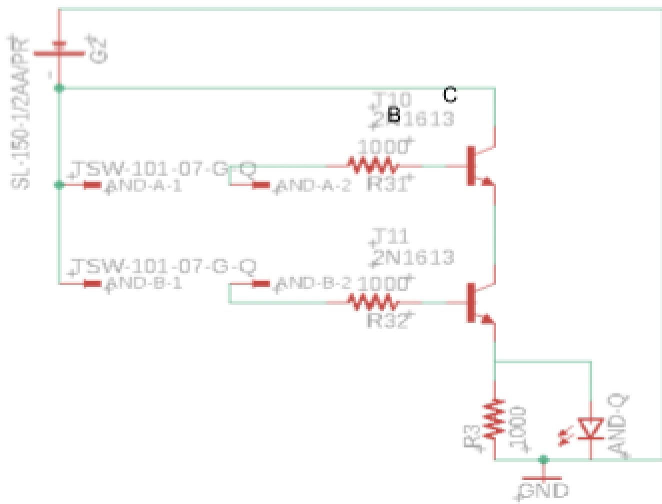

Fig. 16. AND Schematic.

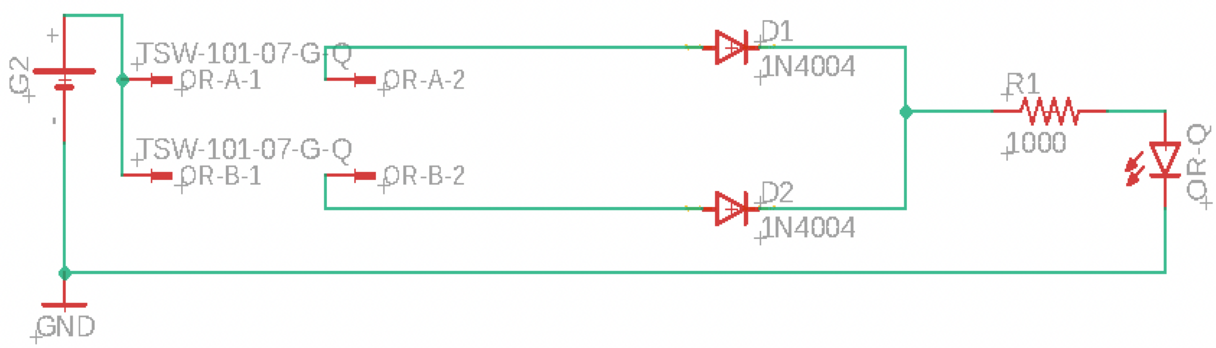

Fig. 17. OR Schematic.

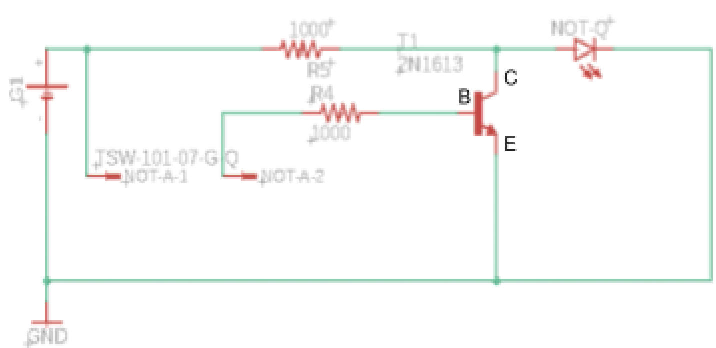

Fig. 18. NOT Schematic.

