Overview: In this lab you will design and prototype a track wire sensor and a beacon detector of your own design for use in your final project. This lab is intended to acquaint you with the behavior of operational amplifiers and comparators, and their use in detecting and filtering signals. You will gain experience using the proto-board to experiment circuits and to build physical circuits from a schematic. You will also learn to order electronic samples.

References: H&H Ch. 5 – 5.09 and CKO Ch. 14, 15, and 18 (especially 18.7).

The library has several of the publications listed in the Horowitz & Hill appendix. The articles, and often the advertisements, are very good information sources.

Bumps and Road Hazards

- Double Check your electrolytic capacitors’ orientations before you turn on the circuit. Incorrect orientation will cause your capacitor to either explode or work poorly.

- Don’t insert the o-scope (oscilloscope) probes directly into the protoboard. Report breaking any of these and other things so we can get them fixed quickly.

- Turn off monitors when testing your beacon detectors. Your beacon detectors, correctly tuned, will be influenced by monitors (as well as other rogue beacons).

Debugging Recommendations

- Always check POWER and GROUND. 90% of problems are from not plugging things in….

- Debug iteratively. Verify a small part is outputting the right signal and then expand. Oscilloscopes are your friend.

Minimum Parts Required: 1 CMPE118L Student Lab Kit. See BELS (basement of BE) for any parts you need that are not in the parts kit. They are open after 2pm and have a wide selection of parts.
Pre-Lab Instructions

1. Questions
   a. What are the values of resistors with the following color codes:
      i. red red red
      ii. brown black red
      iii. yellow violet orange
      iv. brown black green
      v. brown black black
      vi. green black yellow
   b. What should you never, ever, insert into the proto board holes?

2. Describe or draw the behavior expected of each module

3. Draw a block diagram of the full track wire sensor circuit in Part 2, one block per module.
   We expect to see the reasoning behind the connections and any tweaks you might need to do.

4. Draw a block diagram of the full circuit, a schematic for each module, and expected input and output of each module for the beacon detector circuit in part 3. We expect to see values on all the components, reasoning, and the math behind its design. You can guess the gain needed on your amplifiers as you don’t yet know how strongly your detector will pick up the signal. THIS WILL TAKE A LONG TIME AND LOTS OF READING. However, an hour of planning and understanding will save you 10 hours in the lab.

There is available software on the lab computers (EAGLE, LT SPICE, and Umlet) to do your block diagrams and schematics. We do not accept messy unreadable pre-labs. If you do it by hand, it must be neat.

Building Circuits in the Lab

Reading: CKO Ch. 9, 14. H&H Appendices C, D, E, I, and J. (and if you are unfamiliar with an oscilloscope, Appendix A, and handout on webpage). H&H Chapter 5 up to 5.10., yes we know it is a lot of reading, but if you complete it you will take much less time in the lab.

Background:

Resistors:
Resistors have 4 or 5 bands whose colors indicate the approximate resistance value of that resistor. Many many websites, Appendix A in CKO as well as Appendices C and D in H&H cover the resistor color code and standard values

Capacitors:
Capacitors come in several varieties. In this lab, we use electrolytic capacitors, ceramic capacitors, and mylar capacitors.

Ceramic and Mylar capacitors:
Ceramic and mylar capacitors are non-polarized, and can be safely inserted backwards. They look like M&Ms or chiclets. They are resilient and will perform
in nearly all circumstances you encounter in this course. However, they have relatively small capacitances.

The ceramic disk capacitors are marked for size in a number of different ways. The most common are:

\[
22 \quad \text{or} \quad 22K
\]

This indicates 22 pico-Farads. For these capacitors a small number is almost always the value in pF. The letter is used to indicate a usable temperature range. Sometimes these caps are marked in a different notation:

\[
103 \quad \text{or} \quad 104
\]

These are most likely .01uF and .1uF respectively. In this case the markings are similar to resistor codes. The first 2 digits represent the value and the last digit the power of 10 multiplier. The resulting number is the number of pF. In the example above we have \(103 = 10 \times 10^3 \text{ pF} = 1e4 \times 1e-12 \text{ F} = 1e-8 \text{ F} = .01 \text{muF} \).

**Electrolytic capacitors:**

The electrolytic capacitors look like little cylinders. Both leads may come out of one end of the capacitor (radial lead), or the leads may come out of opposite ends of the capacitor (axial lead).

