UNIVERSITY OF CALIFORNIA, SANTA CRUZ
BOARD OF STUDIES IN COMPUTER ENGINEERING

CMPE118(218)/L: INTRODUCTION TO MECHATRONICS

LAB 1 – SIGNAL CONDITIONING AND FILTERING

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 a proto-board to experiment with circuits and to build physical circuits from a schematic.

COMMENTS:

This is a long lab. You have some extra time to do it, but for many of you this will be the first time actually building a real analog filter. This is a place where neatness definitely counts. Many problems come from stray wires and accidentally pulling wires out when changing things around.

Always check power and ground. Almost all of your problems are there. Ensure you have good power with the right voltage on it, and that ground is hooked up where you expect.

Incremental development and debugging is your friend here. Build a single block, test input to output to make sure it does what you think, then do the next block, only then hook them together and again check end to end. Make sure what you build matches your schematics (we won't be able to help you if you don't have what you have built documented).

This lab is both harder and longer than Lab 0, so budget your time accordingly (we have also given you four more days to complete it). Do the reading; do it diligently. The filter section of this lab is going to take you a while; it will be frustrating and you will spend a large amount of time doing hardware debugging with an o-scope. Being neat and methodical here will save you untold hours. The more time you prepare, the less time you will flounder in the lab.

We will be around to help, but the more you have prepared, the easier it will be.

PRELAB:

Choose a partner to do the lab with, and join a group together in the "Lab 1 Group XXX" category on CANVAS. For instructions on how to do this, see the CMPE118_LabSubmission document on the website. If you have not chosen a partner by Saturday, we will randomly assign one to you (most likely on Sunday). Note that Piazza is an excellent way to find partners.

After you have read the whole lab and before starting to complete the lab, answer the following questions:

1. What are the values of resistors with the following color codes:
   a. red red red
   b. brown black red
   c. yellow violet orange
   d. brown black green
   e. brown black black
   f. green black yellow

2. What should you never (ever) stick into the proto board holes?

Each part of the lab has prelab exercises. Complete these by yourself (you are welcome to collaborate with your teammate, but the work should be your own) and submit them using the assignment submission on the CANVAS website. The requirements for the prelab deliverables are detailed in each section, make sure you read the lab carefully and answer them all.

Note that you need to electronically submit your prelab and lab report files in a very specific format. See the CMPE118_LabSubmission document on the class website for instructions on how to submit your files and how to verify that you have done so.

PART 0 – PROTOTYPING CIRCUITS BASICS

OVERVIEW:

This is background material that you need to read very carefully. Following the guidelines in this section will help you get this lab done efficiently and more quickly. Again, do the reading and it will save you hours in the lab.

REFERENCE MATERIAL:

- H&H Ch. 5 – 5.10, Appendices C, D, E, I, and J
- CKO Ch. 9, 14, 15, and 18 (especially 18.7)
- Oscilloscope Tutorial from the class website
- Sparkfun Oscilloscope Tutorial (if you are unfamiliar with O'scopes)

PRELAB:

Nothing to do here, this is background information you should read.

BACKGROUND:

Appendix A in CKO and Appendices C and D in H&H cover the resistor color code and standard values. The MPC604 in your kit may be labeled MPC604, 604-I/P or several other variations. The 604 is the important part.

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.

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).

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

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

22 or 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. The exceptions are capacitors marked:

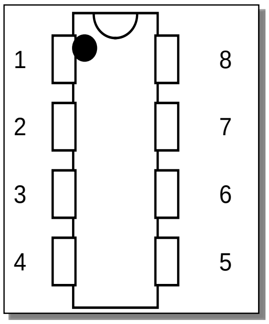
103 or 104

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

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.