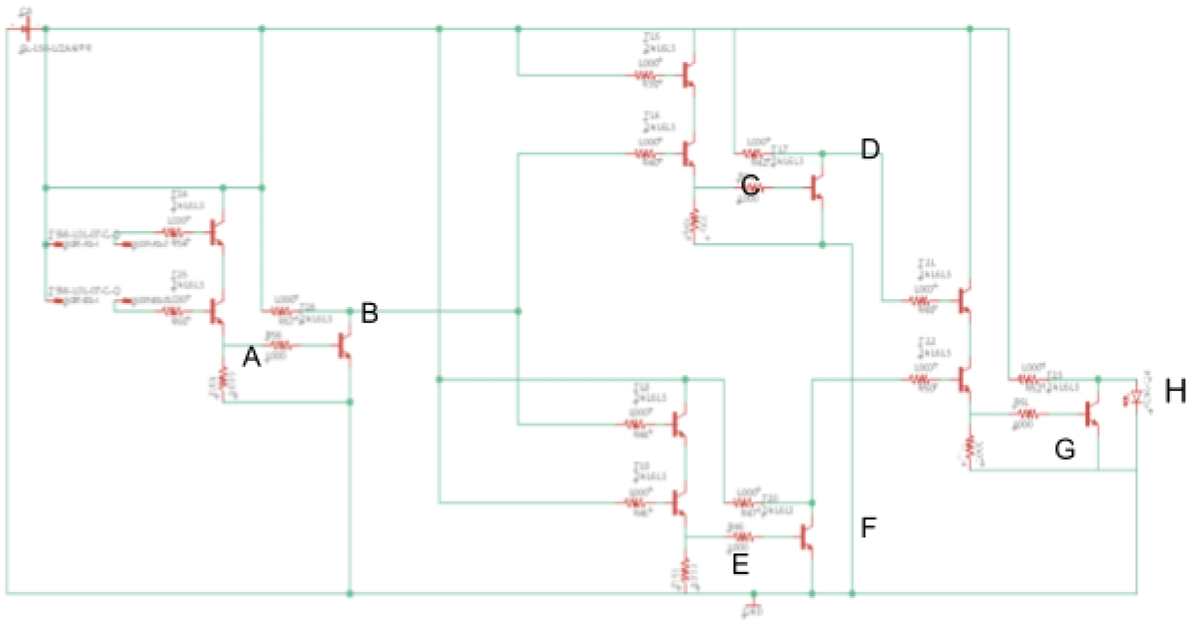

Fig. 19. XOR Schematic.

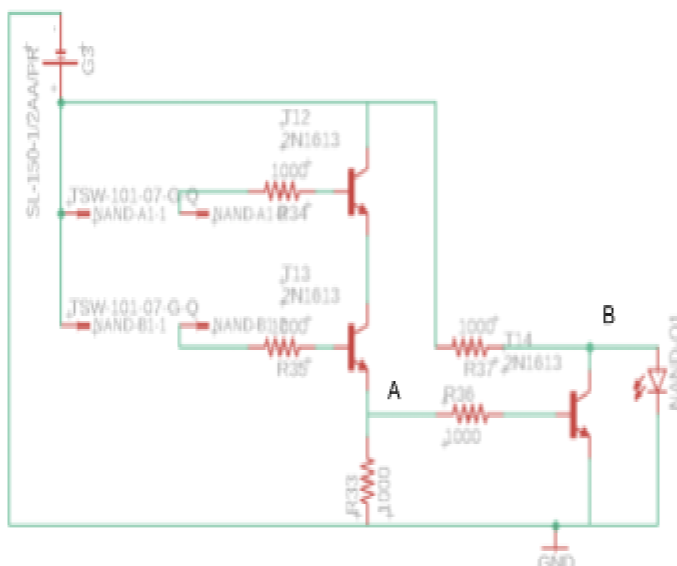

Fig. 20. NAND Schematic.

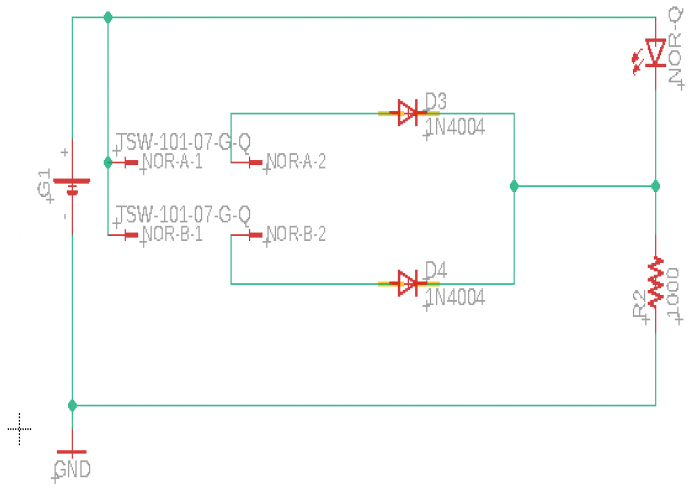

Fig. 21. NOR Schematic.