The tantalum capacitors are the ones that look like little gumdrops. Pay attention to the polarity markings. DO NOT REVERSE THE POLARITY. See note below.

Electrolytic and tantalum capacitors use a specialized electrolytic fluid to provide a high capacitance. They are polarized, so it is important to insert them the correct way. **DOUBLE-CHECK YOUR ELECTROLYTIC CAPACITORS’ ORIENTATIONS BEFORE YOU TURN ON THE CIRCUIT.** If the anode is at a higher voltage than the cathode, an exothermic chemical reaction will begin and **THE CAPACITOR MAY EXPLODE.** Even if it doesn't, you will destroy it.

Both tantalum and electrolytic capacitors are almost universally marked in their value in micro-Farads (mF). Often the mF indicator will also be present.

**Note:** Polarized, tantalum and electrolytic capacitors are marked for the proper polarity. This polarity is **VERY** important! If inserted incorrectly tantalum capacitors have been known to self-destruct **EXPLOSIVELY!!** At the very least reversing the polarity can look like a short to the power supply and prevent anything else in your circuit from working. Examine polarized caps very carefully before inserting. Some mark the positive lead, and some mark the negative lead. Be sure which type you have before you wire it into your circuit.

**Integrated circuits:**

ICs are specified by a sequence of letters and numbers. The first two letters typically specify the manufacturer, while the numbers specify the circuit. So the 555 in your kit may be labeled LM555, NE555 or several other variations. They will be interchangeable in most circumstances.

Understanding ICs begins with the datasheet. These are not just technical specs—
they are also your guide to using the IC. Make sure you have a pdf or hardcopy of your datasheets in a convenient folder, as you will be referring to them often. You can usually find a datasheet with a simple internet search, or looking up the part on the site of a vendor like Digikey.

Below is a typical chip drawing. To determine which pins are which, first find either a) a dot near one of the pins, or b) a semi-circular depression at one end of the chip. Once you have found either of these markings, the pin numbers proceed around the chip counterclockwise (assuming that you are looking at the top of the chip with the depression or dot at the top).

ICs should ALWAYS have a bypass capacitor between power and ground to prevent power fluctuations from interfering with the chip. The bypass capacitor should be at least 10 nF and as physically close to the chip as possible—if you can fit it, stretch the bypass capacitor directly over the chip.

**Prototyping Board (PROTO-BOARD):**

You will be building the circuits for this lab using a solderless breadboard that we refer to as a proto-board. Below is a diagram of the types of connections on the proto-board.

Regions labeled A, B, D, E are the normal hook-up areas. As indicated by the gray lines, horizontal groups of these connections are internally tied together. When a chip is plugged into the board as shown, these strips give you 4 connections to each of the IC pins. The connections in region C are intended as the power and ground busses. Again as indicated by the gray lines, they are tied together vertically. Note, on some proto-boards the connections in region C are broken in the center, leaving 4 vertical strings. Check your board; you may want to jumper these to yield 2 vertical sections, good for distributing power & ground.

Take the time to make your circuits neat and tidy, with wires low over the board. It will only take a few minutes longer to do so, and it will make (the inevitable)
debugging go much quicker. Below is a figure from CKO about the right and wrong ways to put together a proto-board.

The proto-boards are fairly robust, however they are susceptible to damage from wires that are too large. Do not use hook-up wire larger than 24 gauge. This should not be a problem, since we supply your hookup wire. The other thing to watch for is component lead sizes. This will not be much of a problem during the labs, but you should be aware of these limitations since in later quarters you may use these boards to prototype your own circuits.

**DO NOT INSERT O'SCOPE PROBE TIPS INTO THE PROTO-BOARD!**

**Requirements:** Nothing, this part is all background.
Part 1: Circuit Modules

Prelab:
Describe or draw the expected behavior of each module.
1. **Tank circuit**: Either draw a Bode plot for the RLC circuit, or find the expected resonant frequency and quality factor for the RLC circuit.
2. **Split rail buffer**: What voltage do you expect the buffered rail to have? How much current can you draw from it? (Assume this is an MCP6004 op-amp, like the ones in your lab kit)
3. **Non-inverting amplifier**: For the amplifier, sketch an arbitrary input trace and the expected output trace. You’ll need to pick resistor values.
4. **Peak detector**: Sketch an arbitrary input trace and the expected output trace. What is a suitable decay time? What values of R and C achieve this?
5. **Comparator with hysteresis**: Work out the values of resistors you need to make the low threshold 1.0 V and the high threshold 1.8 V.
6. **LED and voltage divider**: The circuit given has a problem. What is it? (Assume the LED is red)

References:
CKO Ch. 14.
https://learn.sparkfun.com/tutorials/how-to-use-an-oscilloscope/all -Sparkfun’s oscilloscope tutorial

Overview:
In this part, you will experiment with the modules you will need for the track wire sensor in part II. In building a complex circuit, it is sound practice to divide the circuit into smaller functional units, and test each one individually.

