Lab 1 – Signal Conditioning and Filtering

Overview:

In this lab you will design and prototype a beacon detector of your own design.

- Understand operational amplifiers and comparators.
- Learn signal detection and filtering techniques.
- Gain hands-on experience with proto-boards and schematics.

Comments:

Lab checkoff:

- Check off each part with a tutor or TA to verify functionality and each team member's understanding. **You need to print out the last page to get signed off. Include this sheet in your lab report.**
- Strongly recommended to check off each part before moving to the next.

Lab1 specific comments:

- This lab involves building a real analog filter. Allocate sufficient time; this lab is probably harder and longer than Lab 0.
- Neatness is crucial to avoid issues with stray or disconnected wires.
- Always verify power and ground connections; most problems arise here.
- Use incremental development: build, test, and verify each block before integration.
- Prepare thoroughly by reading and understanding the material.
- Debugging with an oscilloscope will take time; be methodical and organized.
- Seek help if needed, but preparation will make troubleshooting easier.

PreLab:

1. Choose a partner and join a group on CANVAS. Use Piazza to find partners if needed. If you have not chosen a partner by prelab deadline, we will randomly assign one to you.
2. Complete prelab exercises and submit a PDF file individually on CANVAS. Follow the requirements detailed in each section. Part1, Part2, Part3.

Part 0 – Prototyping Circuits Basics – Background Reading

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:

None.

Background:

Appendix A in CKO and Appendices C and D in H&H cover the resistor color code and standard values. The OpAmp, MPC6004, is available in parts cabinet in the lab.

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.

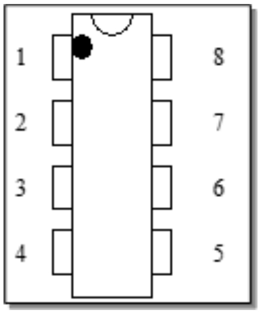
The ceramic disk capacitors are marked for size in a number of different ways. The most common are: **22 or 22K**

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:



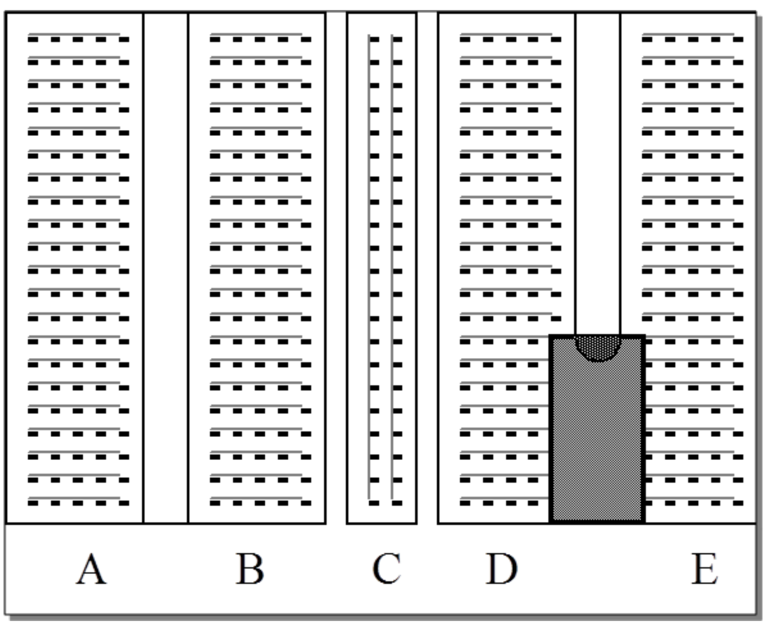
Above is a typical chip drawing. For purposes of determining the pin numbering, note the relative positions of:

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.

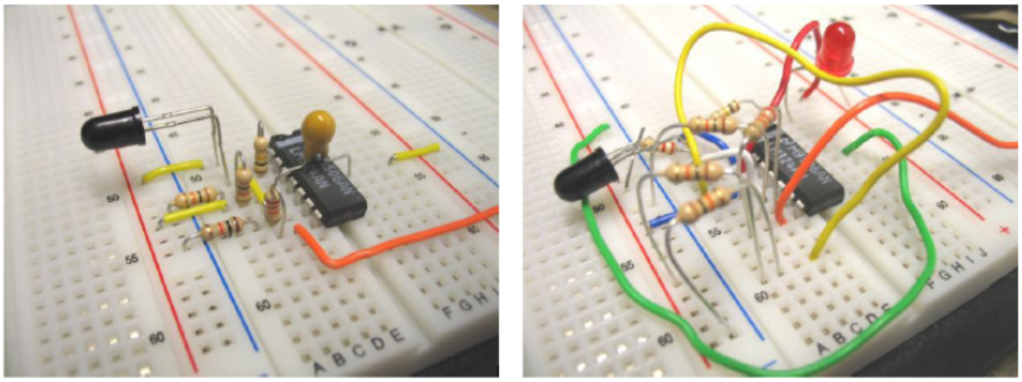
Prototyping Board (Proto-board):

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; they are, however, 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 analyze and build small circuit modules probably needed for the following parts. These functional units should be tested individually to ensure proper operation before integration into the more complex circuit.