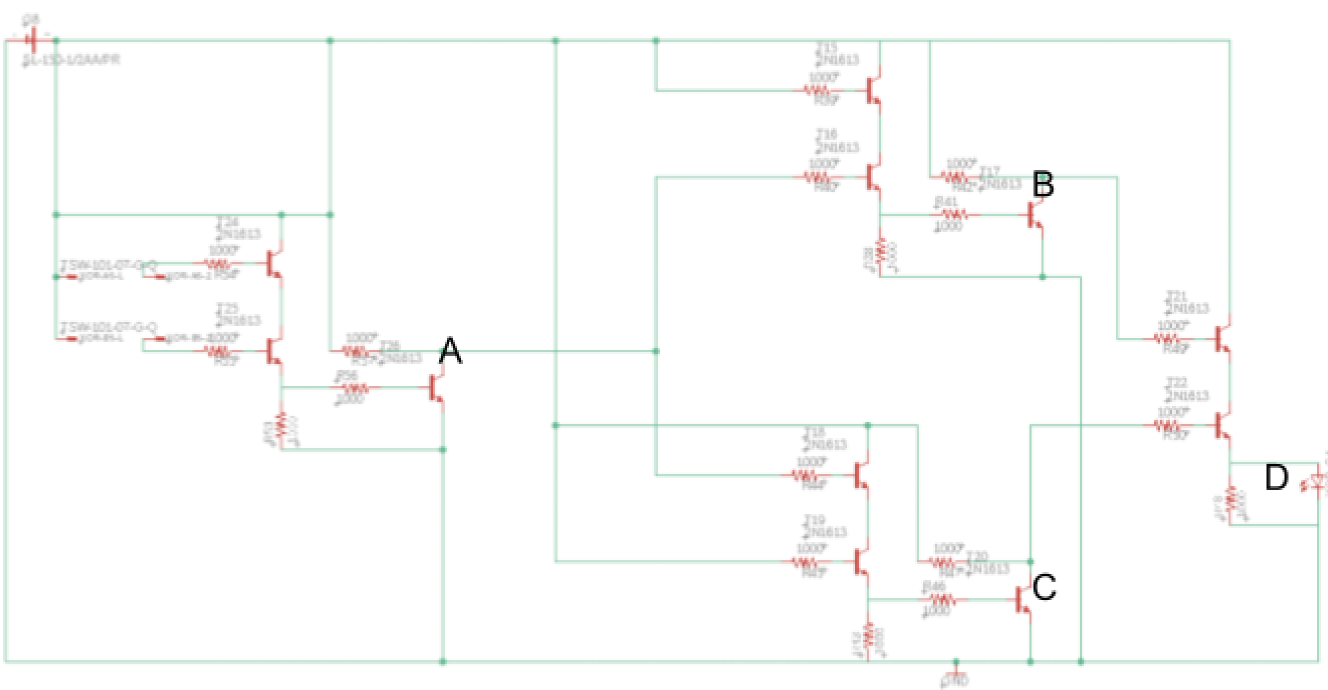

Fig. 22. XNOR Schematic.

