SKIES

*Seeking Knowledge In Engineering and Science*

First Semester Report
Fall Semester 2008

by
Ian Bernstein
Jarvis Hill
Neeraj Jethnani

Prepared to partially fulfill the requirements for
ECE401 / ECE402

Department of Electrical and Computer Engineering
Colorado State University
Fort Collins, Colorado 80523

Report Approved: ______________________________________
Project Advisor

__________________________________
Senior Design Coordinator
Abstract

A recently released study has found that the educational system in the United States ranks merely 18th out of 36 nations [1] covered in the study. In South Korea, 93 percent of high school students graduate on time, compared to only 75 percent of Americans receiving their high school diploma. In order for the US to stay competitive in the global marketplace there needs to be more done to encourage high school students to finish school and pursue high tech careers in fields such as engineering. The SKIES project is a set of labs designed for junior and senior level high school students to promote science, engineering, and math. In the Fall of 2008, based on feedback from high school teachers and students, five labs have been developed to demonstrate the concepts of signal filters, sensor technologies, and electromagnetics. In addition to teaching theoretical concepts, much time was spent planning the labs so that they would be fun for students.
# Table of Contents

Abstract ................................................................................................................................. ii

List of Figures and Tables ................................................................................................. v

Introduction .......................................................................................................................... 1
   Teacher and Student Feedback ......................................................................................... 1
   Lab Ideas .......................................................................................................................... 1

Wiimote Lab: Sensors and Buses ..................................................................................... 3
   Lab Plan ........................................................................................................................... 3
   Lab Write-up .................................................................................................................. 3

Volume Control Lab: Amplifiers ....................................................................................... 11
   Lab Plan ....................................................................................................................... 11
   Design Decision ........................................................................................................... 11
   Speaker choice ............................................................................................................. 11
   Parts choice ................................................................................................................. 11
   Lab Write-up ................................................................................................................ 12

Subwoofer Lab: Low-Pass Filter ....................................................................................... 15
   Lab Plan ....................................................................................................................... 15
   Design Decisions ........................................................................................................... 15
   Lab Write-up ................................................................................................................ 16

Tweeter Lab: High-Pass Filters ......................................................................................... 21
   Lab Plan ....................................................................................................................... 21
   Design Decisions ........................................................................................................... 21
   Lab Write-up ................................................................................................................ 21

Speaker Lab: Homemade Fidelity Speakers .................................................................... 24
   Lab Plan ....................................................................................................................... 24
   Design Decisions ........................................................................................................... 24
   Parts Choice ................................................................................................................ 24
   Lab Write-up ................................................................................................................ 25

Potential Customers ........................................................................................................... 28

Marketability ...................................................................................................................... 29

Conclusions and Future Work .......................................................................................... 30

Semester Conclusions ....................................................................................................... 30
## List of Figures and Tables

**Wiimote Lab: Sensors and Buses**
- Image of Wiimote 3
- Remove screws 4
- Green PCB 5
- Accelerometer 5
- MEMS Accelerometer 6
- Camera Module 6
- DarwiinRemote Application Icon 7
- DarwiinRemote – Show IR Info 8
- DarwiinRemote – Find Wiimote 8
- DarwiinRemote – Acceleration Graph 9

**Volume Control Lab: Amplifiers**
- Figure 1 – Basic Op Amp Connection 12
- Figure 2 – Pin Connections 13
- Figure 3 – Volume Circuit 13

**Subwoofer Lab: Low-Pass Filters**
- Figure 1 – Low-Pass Circuit 16
- Figure 2 – Pin Connections 17
- Figure 3 – Bode Plot 19

**Tweeter Lab: High-Pass Filter**
- Figure 1 – High-Pass Circuit 22
- Figure 2 - Breadboard 23

**Speaker Lab**
- Homemade Speaker Image 25

**Appendices**
- Budget 35
- Timeline 36
**Introduction**

The SKIES project is a newly formed project. It stands for Seeking Knowledge In Engineering and Science. It started off as an effort introduced by Olivera Notaros of the ECE department at Colorado State University (CSU). The goal of the project has been and will be the creation of labs for junior high and high school students that are both interesting, as well as educational to the field of engineering with special emphasis on Electrical Engineering.

**Teacher and Student Feedback**

The projects created are a collaborative work that was created based on inputs from various high school teachers from around the northern Colorado region, specifically Loveland high school and Rocky Mountain high school here in Fort Collins. The teachers from these schools were either involved in the creation of their own labs or have experience in the area which gave the labs we created professional input from the expertise of people who understand the learning process when it comes to the educational level their students are currently at. The teachers that contributed the most included:

- John Fialko and Robert Ufer at Rocky Mountain High School (Fort Collins, CO)
- Ken Gwynn at LHS (Fort Collins, CO)

We were also able to receive inputs from the students themselves from a high school engineering exploration day held at the engineering building of the CSU campus. This allowed project members to meet with the students themselves and receive valuable input and understand what interests them in the field of engineering. Based on the combined input of the teachers and the students, the specific goals of the lab creation process were laid out.

The labs created for the fall 2008 semester were achieved as a collaborative work between the three members of the SKIES project. Members include:

I. Ian Bernstein
II. Jarvis Hill
III. Neeraj Jethnani

With our supervisor being: Olivera Notaros.

**Lab Ideas**

The majority of the time for this project was focused on inputs and idea creation which lead to the creation of 5 main labs. These labs are respectively called:

I. Wiimote Lab.
II. Volume Control Lab
III. Low-Pass Lab
IV. High-Pass Lab
V. Home-Made Speaker Lab

The labs were specifically tuned to challenge students of various levels of engineering and science understanding.
The Wiimote lab was created to give students some understanding as to the inner workings of the Wiimote while teaching them aspects of engineering related to sensors and telecommunications.

The volume, low pass and high pass labs are tuned to teach the students the understanding of signals as well as analog circuitry. It was also created to be a fun and interesting lab in that it teaches the application of analog circuitry while providing immediate feedback to the students in terms of the audio outputs.