PIN IDENTIFICATION:

To the right is a typical chip drawing. For purposes of determining the pin numbering, note the relative positions of:

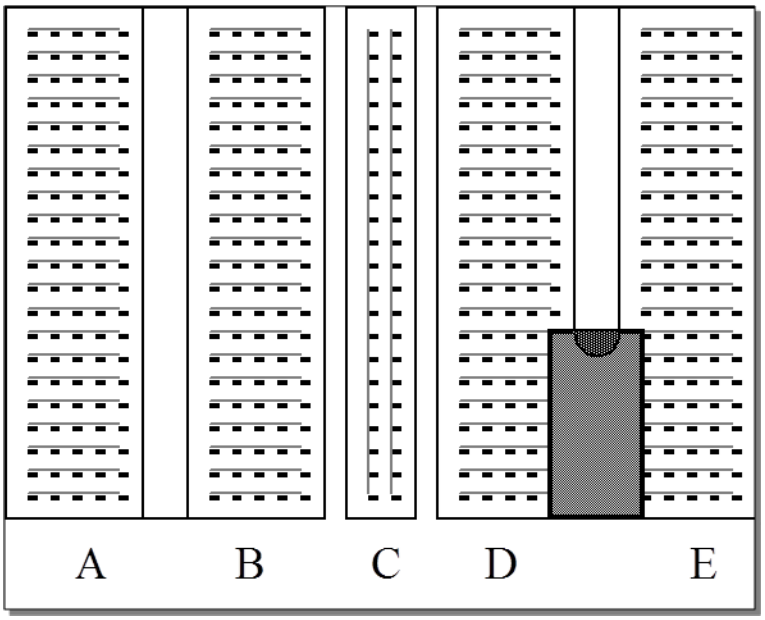


1. A dot near one of the pins,
2. Alternatively a semi-circular depression at one end of the chip.

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). The highest numbered pin is always opposite pin 1.

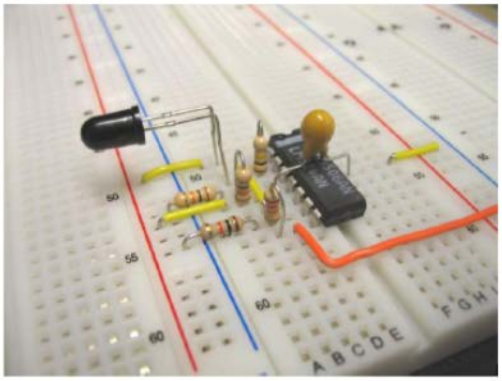
PROTOTYPING BOARD (PROTO-BOARD):

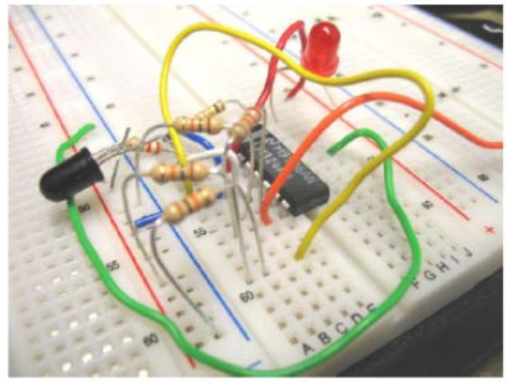
You will be building the circuits for this lab using a solderless breadboard that we refer to as a proto-board. Below is a diagram of the types of connections on the proto-board.



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 and 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 (very) 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 are supplying hook-up wire in the labs. 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! You will bend the probe tips and break them (and they are pricey).

For the lab report, there is nothing to include, since this is just background material.

PART 1 – CIRCUIT MODULE BASICS

OVERVIEW:

In this part, you will experiment with the modules you will need for the track wire sensor in Part 2. In building a complex circuit, it is sound practice to divide the circuit into smaller functional units, and test each one individually.

In this section you will first analyze then build small circuits that do specific things (pieces that you need). These will come in handy in later parts of the lab; take the time to figure out what is going on and see how they each work.