Intermediate Circuit Schematic

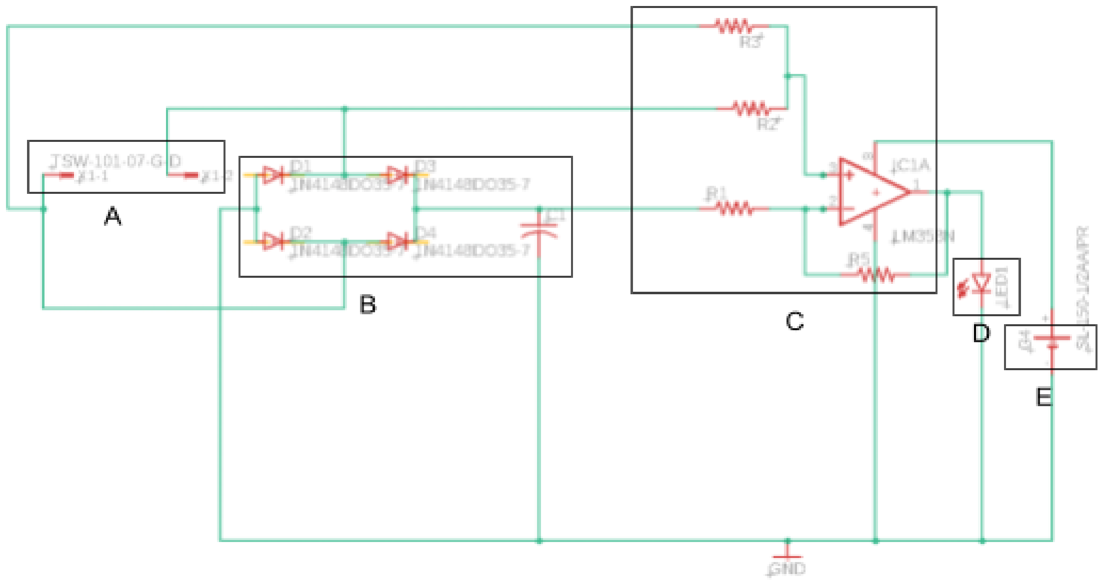

Fig. 23. Intermediate Circuit Schematic.

Advanced Circuit Schematic

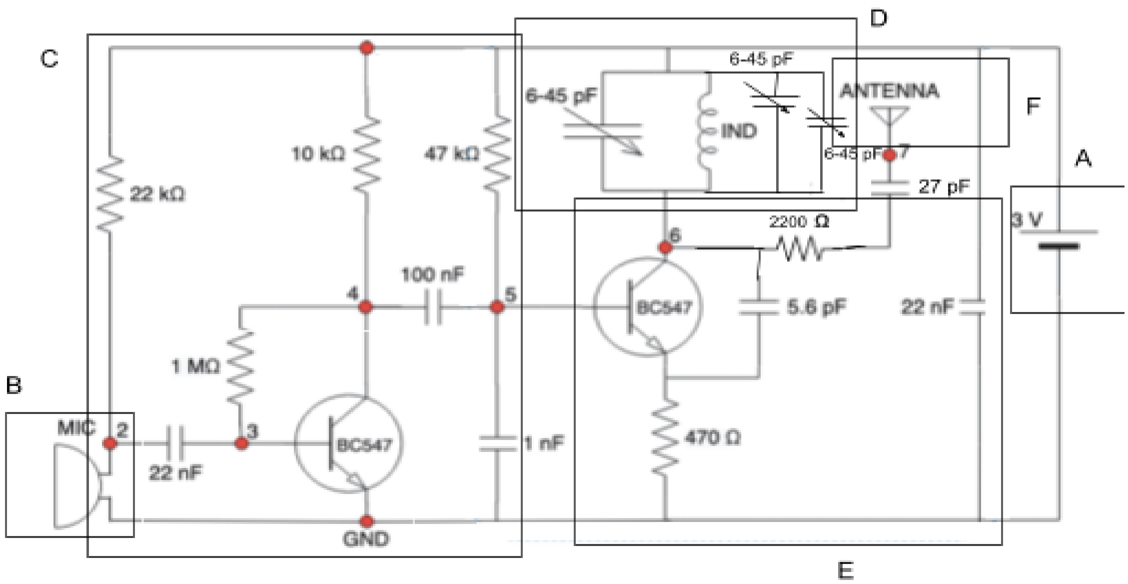

Fig. 24. FM Transmitter Circuit Schematic.

Appendix B

Answers to the Logic Gate Truth Tables

TABLE II
AND GATE TRUTH TABLE

A	B	Z
0	0	0
0	1	0
1	0	0
1	1	1

TABLE II
OR GATE TRUTH TABLE

A	B	Z
0	0	0
0	1	1
1	0	1
1	1	1

TABLE IV
XOR GATE TRUTH TABLE

A	B	Z
0	0	0
0	1	1
1	0	1
1	1	0

TABLE V
NOT GATE TRUTH TABLE

A	Z
0	1
1	0

TABLE VI
NOR GATE TRUTH TABLE

A	B	Z
0	0	1
0	1	0
1	0	0
1	1	0

TABLE VII
NAND GATE TRUTH TABLE

A	B	Z
0	0	1
0	1	1
1	0	1
1	1	0

TABLE VIII
XNOR GATE TRUTH TABLE

A	B	Z
0	0	1
0	1	0
1	0	0
1	1	1

Appendix C

TABLE IX
R&V OF POWER SUPPLY

Requirement	Verification
1. Battery must supply $5 \pm 4\%$ [V] to all three of the circuits.	1. Connect batteries for each circuit with an oscilloscope 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.