The Home Made Speaker Lab will challenge students to improve upon an existing design while fulfilling an important aspect of electrical engineering involving physical electronics in terms of learning about electromagnetism.

Each of the labs fulfils an important aspect of electrical engineering while continuing to give the students a chance to improve upon the ideas generated and learn the basics of the applied engineering designs.
Wiimote Lab: Sensors and Buses

Lab Plan
After receiving feedback from students we found that they really wanted to see how engineering related to real-world devices. With over two million units sold by December 2008, the Nintendo Wii is currently the best selling game system on the market and we felt that this platform would be a good choice for our “Hack Lab,” which was later renamed to the “Wiimote Lab.” The controller that the Wii uses, also known as the Wiimote, has been popular for hacking among electronics hobbyists and is fairly simple to disassemble so we decided to use it as the focus of our lab to discuss sensors and communication buses. The Wiimote contains an MEMS accelerometer, an infrared camera, and a Bluetooth communication system so this provided us a good base to talk about sensor technologies and data interpretation. After learning about the Wiimote we hope that students will show off their knowledge to friends and hopefully use the techniques learned in this lab to learn about other devices they use in their homes.

Lab Write-up

Introduction:
In this lab you will learn about sensors and communication buses by hacking a Wii remote controller (Wiimote). You will then use the Wiimote and interpret its sensor data to determine how the sensors are being used so that you can determine other potential uses for the sensors. If you are not familiar with the Wii it is a gaming console released by Nintendo in 2006 and that uses a motion sensitive remote control instead of the more generic joystick control of other popular consoles like the Sony Playstation or Microsoft's xBox.
Procedure:
First you will start out by hacking a broken Wiimote (marked with black tape) so that you can see what the layout of the PCB (Printed Circuit Board) looks like and see where the sensors are located.

1. Remove the battery cover and the two batteries. Then remove the four screws as pictured below (be careful not to strip the screws).
2. Carefully pull the two pieces of the case apart. Be sure to keep the button side of the case facing down so that all the buttons don't fall out of place and don't misplace the screws so you can reassemble the controller.

3. You can now take the green PCB board out of the case for examination.

**Accelerometer**

Locate the accelerometer as shown below. The accelerometer is used to measure acceleration in three axes and is the sensor that is used to determine how you are swinging the remote in Wii games. In particular the accelerometer used in the Wiimote is the ADXL330.
Accelerometers are manufactured using a relatively new technology called "MEMS Technology." MEMS stands for MicroElecroMechanical System. In the image below you can see a micro machined MEMS three axis accelerometer under a microscope. The average human hair is about 80 micrometers in diameter and you can see that this accelerometer is roughly 200 micrometers wide or three hair widths! The four maze-looking parts in the corners are actually springs and as the device is moved the center part of the accelerometer moves, expanding and compressing these springs. Meanwhile, electricity is flowing through these springs and as the springs expands or compresses the spacing changes, this in turn changes the capacitance which is an electrical property that can then be detected and outputted on the wires you see coming out of the chip. As you can imagine the device is quite fragile so a micro machined cover is placed over the accelerometer and then it is encased in the black plastic case you see on your PCB.


**Camera**

One thing most people don't realize is that there is actually a small infrared camera on the end of the Wiimote. Locate the camera as shown in the picture below.
You might be wondering what the camera is for and the answer relates to the "sensor bar" that you place on top of your TV. The sensor bar is really not a "sensor" but in fact two infrared LED lights. When you point the Wiimote at your TV the infrared sensitive camera picks up the lights and uses this data to determine where you are pointing the Wiimote, rather than using the accelerometers. The reason for this is because accelerometers are good at detecting motion in the X, Y, and Z directions but they can’t detect rotational acceleration (as when you rotate the remote to move the cursor around on the screen). In order to detect rotational accelerations you need what is called a gyroscope (also based on MEMS technology). Unfortunately gyroscopes are pretty expensive so engineers at Nintendo came up with the camera/sensor bar idea to reduce the price of the controllers to an affordable level.

**Part identification**

In some of your other labs you may have been breadboarding with components that don't look like the parts you see on the Wiimote PCB. This is because most devices, especially small devices like the Wiimote, use what are called SMD (Surface Mount Devices). These parts are much smaller than the ones you use in your lab but the functionality is the same of their larger versions, only the packaging has changed. To see a photo comparison click [HERE](#). On integrated circuits the part number is usually a letter or set of letters followed by a set of numbers. This is then followed by more letters and numbers that give the exact model of the chip but aren't necessary when trying to determine what it does.

**Question:** Locate the "Broadcom" chip and try typing in the part number to determine what the chip does. The part number you type in should look something like the form of the accelerometers "ADXL330" part number.

**Reassemble**

Follow the above steps in reverse to reassemble to Wiimote. If any buttons fell off, carefully place them back in the correct spots before placing the case back together. Again, be careful not to over tighten and strip the screws.

**Data Interpretation**

Now that you have reassembled the Wiimote you are now ready to see how the sensors work.

**Mac Instructions**

If it is not already loaded on your computer you will need to download an application called "DarwiinRemote" which you can get [HERE](#).

Once it is loaded on your computer open the application as shown below.
Under the “Window” menu select "Show IR Info".

Now click the "Find Wiimote" button and then press the "1" and "2" buttons on the actual Wiimote.
Finally click the "IR Sensor" button that's right above the "Find Wiimote" button.

You should now see a graph of the accelerations of the remote and a view of what the infrared camera sees. Wave the remote around and you should see the graph change.

Question: Set the remote down flat on your table. Why does the "Wiimote accel." section report an acceleration value of about -1.0 on the Z axis?

Question: With the Wiimote still flat on the table note the values of the X, Y, and Z accelerations. Slowly tilt the Wiimote to about a 45 degree angle. What happens to the X, Y, and Z values? Finally tilt it all the way up on its side. What are the values now?

In order to interpret sensor data you need to scale it. When the remote is sitting flat on the table we will say the remote is at 0 degrees. If you tilt it all the way to one side (90 degrees) you will get a value of 1 for that axis. Multiplying the acceleration by 90 will now give you 90 for an acceleration of 1. So:

Degrees remote is tilted = Acceleration * 90. This is the same for both the X and Y axis.