REFERENCE MATERIAL:

- CKO Ch. 14
- Oscilloscope Tutorial from the class website
- Sparkfun Oscilloscope Tutorial (if you are unfamiliar with O'scopes)
- Implementing a Track Wire Sensor document

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 (Q) 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). Where do you need to inject its output?

3. Non-inverting amplifier: For the amplifier, sketch an illustrative input trace and the expected output trace. You'll need to pick resistor values. Make sure this is for single-ended (0-3.3V) power.

4. Peak detector: Sketch an illustrative input trace and the expected output trace. What is a suitable decay time given the input? 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 1.0v and the high threshold 1.8v.

6. LED and buffer: Design a circuit to take the buffered output of the comparator and throw an LED and digital signal. How much current do you expect the LED to draw when the input is at 3v? What about 0v? For each case, is the LED on or off? What are the shortcomings of your circuit?

BUMPS AND ROAD HAZARDS:

Polarized capacitors must be plugged in correctly. If you reverse polarity them, they will be damaged (and pop like a firecracker). Reversing polarity on any IC will usually destroy it (letting out the magic smoke). You want to operate your OpAmps in single-ended mode (0-3.3V power).

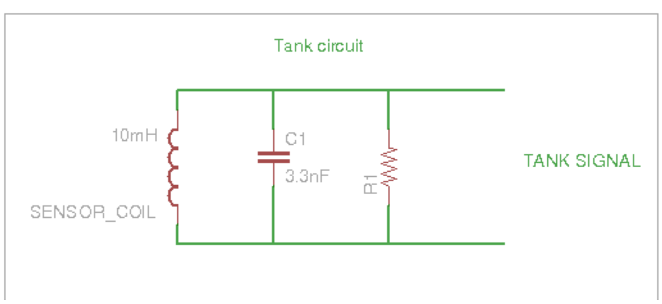
OUTLINE:

You will be building several modules here for use with the Track Wire detector. Build them each neatly and test them extensively. Make sure there is room around each module to hook things up and test them; use a separate chip for each module (you have tons in your kits).

Solenoid/Inductor: The track wire carries a current which oscillates at a frequency of 24-26 kHz with peak-to-peak amplitude of approximately 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 correct 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/inductor directly to an o-scope probe with ground on one end and the probe on the other and observe the resulting traces. Include those traces in your lab report with a short paragraph on what you observed.

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. That is, the tank circuit is a passive amplifier.



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.

Build the Tank Circuit and hook it up to your solenoid and see what it looks like on the o’scope when you are sensing the track wire circuit. Show your output to TA/tutors for checkoff. Include the traces in your lab report, and a short paragraph of what you observed.

Keep your tank circuit together as it will be the input stage for your track wire detector in Part 2.

Split Rail Buffer: 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). By using an OpAmp as a buffer the voltage divider is impedance isolated from the output. The output now has the impedance of the OpAmp (effectively infinite).

Create a Split Rail Buffer with an output of 1.65V from a 3.3V rail. Make sure you put a filter cap on the voltage divider. Demonstrate your buffered output to the TA/tutors for checkoff.

Non-Inverting Amplifier: The non-inverting amplifier has very high input impedance, ensuring that the input has very little load on it (important for sensors that cannot source much current). The non-inverting amp is used extensively in filtering circuits, but has a limit that it cannot have a gain of less than one (no attenuation).

Design and build a non-inverting amplifier that has a gain of 2. Hook the output of your tank circuit to the input of the non-inverting amplifier, and demonstrate both traces on the scope for checkoff. Include the traces and a short paragraph of your observations on this in your lab report.

Peak Detector: A peak detector is an active rectifier that follows the voltage up to the highest point and holds there. 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 (which isn’t particularly useful). A switch/FET can be used to drain the capacitor, or a simple resistor can be used to make the peak detector “leak” charge off of the capacitor.