Reference Material:

- CKO Ch. 14
- Oscilloscope Tutorial from the class website
- Sparkfun Oscilloscope Tutorial (if you are unfamiliar with O'scopes)

PreLab:

Read Appendix A: Circuit Building Blocks. Describe or draw the expected behavior of each module:

1. 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?
2. 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.
3. 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?
4. Comparator with hysteresis: Work out the values of resistors you need to make the low threshold 1.0v and the high threshold 1.8v.
5. 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:

- Plug polarized capacitors correctly; reversed polarity damages them or causes them to pop.
- Reversing IC polarity destroys it (releases "magic smoke").
- Operate OpAmps in single-ended mode (0-3.3V power).
- Place 0.1μF ceramic bypass capacitors between each power pin of the IC and ground.

Tasks:

1. Build the following circuit modules on a solderless proto-board. 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).
   - **Split Rail Buffer:** Create a 1.65V buffer from a 3.3V rail using an OpAmp. Add a filter capacitor.
   - **Non-Inverting Amplifier:** Design a gain-2 amplifier. Connect the waveform generator to test. Demonstrate traces on the scope and include observations in the lab report.
   - **Peak Detector:** Build an active rectifier with an RC time constant. Verify functionality by connecting it to the amplifier output. Show traces and explain operation in the lab report.
   - **Comparator with Hysteresis:** Design an inverting comparator with thresholds of 1V (low) and 1.8V (high). Verify trip points using a variable power supply. Include calculations and diagrams in the lab report.
   - **LED and Buffer:** Add a buffer to isolate the comparator output and drive an LED. Ensure 0V input lights the LED and 3.3V input results in 3.3V output.

2. Get checkoff from a TA/Tutor.
3. For the lab report, include schematics and output of each stage, along with a discussion of your design choices and supporting calculations. Include all the points listed in the bullet points within each module description.

Part 2 – 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:

- Plug polarized capacitors correctly; reversed polarity damages them or causes them to pop.
- Reversing IC polarity destroys it (releases "magic smoke").
- Operate OpAmps in single-ended mode (0-3.3V power).
- Place 0.1μF ceramic bypass capacitors between each power pin of the IC and ground.
- Verify phototransistor orientation: collector (longer lead) is on the right when facing the bump.

Tasks:

- Connect phototransistor in sourcing configuration:
  - Collector to +3.3V, 100k load resistor to ground.
  - Place phototransistor opposite minibeacon, aim at IR LED.
  - Use bench-top power supply for +3.3V and ground.
  - Observe output at load resistor top using oscilloscope.
- Repeat for sinking configuration:
  - Emitter to ground, observe output at load resistor bottom.
  - Test with 100k and 1k load resistors.
  - Compare impact of smaller load resistor on output.
- Design and prototype transresistive OpAmp stage:

- Maintain 1.65V across phototransistor.
- Output gain: 1V/mA.
- Include complete schematic with component values.

- Test and document:
  - Observe phototransistor and OpAmp outputs using oscilloscope.
  - Include schematics, oscilloscope traces, and explanations in lab report.
  - Demonstrate circuit to TA/tutors for checkoff.

Part 3 – Beacon Detector

Overview:

This assignment is to design and prototype a full beacon detector. 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 beacons with 1.5, 2, 2.5 kHz.