   Side-to-side Tilt Angle (degrees) = X Accel. * 90
   Front-to-back Tilt Angle (degrees) = Y Accel. * 90

Question: If the Wiimote's acceleration values read X: 0.5 Y: 0.6, how is the Wiimote oriented in degrees? Work this mathematically before testing your results. Show your work.

To demonstrate the IR camera you will need an infrared source such as a TV remote control or a lighter. Point the end of the TV remote directly at the end of the Wiimote and hold down a button. You should see a flashing white spot. You can also point the Wiimote at a lit lighter and you should also see a white dot. Flame emits a lot of light in the invisible infrared light spectrum as well as the visible spectrum.

Question: What is another use for an infrared camera?
Communication Bus
In order to communicate wirelessly with the Wii game console itself, the Wiimote uses a wireless protocol called Bluetooth. Bluetooth is fairly slow at about 3Mbit/s (your WiFi connection on your laptop runs at about 54Mbit/s); however, it is designed to consume low power which makes it ideal for small battery powered devices such as cell phones, wireless mice, and the Wiimote.

Question: What is the typical range of Bluetooth?

Conclusion
Now that you have learned how the Wiimote works you can use the internet to learn how other devices you own work. If you want to see what else can be done with the Wiimote check out these links:
http://www.youtube.com/watch?v=Jd3-eiid-Uw
http://www.youtube.com/watch?v=0awjPUkBXOU

Or some more advanced projects:
http://blog.makezine.com/archive/2008/11/hacking_the_wiimote_ir_ca.html
Volume Control Lab: Amplifiers

Lab Plan
The idea for this lab was to provide student with the basics understanding of op-amp operations. Most students have never used op-amps in actual classrooms as well as in application. This would provide them with the basic understanding of op-amp operation. This section is especially important since the next labs (low pass, high pass labs) will also make use of the same theoretical applications of the op-amps. In order for those two labs to go well when the students build the circuit, they will have to have the complete understanding achieved from completing this volume lab sections.

The lab instruction themselves are not finalized and are an evolving piece of work that will change appropriately based on the input and feedback received from each instructors from different schools. This is one of the things planned for current and future improvements to the labs.

Design Decision
In order for them to understand the op-amp operation, we decided to make use of a simple non-inverting op-amp configuration that makes use of a potentiometer that ranges from 0k-22k. The audio inputs that were used for testing purposes have been ranging from computer audio ports to mp3 players to cell phone audio outputs. The reason for the range of inputs tested and used was so that students would be able to use various inputs to test their circuits and not be limited to certain sources.

Speaker choice
We originally started the labs with making use of circuit powered speakers. This presented a problem to us since the circuit designed was not able to deliver enough current due to current impedance mismatching. Because of this, we made use of a discarded used Dell powered speaker set that was able to output the signal without providing a heavy load on the circuit. This choice also allows us to amplify the output further so that the audio signal can be clearly heard from the input for all forms of the circuit used in all three labs built using the TL074CN.

Parts choice
We made use of a TL074CN 8 pin DIP in this lab, as well as the high pass and low pass filters. The reasons for this were:

1. Low supply voltage requirement: this allowed us to make use of 29 volt batteries as power sources for the operation amplifier.
2. High output gain: gave a noticeable increase in output due to the small input voltage
3. Good current output from the op-amp to drive the signal to the speakers.

We also made use of a variable resistor that would act as a volume dial and control the output of the audio signal. We did this because it seemed rather annoying for the students to have to switch out resister values when they could have used a potentiometer instead.
Lab Write-up

Volume Control Lab: Amplifiers

In the world of electrical engineering, there are many different specialties and areas of application. Some of the areas are analog circuits, signals, and electromagnetic. In this lab we will explore the world of signals as well as circuits.

Welcome to the world of Electrical Engineering. This lab will give you hands on experience when it comes to understanding how circuits and signals interact with one another. In this lab, we will learn how audio signals work and how audio filter are built. There will be an explanation on the theory, the build and questions which you will need to answer by experimenting with the circuit as well as doing some calculations. Let’s get started.

For these filter experiments, we will use a device called an Operation-Amplifier also called an Op-amp. We will begin by showing how an op-amp works. Its main function is to amplify any signal that is inputted into it. As you can see from the image below, there are 4 inputs to an op-amp:

1. An Inverting input
2. A non-inverting input
3. Positive voltage source(+Vcc)
4. Negative voltage source(-Vcc)

We use the voltage sources (+Vcc and -Vcc) to power on the op-amp.

Items needed for this lab:

- It’s always good practice to wear your safety goggles.
- Breadboard
- 1 - TL074CN 8-pin DIP
- Resistors, capacitors, and various wires
- 2 - 9-Volt batteries connected to snap connectors
- A pair of powered speakers (with power adapter)
- Digital Multimeter

Basic op-amp connections

\[ (+) \text{ non inverting input}(X) \]
\[ (-) \text{ inverting input}(X) \]
\[ +\text{Vcc} \]
\[ -\text{Vcc} \]
\[ \text{Output } (y) \]

Figure 1
The above figure 1 shows how op-amp connections are set. In order to power up the op-amp, we need two voltage source (+Vcc, -Vcc). In this lab, we will use 2 +9 Volt batteries in order to power the op-amp (pin 4 and pin 11 respectively).

When the signal is connected to the (-) input, we call it an inverting connection. The output will then have an inverted output. Example: if 5 Volts is connected to the inverting input, the output will have a negative voltage outputted such as -5Volts (if gain = 1 or unity).

**PIN CONNECTIONS (top view)**

![PIN CONNECTIONS Diagram](image)

You can find the above circuit (figure 2) and more information about the specification of the TL074CN op-amp circuit at the address below.