The time constant of the “leak” is the RC time constant. Choose a reasonable time constant that you can make using the parts in your lab kit. Build the peak detector and verify that it works. Hook the output of the non-inverting amplifier to the peak detector and show the traces of the track wire through the stages to the TA/tutors for checkoff. Include the traces in your lab report, and a short paragraph on how the peak detector operates.

Comparator with hysteresis: The comparator is an open collector (open drain) output device that is very similar to an OpAmp, but has been tuned for fast non-linear response. This is used to snap the output hard over from one side to the other (shorting to ground or letting go). The comparator (LM339) can be used to create a hysteresis bound on the input (sometimes called a Schmitt Trigger).

A regular OpAmp can be configured to act like a comparator (see this app note for details), but the hysteresis bounds are not nearly as easy to set, nor does it work as well as the actual comparator. See Appendix A to the lab for calculations on comparator threshold setting.

Design and build an inverting comparators with a low threshold of 1V (3.3V output) and a high threshold of 1.8V (0V output). Use one of the variable power supplies to verify it trips at the right levels and demonstrate this to the TA/tutors for checkoff. Include your calculations and circuit diagrams in the lab report.

LED and Buffer: The output of the comparator swings from 0-3.3V, but it is an open collector output with a pullup resistor. This means you need to buffer your output voltage in order to stay within the specs of the Uno32 if you are also driving an LED. Additionally, it is very useful to have an LED which indicates if you have the signal or not without having to read a pin on the Uno32. It is important to note that the comparator cannot drive the LED directly without altering the hysteresis bounds, so you will need to insert a buffer (non-inverting OpAmp with a gain of 1) between the output of the comparator and the LED/Level shift stage.

This circuit consists of a buffer to isolate the output, along with a drive stage to light the LED when the signal line goes low. Ensure that a 0V input lights the LED, and that a 3.3V input results in 3.3V output. Demonstrate the input to output of the circuit to the TA/tutors for checkoff.

PART 2 – TRACK WIRE DETECTION

OVERVIEW:

This assignment will have you prototype a working track wire detector, all the way from the inductor/solenoid sensor to a digital signal suitable for injection into the Uno32.

REFERENCE MATERIAL:

- CKO Ch. 14
- Oscilloscope Tutorial from the class website
- Sparkfun Oscilloscope Tutorial (if you are unfamiliar with O'scopes)
- Biasing OpAmps (from MIT open courseware)
- Implementing a Track Wire Sensor document

PRELAB:

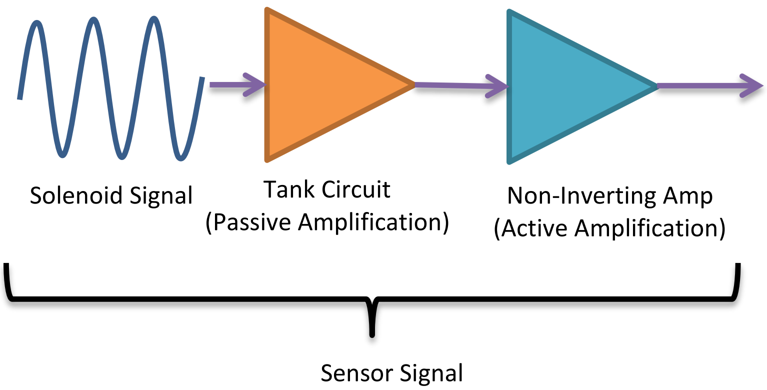
Figure out what the inputs are likely to be for each stage of the detection circuit, and what the output should look like (which is the input to the next stage).