The final class project will contain track wires, which are transmitting antennas that signal your robot. The goal for your track wire sensor is for it to read a sensor coil and report when a track wire is within range.

Requirements:
A. Modules are built neatly and easy to read by staff. You will be asked to remake it if they are messy.
B. **Solenoid Raw**: Observe scope traces
C. **Tank Circuit**: Hook it up to the solenoid to get observable track wire detection
D. **Split Rail Buffer**: Create a split rail buffer that outputs a steady 2.5 V.
E. **Non-Inverting Amplifier**: Hook the solenoid up to it and double the solenoid’s output.
F. **Peak Detector**: Hook the solenoid up to it and detect the peak of the solenoid’s input
G. **Comparator with hysteresis**: Low threshold of 1.0 V outputs 0V and High Threshold of 1.8 V outputs 5V. Use the Voltage Box to give it an input voltage. Threshold’s must be within 10%.
H. **LED and Voltage Divider**: When given 5 V, LED lights up and circuit outputs 3V +/- .3. When given 0V, LED is dim and the circuit outputs 0V.

Checkoff:
The staff will select a module and ask you to connect the output to an oscilloscope. You will then provide the appropriate input and demonstrate that the module performs
In the report: Pictures of all your modules.

Which solenoid positions and orientations produce the strongest signals? Also include scope traces of the unfiltered solenoid, the solenoid as part of a tank circuit, amplifier, rectifier, and comparator. Also describe any surprises, any issues you encountered, and how you resolved them.

General Tips: You can assemble all of these modules using a single quad op-amp chip – but don’t! That’s the next part of the lab. For now, spread the modules out on your breadboard, or maybe even across both of your breadboards.

Solenoid

The track wire carries a current which oscillates at a frequency of 24-26 kHz with a peak-to-peak amplitude of about 150mA. This in turn generates an oscillating magnetic field around the wire. If you put a coil of wire in this oscillating field with the right orientation, the coil will experience an oscillating EMF, which you can detect as a voltage.

Verify that this is the case by hooking up the solenoid directly to an oscilloscope probe as in the picture and observing the resulting traces.

Tank Circuit

A tank circuit is an LC oscillator (a simple harmonic oscillator --imagine water sloshing back and forth in a tank). The sensor solenoid can double as both a signal source and a tank inductor. In this case, the resonant frequency of the oscillator is
close to 25kHz, so the track wire will induce large oscillations in the tank.

The resistor is a “Q-killer” resistor – it lowers the quality factor of the filter, at the cost of gain. This resistor is not necessary for this lab, but you may find it useful if you want the same circuit to give consistent results from track wires driven at slightly different frequencies.

**Split Rail Buffer**

![Split-rail buffer diagram]

In many circuits, it is useful to have a rail whose voltage is between two power rails. One option is to use a voltage divider, but this makes the divided voltage sensitive to current draws (i.e., a voltage divider has a high output impedance). Solve this problem using the world’s simplest amplifier to buffer the divided voltage. Now the rail has the output impedance of the op-amp.

**Non-inverting amplifier:**

![Non-inverting amplifier diagram]

The non-inverting amplifier has a very high input impedance. That makes this amplifier draw a very small current.

**Peak Detector:**
The peak detector stores charge on the negative input using a capacitor. The diode prevents discharging, so the op-amp can only raise the voltage on the capacitor, but cannot lower it.

**Comparator with hysteresis:**

An op-amp can be used as a comparator by removing the feedback to the negative input. This will cause the op-amp to always produce an output at one rail or the other. Hysteresis can be added by putting in a feedback resistor to the *positive* input. This circuit is also known as a Schmitt trigger.

**LED and Voltage Divider:**
If you read CKO chapter 31 (as you should), you will encounter troubleshooting rule number 4: “Include elements that provide observability of the internals of your system.” One such element is a visible LED that indicates the presence of a signal, like the LED in this circuit.