We will use the circuit above to create a simple op-amp circuit that takes an input and multiplies it to give a more powerful output. It will have the exact same copy of the original signal except amplified. We then use the variable resistor to control the output ($R_f$), much like the volume control on your audio receiver or stereo. In fact the volume dials on audio receivers are actually potentiometers (variable resistors). When we turn the dial, we change the resistance of the circuit, driving more current in through the op-amp and amplifying the signal.
Note on the speakers:
For this lab, we are using powered speakers so you won’t have to worry about a part of receiver design involving impedance matching. Most speaker systems draw their power through the signal that comes in, however this makes the circuit more complicated. Powered speakers such as the ones in this lab allow you to concentrate more on the theory of signals without the complication of impedance matching. Don’t worry if this section confused you, it’s more of an explanation as to why your home receiver audio system doesn’t use another power cable to power the speakers.

Procedure:
1. Build the circuit in figure 3 using the provided TL074 op-amp.
   - Make sure to connect the 9 volt batteries correctly to the op-amp.
   - Connect the speaker to the output pin of the op-amp (Ex. Pin1). Connect both red and yellow cables to the output since the output will be a mono signal. Also don’t forget to connect the green cable (ground) to the ground connection on your circuit.
2. Connect the circuit to an audio signal from an audio source such as a computer or mp3 player. If you don’t have any music files on you, visit an online radio station or Pandora.com
3. Vary the resistance on the variable resistor by turning the dial on it left or right and observe the change in the volume coming from the speakers.

Questions:
1. Set $R_f$ to 10KΩ and calculate the amplification. Think of what amplification means and use the voltage divider rule shown below.
   \[
   Vin = \frac{R_1}{R_f+R_1} \times Vout
   \]
   \[
   Gain = \frac{R_f+R_1}{R_1}
   \]
2. Assume Vin = 1V and $R_f$ = 10KΩ. if the resistance for the whole circuit(no speaker) to be 8 ohms and the speaker to have a resistance of 8 ohms as well, figure out what the current is going through the speaker. (Hint: the circuit is reduced to 2 loads and a voltage source). Guess what would happen if the circuit resistance was different from the speaker resistance.
3. If we removed $R_f$ from the circuit, what would happen to the volume (Amplitude) of the signal? Explain why.
4. Based on what you’ve learned from creating this circuit, try changing both resistance values by connecting another potentiometer to the circuit where $R_1$ is and try to maximize gain. You will notice there is a certain point where the gain won’t increase anymore regardless of what you do. Explain why this is so.
**Subwoofer Lab: Low-Pass Filter**

**Lab Plan**
The volume control lab introduced students to the characteristics of an op-amp non-inverted circuit. It gave insight on how amplifiers are used to amplify your audio signal and how op-amps are used in the student’s every-day electronic devices. Students do not gain or retain things from ‘bored-learning’, we created these labs again, to be fun, hands-on and lastly to spark interest in the science and engineering fields. This is easily achieved when you take the curriculum and combine it with something they can connect with.

An important aspect of this generation’s lifestyle is music, but more importantly, how we listen to our music. You see students walking around with their iPods in their ears strumming on their air guitars or whaling away on their customized set of air-drums. Our generation is notorious for tweaking their car stereo systems, adding 1000 Watt subwoofers along with 1500W amps to their individualistic vehicles, which personify their personality, or maybe that is just me. Expanding off the volume control lab, the Subwoofer Lab demonstrates to students how low-pass filters are utilized in the fabrication of the subwoofers in their home stereo or car stereo systems. We also mention that the output is a duplicate of the input audio signal, except amplified and we wanted them to construct the filter on a protoboard to gain knowledge on circuit constructing and reading circuit schematics. We kept in mind things we would have interested us when we were in high school.

**Design Decisions**
In our low-pass filter, we made use of the TL074CN op-amp because it can operate with low voltage inputs, allowing us to use two 9V batteries to represent a power supply because not every school has access to one. Though we took classes on linear systems and filter design, we had to figure out how to input the audio signal, from a computer or iPod, to the amplifier and what type of amplifier circuit to use. Initially, we started out designing a first-order low-pass filter but while gaining insight we noticed the subwoofer quality was poor, it was passing frequencies beyond our calculated cutoff frequency, \( \omega_c \). We found that the first-order low-pass filter only had a frequency roll-off of 6db per octave. The quality of a subwoofer depends on how quickly the low-pass filter cuts or attenuates frequencies greater than its cutoff (\( \omega > \omega_c \)), which implies faster frequency roll-off better subwoofer quality. Roll-off frequency can be achieved by adding capacitors to the circuit. So after about a month of experimenting with several designs, we decide to create the lab having students implement a second-order low-pass filter (i.e. it had two capacitors instead of 1) providing 12db per octave. We felt this filter will do a better job of demonstrating characteristics of analog systems and show them the concepts we were trying to edify. Then the task was to create an appealing lab report that contained a high-quality mixture of intuitive and theoretical questions, while exposing students to analog systems.

For this lab, we decided to use powered speakers so there would not be a need to worry about a part of receiver design involving impedance matching. Most speaker systems draw their power through the signal that comes in, however this makes the circuit more complicated. Powered speakers such as the ones we used allow you to concentrate more on the theory of signals without the complication of impedance matching.
Lab Write-up

SUBWOOFERS & LOW-PASS FILTERS

Introduction
One thing that appears to be important to our generation is music and to obtain the maximum music experience, whether it is in our cars or in a home theater system, is bass or “bumps”. You often see drivers adding big subwoofers to their vehicles to over amplify these low tones. Amplifying bass is comparable to the difference when watching a movie on a 60-inch flat-screen HDTV (high definition/resolution television) screen or watching it on your friend’s 20-inch SDTV (standard definition television).

Bass is actually enhanced by implementing a low-pass filter. You will soon see that passing an audio signal through a low pass filter is how subwoofers are fabricated. A low-pass filter is a filter that passes and amplifies low-frequency signals; hence low-pass but cuts out high-frequency or high pitch sounds such as singing. In audio applications it is sometimes referred to as a high-cut filter, or treble cut filter. In this lab you will learn the frequency and gain characteristics of a low-pass filter and how it’s utilized to filter out high frequency audio signals and amplifies the low signals (tones), essentially bass. You will gain insight on how your home stereo and or car audio system functions (i.e. what happens when you push volume up or down, hit the bass boost button, etc.)