BUMPS AND ROAD HAZARDS:

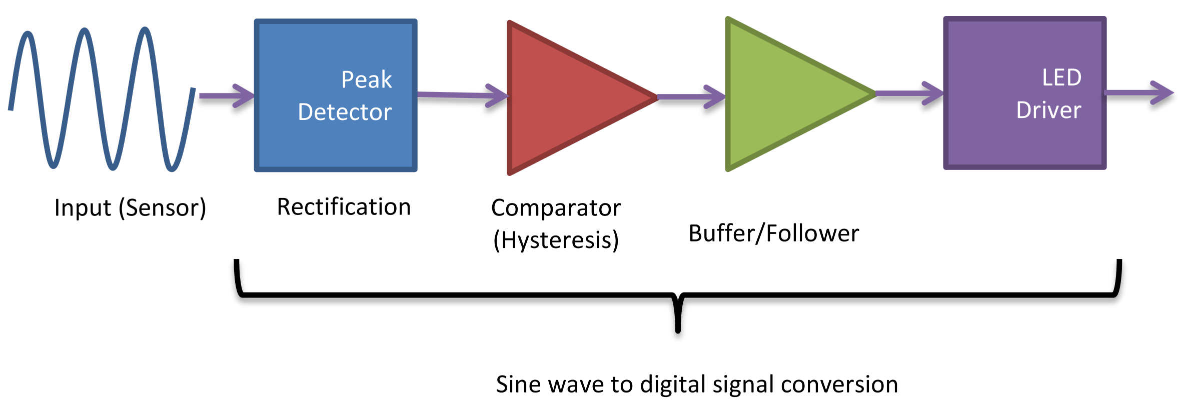
Polarized capacitors must be plugged in correctly. If you reverse polarity them, they will be damaged (and pop like a firecracker). Reversing polarity on any IC will usually destroy it (letting out the magic smoke). You want to operate your OpAmps in single-ended mode (0-3.3V power).

OUTLINE:

You are going to build a track wire detection circuit using the solenoid/inductor and tank circuit from above (as the sensor input) and then create the stages necessary to get to a digital signal that indicates the presence of the track wire if you are within 2 inches of the wire. Your circuit will output between 2.7 and 3.3V when the track wire is detected, and 0-1.8V when it is not. An LED should light indicating the output (polarity is up to you).



The first part of the detection circuit is to read the actual sensor signal, and get it into a useful range. For the Track Wire, the tank circuit is a passive amplification (based on resonance) and then it is fed to a non-inverting amplifier with appropriate gain. In CMPE118, we operate all of our OpAmps as single-ended, meaning that the supply voltage is 0-3.3V. You might need a split-rail buffer (voltage divider) to bias your non-inverting amp to get your sine wave centered where you need it. The output of the Sensor should be an amplified sine wave, within a useful voltage range. For your lab report, include o-scope traces of the output of each stage of the sensor signal, and comments on your design and why you chose those particular gains and biases. Include a schematic, your calculations, and a short discussion.



The next stage is the block that converts the presence or absence of the sine wave into a digital signal. At the input goes the sensor signal you generated above (a sine wave with a bias) and at the output is a digital signal that varies from 0-3.3V and also lights an LED. It is very important to have an external indication of the signal for debugging.

Typically, the conversion from sine wave to digital signal requires several stages. The first step is to convert the sine wave to something with DC content. This is done using rectification (often called peak detection). This can be done with a simple diode and capacitor, or using an OpAmp which will overcome the diode drop and hold the voltage. You will need a resistor to drain the voltage off of the capacitor. This is a simple RC time constant, and needs to be balanced between latency of detection and going too fast so it simply follows the sine wave.

The output of the peak detector is then fed into a comparator with appropriate thresholds set so that the output snaps between high (3.3V) and low (0V). A hysteresis bound on the thresholds makes it robust to noise in the signal. If using an LM339 comparator, it requires a pullup resistor on the output since it is an open collector design.

A buffer or follower is inserted between the output of the comparator and the input of the voltage shifter/LED indicator in order to isolate the feedback network of the comparator. Leaving this out will result in your thresholds moving significantly (and it is difficult to calculate since it requires knowledge of the forward voltage drop of the LED).

The last stage is a simple buffer and LED driver in order to keep the output between 0-3.3V. The LED is used to indicate that the signal has been detected, and is very useful to put in all of your sensor circuits.