Should your robot ever fail to respond to track wires, your first troubleshooting task will be to determine whether the error lies in your circuit or in your code. This LED will make that first bisection quite simple.

Also included is a voltage divider that prepares the output for interfacing with the PIC32. The pins of the PIC32 should not be driven above 3.3v, so it is important to condition the 0-5v signal before connecting it to the microcontroller.
**Part 2: Track Wire Sensor**

**Prelab:** A block diagram showing how the modules from Part 1 should be connected and expected outputs and inputs to each module.

**References:** CKO Ch. 14

**Overview:** In this part you will integrate and modify your modules from Part 1 to form a circuit that detects if track wire is within 2 inches of the solenoid. While your individual modules may appear to work perfectly on their own, integrating them into a single system will reveal many new problems. Integration is often the hardest part of any project.

**Requirements:**

A. Sensor is built neatly and easy to read by staff. You will be asked to remake it if it’s messy.

B. Circuit sends high signal when track wire is within 2 inches of solenoid (+/- 0.1). You may choose the orientation of your sensor coil.

C. Circuit outputs 2.7V -3.3 V when track wire detected, 0-1.8V when track wire is beyond 2 inches.

D. An led should visibly turn on when output is high and be off when output is low.

E. Any delay in the output should be small enough that a human cannot detect it.

**Checkoff:** Demonstrate your working track wire sensor.

**In the report:** Picture of your circuit, Your final schematic. Description of all surprises/undesirable behaviors and the steps you took to fix/mitigate/circumnavigate them.

**General Tips and Tricks:** Copy the modules from part 1. **DO NOT DISSASSEMBLE YOUR ORIGINAL WORKING MODULES.**

Compare the behavior of your new modules to the ones you already tested in Part 1. If two modules don't behave identically, find out why and describe your findings in the report.

Once you’ve done that, THEN connect the modules. Start by connecting just two modules, and verify that they work together. Keep adding one module, then testing. Describe the results of each new addition.

If you run into trouble, start debugging by looking at the signal on the wires connecting module 1 to module 2. Is it what you expected? Is it what you want? If not, why not? Repeat for the wire connecting module 2 to 3, and so on.
Part 3: Beacon Detector

Prelab: A block diagram of the circuit you intend to build, with a description and/or sketch of the intended behavior of each module. (You can use Umlet on the lab computers)

A circuit diagram of each module. (You can use Eagle or LT Spice on the lab computers).

SPEND PLENTY OF TIME ON THIS PORTION OF THE PRELAB. An hour spent on research or design here usually saves many hours in the lab. Also make two copies: one to turn in and one to use.

References:
CKO 13.5.1.2 is essential reading on phototransistors.
CKO Ch. 14, 15 for help designing the circuit.
H&H Ch. 5-5.09 for a discussion of analog filtering, and a recipe for easy active filters.
Handout on Analog Filtering
LM7805 datasheet for information on regulating a 5v rail from a 10v supply.

Background: The final project in this course will involve detecting IR beacons, which your robot will need to locate. In this part of the lab, you will use the methods of the previous two parts to design and prototype a circuit which can detect the IR light from the beacons.

Be warned, while many parts of this circuit are similar (or even identical) to the previous circuit, you will find that the IR signal is much trickier to filter and amplify.

Overview: In this part you will design a circuit that can detect whether or not it is pointed at an Infrared Emitting beacon of a particular design. The hard part of this circuit is that it must be able to detect the IR lights in a large range (0.5-8+ feet). The team who comes up with the longest range gets bragging rights. You will use the methods (though not necessarily the modules) of the previous two parts to design and prototype a circuit which can detect the IR light from the beacons.

You may use as many op-amps as you need (although if you are using more than 8, you should probably consider a new strategy). You may use any ICs or MOSFETS in your lab kit, including a 555. If you are daring, you may obtain other ICs and attempt to use those, although you should run your strategy by a TA first. They will appreciate your initiative, even if they shoot down your idea.

Beware that the TAs and tutors will be unable to help you if you design a circuit they can't understand.

Specifications: Beacon Signal (that which you must detect):

A. 50% duty-cycle on/off wave at a frequency of 2 kHz

B. Amount of light from it is at least 0.05 mW/cm²

Other sources of light you might need to filter:
C. 120 Hz noise from the ceiling lights of no more than 0.03 mW/cm².