Items needed for this lab:

- It’s always good practice to wear your safety goggles.
- Breadboard
- 1 - TL074CN 8-pin DIP
- Resistors, capacitors, and various wires
- 2 - 9-Volt batteries connected to snap connectors
- A pair of powered speakers (with power adapter)
- Digital Multimeter

Procedure
We will use the circuit below in figure 1 to create a simple low-pass filter that takes an input and multiplies (amplifies) it to give a more powerful output relative to the input. The output is a duplicate of the input audio signal, except amplified.

Figure 1
You can find the above circuit (figure 2) and more information about the specification of the TL074CN op-amp circuit at the address below.


Note on the speakers:
For this lab, we are using powered speakers so you won’t have to worry about a part of receiver design involving impedance matching. Most speaker systems draw their power through the signal that comes in, however this makes the circuit more complicated. Powered speakers such as the ones in this lab allow you to concentrate more on the theory of signals without the complication of impedance matching. Don’t worry if this section confused you, it’s more of an explanation as to why your home receiver audio system doesn’t use another power cable to power the speakers.

1. Build the circuit in figure 1 using the provided TL074 op-amp.
   - Make sure to connect the 9 volt batteries correctly to the op-amp.
   - Connect the speaker to the output pin of the op-amp (Ex. Pin1). Connect both red and yellow cables to the output since the output will be a mono signal. Also don’t forget to connect the green cable (ground) to the ground connection on your circuit.

2. Connect the circuit to an audio signal from an audio source such as a computer or mp3 player. If you don’t have any music files on you, visit an online radio station or Pandora.com.

3. Listen to the song that you have playing. Now replace \( R_2 \) with a \( 0 \rightarrow 22\,\text{K}\Omega \) potentiometer (resistor that’s able to vary its resistance). Set the potentiometer to the previous value \( R_2 = 10\,\text{K}\Omega \). Now increase the resistance value of your filter by changing to \( R_2 = 20\,\text{K}\Omega \) (20,000\( \Omega \)).
What happens to bass/subwoofer quality? Does it appear to increase or decrease?

The bass should increase. Increasing the value of $R_f$ should increase the gain of your circuit, $\text{gain} = |H(j\omega)| = \frac{R_f}{R_1}$ is a function of $R_1$, as $R_f$ increases the expression $\frac{R_f}{R_1}$ (the gain of the filter) increases.

4. Now vary the potentiometer between $0\rightarrow9\text{K}\Omega$. Does the bass appear to increase or decrease?

The bass should decrease. Decreasing the value of $R_f$ should decrease the gain of your circuit, $\text{gain} = |H(j\omega)| = \frac{R_f}{R_1}$ is a function of $R_1$, as $R_f$ decreases the expression $\frac{R_f}{R_1}$ (the gain of the filter) decreases.

5. Change $R_f$ back to $10\text{K}\Omega$. Now increase the capacitance by changing $C_1 = 150\text{nF}$ ($100\times10^{-9}\text{F}$). What happens to bass/subwoofer quality? Does it appear to increase or decrease?

The bass should decrease. Increasing the value of $C_1$ should increase the gain of your circuit $\text{gain} = |H(j\omega)| = \frac{1}{\sqrt{1 + (\omega\tau)^2}}$, $\tau = 2\pi CR$, where the total capacitance $C = C_1 + C_2$, you can see that the time constant, $\tau$, is a function of the capacitance. As $C$ increases, $\tau$ increases, which increases the value of the expression $\sqrt{1 + (\omega\tau)^2}$, which implies that when computing $\frac{1}{\sqrt{1 + (\omega\tau)^2}}$, the gain of the filter decreases as the capacitance increases.

Circuit Theory (Low-pass filter):

The purpose of this section is to give a little intuition about frequency characteristics of low pass circuits and how they function. We know that you may not understand everything or anything in this upcoming section and that is ok. The overall goal of this lab is to show how engineering principles are applied in creating low-pass and high-pass filters which are utilized in making tweeters and subwoofers.

The “gain” of the low-pass filter is a ratio of the input signal to the output signal. It essentially tells you how much the filter amplified the output signal or how much larger the output signal is in relation to the input signal. The audio input signal is denoted by $[A_{\text{in}}]$ and the output signal is denoted by $[A_{\text{out}}]$ where the magnitude of the gain is determined from, $G = \frac{A_{\text{out}}}{A_{\text{in}}} = \frac{1}{\sqrt{1 + (\omega\tau)^2}}$ where $\omega$ stands for frequency and $\tau$ is the time constant of the circuit. You will learn more about what the symbols ($\omega$, $\tau$) mean later in the lab.

The gain characteristics of the low-pass filter can be easily seen in graphs called “Bode Plots”. Bode plots are used to show how your gain responds to a range of frequencies, ($\omega$), which is called the ‘frequency response’ of the filter. The bode plot of the low-pass filter is pictured below:

Filter cutoff frequency ($\omega_C$): is the boundary of all filters, not just low-pass, where the input signal (audio signal, $A_{\text{in}}$) is no longer amplified. Frequencies above $\omega_C$ are cutout (do not receive amplification), ideally you will not hear them.

$$\omega_C = \frac{1}{\tau}$$
Looking at the Bode Plot located in Figure 3, the top graph is a plot of the gain for a range of frequencies, \( \omega \). The magnitude goes down due to the inverted configuration of the op-amp used in the low-pass design. You can see that the graph starts out as a constant value then proceeds to slope downward towards zero. The constant portion is due to all frequencies that are passed by the filter (\( \omega < \omega_c \)) the downward sloping portion is due the filter cutting off frequencies higher than the cutoff frequency, here \( \omega > \omega_c \). In a proper low-pass filter, as the frequency of the signal increases, \( \omega \to \infty \), the gain decreases, \( G \to 0 \).