Reference Material:

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

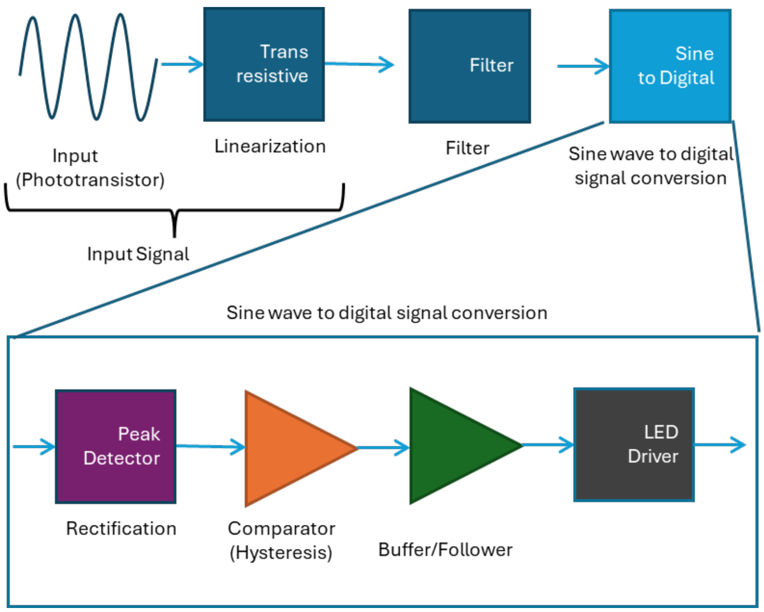
PreLab:

- Design a filter to allow 2kHz signals while rejecting 1.5kHz and 2.5kHz signals.
- Analyze the filter's performance by dB magnitudes and determining the output for sine wave inputs at 1.5kHz, 2kHz, and 2.5kHz with a 100mV peak-to-peak amplitude centered at 1.65V.
- Provide the filter type and a complete schematic of the designed filter circuit.
- Utilize tools like FilterLab to assist in the design process if needed.

Bumps and Road Hazards:

- Plug polarized capacitors correctly; reversed polarity damages them or causes them to pop.
- Reversing IC polarity destroys it (releases "magic smoke").
- Operate OpAmps in single-ended mode (0-3.3V power).
- Place 0.1μF ceramic bypass capacitors between each power pin of the IC and ground.
- Verify phototransistor orientation: collector (longer lead) is on the right when facing the bump.

Tasks:



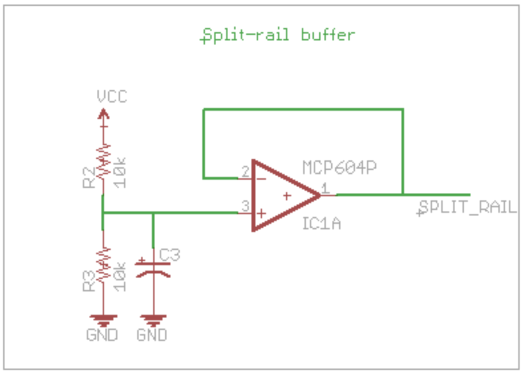
- Design and prototype a complete beacon detector circuit.
- Build a filter to pass 2kHz signals while attenuating 1.5kHz and 2.5kHz signals.
- Ensure the output is a digital signal: "high" (2.7–3.3V) or "low" (0–1.8V) when the 2kHz beacon is detected.
- Achieve a detection range of 1–2 feet from the source (miniBeacon from Lab 0).
- Include an LED indicator to show the presence of the 2kHz beacon, ensuring steady output and ±5 degrees of axis tolerance. Reject signals at 1.5kHz and 2.5kHz.
- Build and test each module separately on a solderless protoboard before integrating them.
- Demonstrate the functionality to TA/tutors for checkoff.
- Include a complete schematic and detailed block-by-block explanation in the lab report.

Tips:

- Allocate ample space and maintain neatness.
- Do the best you can with available parts; you may not have exactly what you need.
- Test repeatedly to identify and fix bugs.
- Add bypass capacitors between power and ground for each OpAmp, Comparator.
- Preserve working hardware; replicate instead of dismantling.
- Shield phototransistor from unwanted light sources.

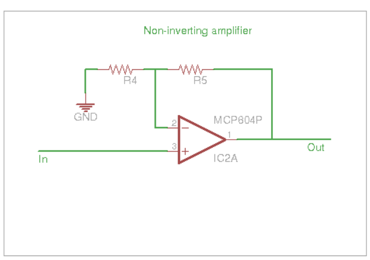
Appendix A: Circuit Building Blocks

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).



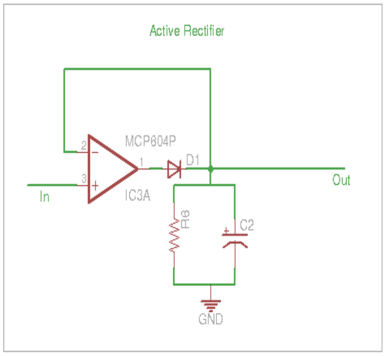
Create a Split Rail Buffer with an output of 1.65V from a 3.3V rail. What is the purpose of the capacitor in the circuit?

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).