D. Sunlight at intensity of no more than 0.1 mW/cm²

**Other sources you DONT need to filter:**

E. 50Hz computer monitors. Turn them off when testing and iterating. They will overwhelm your circuit.

**Your circuit must:**

A. Sensor is built neatly and easy to read by staff. You will be asked to remake it if it’s messy.

B. Use a Lite-ON LTR-301 phototransistor

C. Detect a beacon from 6 inches to 8 feet away at + 5 degrees (ie it should not detect the beacon if not pointed directly at the beacon)

D. Have A visible LED indicates the presence of the beacon (polarity is your choice).

E. **When beacon detected:** Circuit outputs a steady high of 2.7V - 3.3 V and turns on an led. The 2.7-3.3V is the reasonable amount for a PICC32 input pin.

F. **When beacon not detected:** Circuit outputs a steady low of 0-1.8 V and turns off the LED

G. The output should not oscillate, the LED should not flicker, and the transition of LED from off-on and vice versa should be a half second or less.

H. The power supply is between 9 and 12v. Any lower-voltage rails must be regulated and reverse polarity-protected.

**Checkoff:**

Demonstrate your working beacon detector that meets the requirements

**In the report:**

Document the behavior of your circuit. Include o-scope traces of the signal on the wires connecting modules. Include a picture and final schematic.

What unexpected behaviors does your circuit exhibit?

How might you improve upon it?

**General Tips and tricks:**

First build and test the modules you plan to use in the circuit. ALWAYS remember to test incrementally.

Hint: You may find that mechanical design is as important as electrical design here. Find ways of shielding your phototransistor from unwanted noise. There are a lot of materials that will handle some of your filtering for you.
Part 4: Sampling Parts

Prelab: Nada

References: Lady Ada’s getting samples tutorial: http://www.ladyada.net/library/procure/samples.html

Background: You are going to be building a lot of circuits over the next year and lab kits don’t always cut it. Sampling is not only an easy way of trying out parts, it’s a free way to get the ones you need.

Overview: Order some free samples online. Spend some time browsing the possibilities, spec sheets, and abbreviations. What’s available from different manufacturers? How much of the spec sheet do you understand? Time how long it takes to get here. What credentials do you need to order? Call people if you are confused: companies will often put you in touch with an engineer and answer all your small questions about parts— it’s a really easy way to gain inside information and its free.

Specifications:

1. Generally, feel free to sample anything you want but:
   a. Order PDIP not Surface Mount. Surface mount are generally for printed PCB boards only. You are using perf board for the project.
   b. Parts come Fed-ex. Find a personal mailbox that works. If you cannot, ship to: Computer Engineering, 1156 High Street – SOE3, Santa Cruz, CA 95064-1077 and pick it up at BELs.

2. Order Something from Texas Instruments (www.TI.com)
   a. Suggestion: Low dropout regulator (3.3V and 5V regulators are clutch in the project): LP2950-50LPRE3 in the TO-93 package http://www.ti.com/product/lp2950-50
   b. Suggestion: Motor Drivers, Filter chips, Rail to rail op amps

3. Order Something from Microchip
   a. Suggestion: Our favorite op-amps: MPC609-I/P or MCP6024-I/P

4. Bonus: Order something from Fairchild
   a. Suggestion: IR photo-detectors [QSD124], slotted photo-interrupters [QEVO0039], and some Reflective Sensors [QRD1114])
   b. They do not sample to gmail or .edu addresses. If you succeed, brag about it on piazza and say how

Check-Off: None. Include proof of ordering in your lab report.

In the report: Order confirmation of the parts that were sampled, and a short description of why you sampled this particular part. Make sure you put a copy of the datasheet in your dropbox so you know how to use the part you sampled when it arrives.
**Comparator Configurations**

The basic configuration for an inverting comparator with hysteresis is the one shown below. What will you need to change for an op-amp?

![Comparator Configuration Diagram](image)

**Configuring Comparator:**

To calculate values for the resistors to achieve particular set points, follow the simplified procedure given below:

1) let the lower trip point = $V_{a2}$
2) let the upper trip point = $V_{a1}$
3) let the differences in the set points $V_{a1} - V_{a2} = DV$
4) let $R_4 = 3.9K$
5) let $R_3 = 1M$
   (these last two items are the simplifications from the general solution)
6) let $n = DV/V_{a2}$
7) let $R_1 = nR_3$
8) solve for $R_2$ such that:

The above assumes that the supply voltage is +5V.