The bottom plot labeled ‘phase’ is the phase plot of your filter. Do not worry about this but if you’re feeling inquisitive, you can wikipedia ‘bode plots’ to gain further intuition. Wikipedia will also give you more insight on the magnitude plot as well.

**Time constant** (\( \tau \)): tells you how long your filter takes to reach the outputted amplified signal (i.e. the magnitude/gain, \( G = \frac{1}{\sqrt{1 + (\omega \tau)^2}} \)).

\[
\tau = 2\pi R \times C \quad [\text{seconds}]
\]

**Questions:**

With \( C = 100 \text{ nF} = (100 \times 10^{-9}) \), where F = farads, which is the unit capacitance is measured in

1. What is the cutoff frequency of the your low pass filter _________

1a. Consider the Bode plot of the simple low-pass filter. Now look at the magnitude plot and see what happens at and after your calculated cutoff-frequency, \( \omega_c \). From the plot, what appears to happen to the gain/magnitude as \( \omega > \omega_c \)?

2. What is the time constant of your filter_______ seconds

3. Compute the gain of your filter at the following frequencies:
Gain equation: \[ G = \frac{1}{\sqrt{1 + (\omega / \omega_c)^2}} \]

*plug \( \omega_1, \omega_2, \omega_3 \) into the gain equation*

a). \( \omega_1 = 50 \)

\[ G_1 = \]

b). \( \omega_2 = 110 \)

\[ G_2 = \]

c). \( \omega_3 = 150 \)

\[ G_3 = \]

4. From your gain calculations above, does it appear that your filter is operating properly, in that the gains \( \omega_1, \omega_2, \omega_3 \). Explain. (HINT: Think of what low-pass filters do to frequencies that are within and that exceed the cutoff-frequency, \( \omega > \omega_c \). )

5. So Jarvis turns on his new stereo system while riding in the car with his friends. He really wants to impress his friends with the amount of bass his car stereo system produces. So he hits the ‘Bass boost’ button, the amount of bass the subwoofer produce, doubles. What has been done to the low-pass circuit in the subwoofer?
Tweeter Lab: High-Pass Filters

Lab Plan
After completing the “Subwoofer & Low-pass Filters” lab, students will know how low-pass filters amplify signals within, \( \omega < \omega_c \) and outside \( \omega > \omega_c \) of the cutoff-frequency; how to add bass to their home stereo and or car stereo system by varying the resistance and capacitance of the speaker’s low-pass circuit and provides them with intuition on the functionalities of their stereo systems (e.g. what happens when I press the bass boost button, turn up the volume, etc.)

We wanted to expose students to the opposite side of the spectrum by showing them how tweeters are made while demonstrating most of the same concepts and institution. The key to a good sound system is finding that ratio between bass and lyrics. Expanding off the subwoofer lab, this lab demonstrates to students how high-pass filters are utilized in the fabrication of the tweeters in their home stereo or car stereo systems and how tweeters amplify high frequency signals and attenuate low frequency signals. This will enable them to identify differences between subwoofer and tweeter design.

Design Decisions
In our high-pass filter, we made use of the TL074CN op-amp because it can operate with low voltage inputs, allowing us to use two 9V batteries to represent a power supply because not every school has access to one. Since we started out designing the low-pass filter, we went straight to a second-order high-pass filter design to bypass the problems we encountered while designing the low-pass filter. As a result of the faster roll-off frequency we felt this filter will do a better job of demonstrating characteristics of analog systems and show them the concepts we were trying to edify. Then the task was to create an appealing lab report that contained a high-quality mixture of intuitional and theoretical questions, while exposing students to another division of analog systems. Like the subwoofer lab we decided to use powered speakers

Lab Write-up

Tweeters: High-Pass Filters

Introduction
Audio Treble is one of the main focuses of audio engineers. Car receivers often have equalizer settings to enhance hg or using smaller specially designed speaker to amplify the high frequency parts of an audio signal. One example would be amplifying the voice of your favorite singer, especially if the voice has a higher frequency aspect to it. These speakers that can handle the high audio frequencies emitted are commonly called tweeters.

Treble is actually enhanced by implementing a high-pass filter. You will soon see that passing an audio signal through a high pass filter is how tweeters are fabricated. A low-pass filter is a filter that passes and amplifies high-frequency signals; hence high-pass but cuts out low-frequency or heavy bass sounds such as those generated by a bass guitar. In this lab you will learn the frequency and gain characteristics of a high-pass filter and how it’s utilized to filter out low frequency audio signals and amplifying high frequency ones or treble tones. You will gain insight on how your home stereo and or car audio system functions when it comes to the tweeters and how audio routed to those speakers appear to only amplify high frequency audio tones.
Procedure

1. Using your protoboards construct the high-pass filter circuit. Notice how it’s the capacitors and resistors positions are exactly the opposite compared to the low pass circuit from the low pass lab. The circuit below attenuates (thins out) the signal above the cutoff frequency at a rate of 12dB per octave.

![Figure 1](image)

Listen to the song that you have playing. Now replace $R_2$ with a $0\rightarrow22\,\text{k}\Omega$ potentiometer (resistor that’s able to vary its resistance). Set the potentiometer to the previous value $R_2=10\,\text{k}\Omega$. Now increase the resistance value of your filter by changing to $R_f=20\,\text{k}\Omega$ ($20,000\,\Omega$):

2. What happens to treble quality? Does it appear to increase or decrease?
   The treble should decrease. Based on the equation below, this causes the 3dB point to fall and introduce more of the frequency to pass through causing less of a filter effect.

3. Now vary the potentiometer between $0\rightarrow9\,\text{k}\Omega$. Does the bass appear to increase or decrease?
   The treble should increase. Decreasing the value of $R_f$ should cause less of the frequency range through and cause the filter to act as a better filter, this however comes at a cost of the amplitude.

4. Try changing the value of the capacitance $C_1$ and $C_2$ (matching). Note down the results and your conclusion on how the changes affect the circuit.