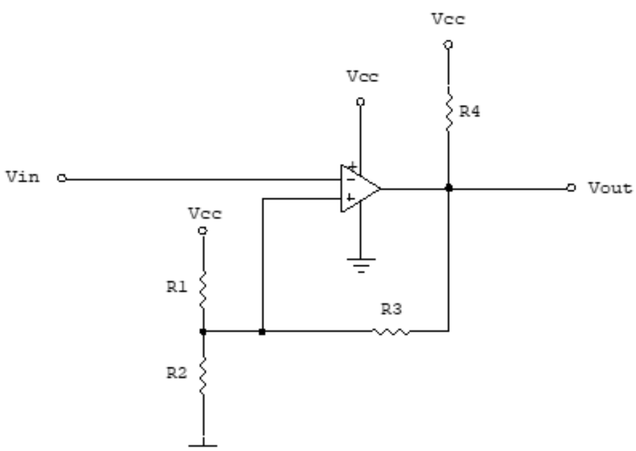
Design and build a non-inverting amplifier that has a gain of 2. Hook the output of your tank circuit to the input of the non-inverting amplifier, and check both traces on the scope.

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 look at the traces of the track wire through the stages on the o-scope.

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).

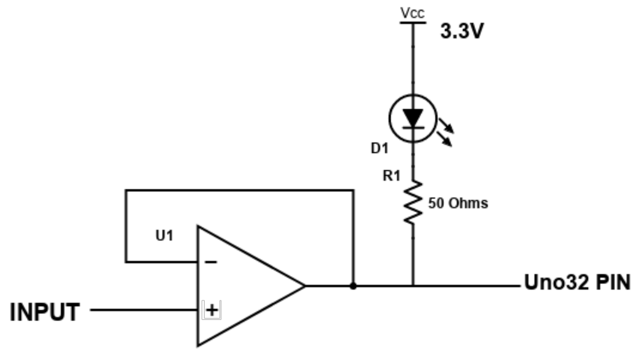


A regular OpAmp can be configured to act like a comparator (see this app note for details), but the hysteresis bounds are not nearly as easy to set, nor does it work as well as the actual comparator. See Appendix A to the lab for calculations on comparator threshold setting.

Design and build an inverting comparator 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.

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/Uno32 input stage.

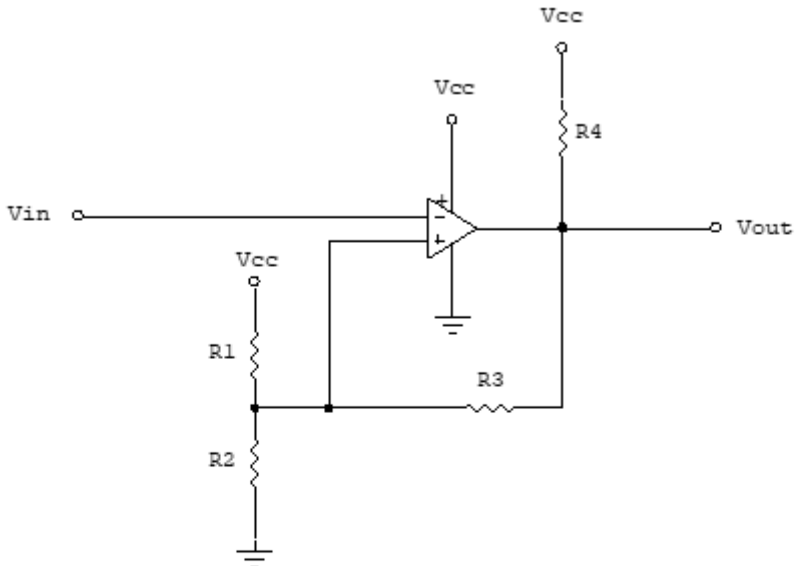


This circuit consists of a buffer to isolate the output, along with a drive stage to light the LED when the signal line goes low. Ensure that a 0V input lights the LED, and that a 3.3V input results in 3.3V output.

Hook all of these together and you should have a working track wire sensor.

Appendix B: Comparator Configuration Worksheet

The basic configuration for an inverting comparator with hysteresis is the one shown below.



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: $R_2 = (R_1 \parallel R_3) / (V_{cc}/ V_{a1} - 1)$

Checkoff and Time Tracking

Student Name:_____________________________________ CruzID______________@ucsc.edu

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

Checkoff: TA/Tutor Initials	Lab Part - Description
	Part 1 – Circuit Module Basics
	Part 2 – Phototransistor and Trans-resistive Amplification
	Part 3 – Beacon Detector