TABLE X
R&V OF SWITCHES

Requirement	Verification
1. Two switches will be needed for the computation of each logic gate in the beginner circuit. 2. The switches will be debounced to eliminate the circuit from reading multiple switch triggers at once.	1. Connect the input to a signal generator to derive a DC voltage of 0V for Low and 5V for High. 2. Connect the output to an oscilloscope to read the voltages for each of the inputs. 3. Verify that the voltage matches each of the inputs made (ground = logic zero, V_{cc} = 5 [V] = logic high) . 4. Make sure that two pins are connected as inputs to each logic gate input. 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.

TABLE XI
R&V OF LOGIC GATE CIRCUIT

Requirement	Verification
1. The correct output for each of the logic gates will be created using series and parallel combinations of resistors and diodes.	1. Connect the input to a signal generator to derive a DC voltage of 0[V] for low and 3V for high. 2. Compare the output displayed on the oscilloscope with the truth table of the respective logic gates.

TABLE XII
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.	1. Hook up the pins of an ammeter on each side of the LED to measure the current flowing across the LED 2. Verify that the value of the current is 20 mA ± 50% 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. 4. The LED will read a value of logic low when the value is below 20 mA.

TABLE XIII
R&V OF PIEZOELECTRIC SENSOR

Requirement	Verification
1. The sensor will 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.

TABLE XIV
R&V OF AC TO DC CONVERTER CIRCUIT

Requirement	Verification
1. A diode-capacitor network will 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.

TABLE XV
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.

TABLE XVI
R&V OF MICROPHONE

Requirement	Verification
1. A microphone will 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.

TABLE XVII
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].

TABLE XVIII
R&V OF FREQUENCY MODULATOR CIRCUIT

Requirement	Verification
1) A tank circuit made of inductor and capacitor will generate an AC current 2) BJT will combine the message and carrier waves	1) Connect the output of the tank circuit to the oscilloscope to 2) Check that the output is generating the correct carrier wave with a frequency of 75 - 100 MHz. 3) Connect the input of the FM circuit, tank circuit and the output of the BJT to the oscilloscope 4) Check that the BJT is correctly modulating the modulated carrier wave

TABLE XIX
R&V OF ANTENNA

Requirement	Verification
1. The antenna will be impedance matched at 50Ω ± 5% 2. The angle for the antenna will be vertically upwards when trying to hear the sound inputted into the microphone. 3. The wire of the antenna needs to be at least 75 cm in length for operation at a 100 MHz frequency.	1. Divide the voltage with the current at the output of the antenna using an oscilloscope measurement 2. Verify that the impedance is correctly matched at 50Ω ± 5% 3. Check to see that the audio that is imputed is correctly transmitted and the audio is clear with the excess noise removed 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.

Appendix D

Soldering Tutorial

How to Solder

When soldering on a PCB, there are two types of soldering: through-hole soldering and surface-mount soldering. In this tutorial, we will be focusing on through-hole soldering as that is the type of soldering used in these projects.

Preparation

At your station you will have: a soldering iron, a moist soldering sponge, solder, a clamp, diagonal cutters, the component(s) you wish to solder, and the board you are soldering onto. Go ahead and turn on your soldering iron so it can get heated up while you prepare the board. Put your component leads through the appropriate holes of the board from the top side. On the bottom side, bend the leads down so the component is held in place. If soldering an IC chip, you only need to bend pins on opposite corners to keep it held in place. You can now place the board into the clamp with the bottom side facing up and close the clamp down to hold the board in place.

Soldering

With the board clamped down and the component held in place, you can begin to solder. In your non-dominant hand, grab some solder with a couple inches sticking out from your hand. With your dominant hand, while being careful not to touch any metal on the iron, grab the iron and hold it similar to how you would hold a pencil. Touch the tip of the iron to the lead of the component and the metal of the hole, and after you have held the iron there for about a second, place the tip of the solder to the component lead and hole next to the tip of the soldering iron. You are not actually touching the solder to the iron. The solder will form a puddle around the hold. At this point, remove your stick of solder from the hole, followed by the soldering iron. The soldering iron will be removed after the stick of solder, otherwise your stick of solder will stay connected to the board. After repeating this process for all leads or pins of your component, you can put your iron back in its stand and use your diagonal cutters to trim any wire excess as close to the board as possible. This makes your board much cleaner and prevents any unwanted connections from being made.