You will need to design and prototype every stage (you will want to test them independently at first), and then connect them to develop a full track wire detector. The requirements are that you can get a solid “high” of at least 2.7V on the output at a distance of 2” from the wire, and steady “low” of less than 1.8V at the output if the current on the wire is turned off. The response should be snappy (less than 200msec delay). Demonstrate the detection of the track wire to the TA/tutors for a checkoff. For the lab report, include a full schematic of what you built, pictures of your circuit, and a detailed explanation of each stage.

PART 3 – PHOTOTRANSISTOR AND TRANSRESISTIVE AMPLIFICATION

OVERVIEW:

In this assignment, you will construct the sensing stage of your Beacon detector, and a transresistive amplifier to get a useable signal out of the phototransitor. You will inject a signal into the sensor using the minibeacons you have soldered up in Lab 0.

REFERENCE MATERIAL:

- CKO Chapters 11, 12, 13, 14, 15 (especially 13.5 on light sensors).
- H & H Chapters 4.01-4.09, 15.02

PRELAB:

Draw neat schematics of the circuits you are going to implement in this part.

BUMPS AND ROAD HAZARDS:

Polarized capacitors must be plugged in correctly. If you reverse polarity them, they will be damaged (and pop like a firecracker). Reversing polarity on any IC will usually destroy it (letting out the magic smoke). You want to operate your OpAmps in single-ended mode (0-3.3V power).

OUTLINE:

Hook up the photo transistor in a sourcing configuration (collector to +3.3V) with a 100k load resistor to ground. The photo transistor should be placed on the opposite end of the proto-board from your minibeacon. Aim the photo transistor at the IR LED (the sensitive region, and the emitter of the LED are opposite the leads) of your minibeacon. Power (+3.3V) and ground are from the bench-top power supplies, plugged into the power and ground rails of the protoboard.

Make sure that you have the phototransistor hooked up correctly. The collector (top of transistor) is on the right side when facing the bump. It also has a longer lead.

Hook the o-scope to the top of the load resistor and see what output you get (try different minibeacons with different frequencies to see the difference).

Now change the circuit to a sinking configuration (emitter to ground) and repeat the exercise, this time looking at the bottom of the load resistor. Change the load resistor from 100K to 1K and do it all over again (sinking and sourcing). What is the impact of the smaller load resistor on the output of the phototransistor?

In your lab report, include the updated schematics, o-scope traces of the four outputs, and an explanation of the differences.

Now, design and prototype a transresistive OpAmp stage with an output gain of 1V/mA. You should maintain 1.65V across the phototransistor. Your schematic should be complete with component values based on the parts in your kits.

Again, using the o-scope and your minibeacons, look at the output of the phototransitor directly, and also the output of the OpAmp transresistive stage. Include the full schematic, the o-scope traces, and a discussion of your observations in the lab report. Demonstrate the circuit to the TA/tutors for checkoff.

PART 4 – BEACON DETECTOR

OVERVIEW:

This assignment is to design and prototype a full beacon detector (that will be the basis of the one you will use in the final project). For the final project in this class, an infrared emitter is going to be used as a beacon to let you know when a target is active. The emitter is driven by a microcontroller and generates a 50% duty-cycle on/off wave at a frequency of 2 kHz. There are several sources of noise and interference, including daylight, monitors, wall current, and many others. You will design a filter to amplify the signal of interest, and reject the others.

This will be tested against a beacon which changes its frequency from 1.5 to 2 to 2.5 kHz.

REFERENCE MATERIAL:

- CKO Chapters 14, 15
- H & H Chapters 5-5.09
- Analog Filtering article from Sensors Magazine

PRELAB:

Analyze your filter blocks (using dB magnitudes) and determine the output when the input to the filter is a sine wave at [1.5 2 2.5] kHz., with a peak to peak amplitude of 100mV centered at 1.65V. You will need to specify the order and type of filter block (i.e.: 4^{th} order Butterworth Low Pass), decide what blocks you need and in what order (i.e.: low pass first, amplification, then high pass). You want to let the 2KHz signal through, but attenuate the 1.5 and 2.5KHz signals.