5. Using the experience you’ve received so far when it comes to configuring the op-amp, come up with the best performance that can be achieved using the parts you have available with you (use the potentiometer and different C values). Compare your speaker output quality with other team members and see what they did differently and how it affected their output. Note the results.
Circuit Theory (High-pass filter)

Many of the concepts to understand filter functions are shown in the Low-pass filter lab (which you should have completed before this one). The cutoff frequency is set by the equation below. Use them to help solve the questions above.

\[
F_c = \frac{1}{2\pi \sqrt{(R_1R_2 + C_1 + C_2)}}
\]

Where \( R_1 = R_2, \ C_1 = C_2 \) simplifies the equation to:

\[
F_c = \frac{1}{2\pi R_C}
\]
Speaker Lab: Homemade Fidelity Speakers

Lab Plan
This lab was created with the idea of providing students with the basic understanding of how speakers operate in terms of the electromagnetic theory as well as the general assembly of a simple speaker. The same theory can be extended to actual commercial production speakers. The biggest reason for this extension into the realm of speakers is to give students a complete overview from the point audio is outputted from an audio source (CD/DVD or any source really), goes through a receiver for audio filtering and finally outputted to the speaker. It completed the idea of audio generation and manipulation section of the ECE labs we have built and experimented with.

Design Decisions
The hardware design instructions for this lab were mostly the work a hobbyist engineer (Mr. Jose Pino) who was willing to allow his design to be used for education purposes. We made use of the design to create a lab instruction set that will challenge students to experiment and come up with better designs or a completely new design of their own.

Parts Choice
1. TRS output cable: We are going to reuse the audio cable that was used in the op-amp labs since this will allow the speaker to receive the input without students having to solder the copper wire to it. They can simply wrap the exposed wire around it.

2. Mono / Stereo audio plug: we used this during developing the demo unit to decide if we wanted to use a mono or stereo source and in the end used a mono one since we were creating a single speaker and not two of them, therefore making it pointless to have a stereo plug.

3. Neodymium magnets: they provided the most powerful magnetic field to price ratio that can produce a very high quality of audio outputted to the foam plate.

4. 38 gauge copper wire: For out demo unit we used a 38 gauge instead of the 30 gauge recommended on the website, mainly because of its availability from the ECE laboratory. It served its purpose but the resistance was slightly higher than recommended and the number of turnings around the magnet was reduced because of it. It still caused then whole unit to operate well but it could be improved with a 30 gauge wire.

5. Foam plate: as recommended from the website, we used a foam plate for the building process since it provided the best vibration vs. rigidity ratio and therefore gave the best audio performance from it.
Lab Write-up

Speaker Lab: Homemade Fidelity Speakers

Introduction:
Disclaimer: Actual hardware creation process created by Jose Pino (www.josepino.com)
This instruction set is created to show how applied electromagnetism work, in this case, the building of a homemade speaker.

Procedure:

1. Have your protective goggles on for safety purposes.

2. Visit http://josepino.com/other_projects/?homemade-hifi-speaker.jpc and follow the online instruction to create the speakers. You should have all the hardware you need available. There is also a YouTube video on the same page that is very useful in giving a general overview for the build process.
   Note: We have provided an audio source cable. Just wrap the exposed copper wire from the speaker around the audio source cable (no need to solder but make sure the enamel is removed from the contact points of the copper wire). Also, don’t use quick drying glue or ones that will adhere permanently so that you can easily make changes to the speakers like the changes you’ll need to do to answer the questions below.

3. Once you’re done building the speaker, use your ammeter to measure the resistance of the coil and test it out by plugging in the provided audio cable to an audio source (cell phone, mp3 player, computer audio port and play an audio file or Pandora, etc). Make sure you have the volume on your audio source set pretty high to make sure there’s enough current flowing through the copper wire.

4. Read the “electromagnetism at work” section below to help with answering the question below.

5. Answer the questions below.

6. Come up with your own improvements to increase the quality of the speakers (last question below).
**Electromagnetism at work**

The main electromagnetic theory at work when it comes to the creation of speakers is Faraday’s law. In the early 1800’s, Michael Faraday discovered that a magnetic field is created when a current is applied to a coil of wire. One of the applications of this theory is in the creation of speakers. As you can see while building the speaker, the current from the audio source goes through the coiled copper wire and generates a magnetic field. This magnetic field interacts with the magnetic field of the magnets to generate a mechanical force that vibrates the foam plate. When the foam plate vibrates, air particles carry the vibration through the air and vibrate the eardrums in our ears which give us the audio we hear. The audio source varies generated is a sin wave with different frequency tones that give the audio its distinctiveness. Since the audio signal is in the form of a sin wave, the current continuously varies in order to create the force that vibrates the foam plate.

**Questions**

1. Why is a copper wire used instead of other materials such as silver?
   
   Copper is used because it has a low electrical resistance that it is easy for the current to flow through it. Also, copper wire can be easily shaped to make a coil.

2. Why do we use foam plate instead of paper or plastic? Try using different types of cone material and see how the quality of the audio generated is affected.
   
   Between the 3 plates, the foam plate provides the best balance between flexibility and reverberation qualities. The paper plate is too rigid and the plastic plate gives off too much feedback.

3. We use the range of 7-8 ohms of wire to create the speaker. Why do you think this value is set?
   
   Try researching speaker circuit impedance matching online. Hint: try reading about thevenin equivalent circuits.

   We use impedance matching to create a thevenin equivalent circuit that will generate the maximum current through the resistance. The reason for the set resistance value is so that industry wide, electronic companies can create circuits that will generate the appropriate current that will work across different products (use different speakers for the same receiver). Otherwise the audio outputted by the speaker will have distortion or low amplitude caused by too much or too little current.

4. What would happen if you increased the number of magnets that is used on the speakers?

   This increases the magnetic field which should increase the amplitude of the speaker.