Your prelab should include a block diagram, as well as your calculations of the signal magnitudes on the other side of your filter given the inputs above.

Your prelab should also include a full schematic of the circuit you intend to build to do the actual filtering to detect the beacon.

Spend lots of time of this! An extra hour here will save you a huge amount of time in the lab.

BUMPS AND ROAD HAZARDS:

Polarized capacitors must be plugged in correctly. If you reverse polarity them, they will be damaged (and pop like a firecracker). Reversing polarity on any IC will usually destroy it (letting out the magic smoke). You want to operate your OpAmps in single-ended mode (0-3.3V power).

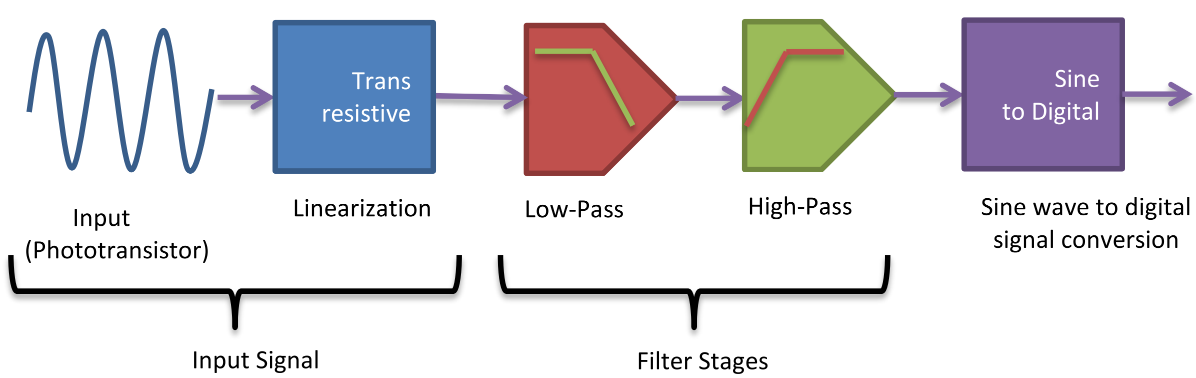
This lab will take a lot of your time. You will be prototyping circuits and will likely get it wrong. If you find yourself frustrated and tired, take a break. Walk away and get some nourishment. Take that time to rest and allow yourself to reset. Be smart about trying to do things when you are tired.

OUTLINE:

You are going to design and prototype a full beacon detector (that will be the basis of the one you will use in the final project). For the final project in this class, an infrared emitter is going to be used as a beacon to let you know when a target is active. The emitter is driven by a microcontroller and generates a 50% duty-cycle on/off wave at a frequency of 2 kHz. There are several sources of noise and interference, including daylight, monitors, wall current, and many others. You will design a filter to amplify the signal of interest, and reject the others.

This will be tested against a beacon which changes its frequency from 1.5 to 2 to 2.5 kHz.

You have already built and tested your input stage to the filter in Part 3 above. In this section of the lab, you will build the filter (bandpass, composed of low-pass and high-pass stages) that will allow the 2KHz to pass, and block the 1.5 and 2.5KHz signals (along with all of the other noise present).



This is going to take some design and calculation to get right. At the output, you want a digital signal that is “high” (2.7 – 3.3V) or “low” (0-1.8V) when the 2KHz beacon is present. The range of your beacon detector should be between 1ft and 6ft from the source (note that our beacons are much brighter than the minibeacons). If you get 0.5ft to 8ft, even better, but not the minimum specification. Your filter should be able to reject signals at 1.5Khz and 2.5KHz. The signal out should be steady (not flickering), and should be good to +/- 5 degrees of axis. An LED should indicate the presence of the 2KHz signal (either polarity is fine).

In thinking about your filter topology, you are going to build a band pass from a low pass and a high pass joined together (with some amplification stages). Which stage should go first? Why?

Once the signal comes out of the filter stages, you need to convert the sine wave to a digital signal in exactly the same manner as you did for the track wire sensor.

You are going to build this filter on your protoboards. Make each part separate, and test it individually before hooking it together. Give yourself lots of room, and be neat and tidy. You won't have the exact parts you need (and Caps are ±20%) so do the best you can with the parts you have. Test everything over and over again to find your bugs. Put bypass capacitors on the power to ground of each and every OpAmp/Comparator chip you use (that is a small cap between power and ground right on top of the chip).

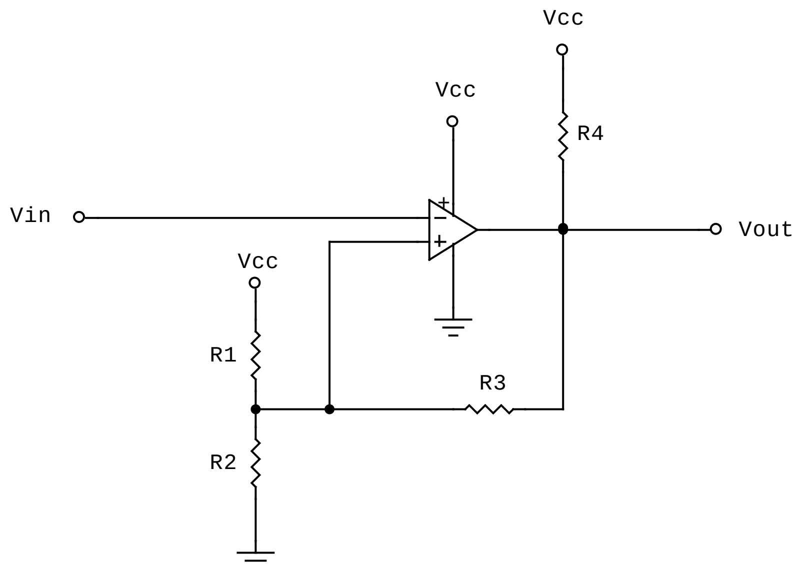
Do not dismantle working hardware, replicate it if you need to. This is especially useful if you want to go back and test if that stage works like the original (working) prototype. If you are going to use multiple voltage rails, use regulators to drop the voltage down to where you need it.

Demonstrate to the TA/tutors that your beacon detector circuit can detect a beacon at 2KHz from 1ft to 6ft range while rejecting the 1.5KHz and 2.5KHz signal for checkoff. In your lab report, include a full schematic of your filter (as you built it), and a detailed block by block explanation of what your design does and what tradeoffs you made to achieve the performance.

HINT: You might need to mechanically shield your phototransistor from light not in front of it.

APPENDIX A: COMPARATOR CONFIGURATION

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



Configuring the Comparator (Inverting configuration):

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: $\Delta V= V_{a1}- V_{a2}$

4) Let $R_4= 3.9K\Omega$

5) Let $R_3 = 1M\Omega$

(Note that the previous two items are simplifications from the general solution)

6) Let $n = \Delta V / V_{a2}$

7) Let $R_1=n \times R_3$

8) Solve for R_2 such that: $R_2 = (R_1 \,||\, R_3) / (V_{cc}/ V_{a1}-1)$

SUMMARY AND TIME TRACKING

Time Spent out of Lab	Time Spent in Lab	Lab Part - Description
		Part 0 – Prototyping Circuits Basics
		Part 1 – Circuit Module Basics
		Part 2 – Track Wire Detection
		Part 3 – Phototransistor and Trans-resistive Amplification
		Part 4 – Beacon Detector

Checkoff: TA/Tutor Initials	Lab Part - Description
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