5. Based on the previous questions, come up with an equation relating number of turns (N), length of the coil(L), and the current through the coil to the magnetic field. Also include \(\mu_0\) which is permeability of free space as being proportional to B. Example:

   \[ B = \frac{\mu_0 \times A}{c} \]
Solution: \( B = \frac{\mu_0 N I}{L} \)

6. Come up with an improved design using simple materials to improve the speaker. Also make use of electromagnet theory to increase its performance (increasing number of turns of the coil, changing the size of the vibrating plate, etc). You should post your improvements on the online blog and get input on what changes can further improve your design.
Potential Customers

The target market for this line of products are students incoming to high schools that have the talent and interest in pursuing an engineering career. Because of the diversity and the range of the electrical engineering degree, we believe there can be a large number of potential students that can be drawn into the electrical engineering program. This can be done with the correct demonstration as to the actual application of the degree in various fields. This is why the line of labs this project will create is very important to drawing the interest of potential engineering students that may otherwise go into other fields that have more obvious result and applications from what they’ve learned in high school.

The lack of information as to the actual application of knowledge gained in high school is also another reason why these labs are very important. Based on inputs received from students, they were excited about experimenting with labs that had actual real life uses and applications instead of just theory that can be applied in the classroom. This is the exact focus that drives the project and will further catch the eyes of schools looking to improve or add to their technology education departments.

At the moment of this writing, the schools that have signed up for pilots programs are:

1. Rocky Mountain High School (integrating to existing program Spring ’09)
2. Loveland High School (No details as to integration yet but interested)

Other potential schools we would like to target include:

1. Poudre High School (Fort Collins, CO)
2. Widefield High School (Colorado Springs, CO)

There are many others we would like to interest and we will be developing labs in spring of ’09 to further include other schools with various levels of available technology and engineering education programs.
Marketability

Considering the increasing uses of technology in the world today, there is a big demand in the marketplace for engineers. Because of this, many schools are trying to meet the demands by improving or creating new pre-engineering programs that give students going into such field a leg up on the competition. With India and China producing large numbers of engineers to meet worldwide demand, the US would fall behind if high school program don’t provide these services. Seeing as they are trying to bridge the gap between high school and university level programs, it would only make sense for them to make use of project such as SKIES to add to their program. The market and demand for highly innovative and interesting labs that will bridge that gap could potentially be marketed nationwide.

Once the program has reached critical mass, I do believe many more schools will adopt this series of labs. It will not only be demanded from the side of the teachers but many students themselves will seek out these programs in order to improve their own understanding of the different areas of electrical engineering. It is therefore the responsibility of all sides to do what we can to provide these labs and improve the overall national quality of fundamental engineering principles. Using these labs, some of those goals can be reached in order to have the knowledge and experience to compete in the global marketplace.
Conclusions and Future Work

Semester Conclusions
We created labs that encompassed multiple engineering concepts and disciplines:

**Concepts & labs:**

- Analog systems:
  - Subwoofers & Low-pass Filters
  - Tweeters & High-pass Filters
  - Crank up the Volume

- Sensors/Telecommunications:
  - Wiimote Lab

- Physical Electronics:
  - Designing your own Speakers

We learned this semester that starting a project can be both gratifying and cumbersome. There’s no prior work to piggy-back off of, no plans, no direction and no project goals. The month or two that it took us to figure out our design scope, we learned how to communicate with teachers and how to engage them in order to gain their time to familiarize us with their perspective on high school students (i.e. what works/what doesn’t work, what concepts to cover, how and when to implement the labs, etc.), which gave or interpersonal skills quite a workout. During this semester we obtain skills for personal growth: how to create structure when there is none; how to develop objectives and goals along with choosing a project direction; communicating effectively and technical writing, just to name a few. I think you would agree that these are attributes that will propel us to be effective leaders.

In a significant amount of our curriculum here at Colorado State University, we learned theory, writing down equations and being oblivious on how they apply to real-world devices and applications. For us, the design process proved very beneficial. A case where the teachers essentially became the students or the students became the teachers, in our case. Designing the filter labs exceeded the teachings of the several signal processing courses in that we learned so much more about filter design, operation and implementation. You would think that these labs would not take an electrical engineer long to create but you have to make sure everything functions properly, figure out all various aspects of the design and develop effective lab reports to convey these concepts to high school students. The design process gave us the intuition and knowledge on how to present these concepts (i.e. structuring lab reports, what questions to ask, keeping it simple). The SKIES Program could a group in an engineering company that concentrates on educating and increasing interest in young-adults about engineering via a sequence of labs. The labs are to be created by the company’s engineers, us, and overseen by the appointed boss/supervisor, Professor Olivera Notaros.

Next Semesters Plans
Since the Senior Design course is a one year requirement, it does not stop here. We have a few plans for next semester. Early next semester we will be contacting high schools and seeing if they are interested in demos. We will use the feedback received at the demos to reconstruct our labs. Also Early on, we will be developing a lab to expose high school math students to the power and applications of matrices by having
them perform nodal analysis on circuits using matrices to solve a system of equations to get the voltages on each node. This lab will show math students that what they are learning is useful also giving them basic circuit analysis skills (i.e. Kirchoff’s Voltage and Current Laws) and a little exposure to electronic circuits.

We have aspirations to develop labs to cover two additional aspects of electrical engineering, controls and digital systems. We have several ideas in mind that make use of multiple programming languages (i.e. assembly, java). Keeping in my mind that we attend CSU, the “Green University” we think it would be beneficial to create labs demonstrating solar, wave and wind energy, while using electrical engineering as basis for lab designs.

We plan to continue working with teachers from Rocky Mountain and Loveland High Schools; they are a good fit with our design project and making it successful. These programs have a strong technical foundation which we could easily implement our labs and receive immediate feedback. Some time before the middle of the spring semester, we will be creating the lab kits. We want these kits to organized and very presentable as well as cost efficient. We are hopeful to receive some donations and coordinating with school budgets to manufacture the kits.
References


Bibliography


Acknowledgements

Tom Aurand - CSU Electrical Engineering Department
John Fialko - Rocky Mountain High School
Ken Gwynn - Loveland High School
Olivera Notaros - CSU Electrical Engineering Department
Robert Ufer - Poudre School District
Ashley Waddell - CSU Office of Development
### Appendices

#### Budget

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