

LABORATORY 2: Linear Systems and Beyond...

Contents

Getting Started!	2
Lab Submission Instructions and Partners:.....	2
Purpose:	2
Student Preparation BEFORE doing this experiment: (Students should be able to)	2
Learning Outcomes AFTER doing this experiment: (Students will be able to)	3
Software and Equipment Required:.....	3
Learning from Proof of Skills applied to this lab:	3
PART A – Defining Linear and Non-linear Devices with Current Voltage Characteristics	4
I-V Characteristics of Resistors and Light Emitting Diodes Background:	4
I-V Characteristics of Resistors and Light Emitting Diodes Experiment:.....	9
Part A: Proof of Concepts List	14
Part B – Solving a Linear Resistive Network using Nodal Analysis and Linear Algebra (Matrix Math)	15
Nodal Analysis and Linear Algebra Background:	15
Nodal Analysis Mechanics with Voltage Differences and Ohm’s Law: In	15
Summarizing Nodal Analysis:	17
Nodal analysis design problem	17
Nodal Analysis and Linear Algebra Experiment	18
Part B: Proof of Concepts List	20
Part C – Operational Amplifiers	20
General Operational Amplifier Basics	20
Operational Amplifier Applications	21
Decision Making Op Amps	21
Mathematical Op Amps	22
Operational Amplifier and Transfer Function Experiment	24
Decision Making Op Amp Circuit Experiment.....	24
Math Op Amp Experiment	24
Part C: Proof of Concepts List	25

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Part D – Applications: Transfer Functions, Linear Algebra, and Control	26
Choose Your Adventure! Alpha Experiments or Omega Exploration	26
Omega Exploration	26
Alpha Experiments	26
Part D: Proof of Concepts List	27
SUMMARY of Concepts.....	27
How You'll Be Graded (with Standards Based Assessment):.....	28

Getting Started!

Lab Submission Instructions and Partners:

- 1) Keep your partners! If a student dropped the course, let us know!
- 2) Decide if you'd like to do an Alpha Experiment or Omega Exploration.
- 3) You will go through each lab section to learn some basic steps. ***Then you will prove specified concepts listed at the end of each section.*** This simply means that you will demonstrate how a specific concept works through clear and concise comparisons of mathematical analysis, simulation, and experimental measurements

The template for the Proof of Concepts document that you will submit can be found here:

https://sites.ecse.rpi.edu/courses/F22/ECSE-1010/AlphaOmega_ProofofConceptstemplate.docx . Please answer any questions related to those concepts and provide mathematical calculation, simulation, and experimental data to support the proof of concept!

Purpose: The objective of this experiment is to introduce you to linearity, some mathematical tools that help you understand complicated systems (linear algebra for example) and provide examples of non-linearity to compare to. To start, you'll determine whether a circuit component is linear by finding its I-V characteristic. Then, we'll introduce principles of linearity to systems and control. We'll define a complicated system as a black box with a transfer function and investigate a literal black box to explore operational amplifiers. ***In ECSE, the idea of linearity affects multiple sub-disciplines.***

Student Preparation BEFORE doing this experiment: (Students should be able to)

- Apply Ohm's Law to determine the current through a resistor
- Determine the values of series and parallel combinations of resistors
- Download and install software on a Windows machine or Mac machine

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Learning Outcomes AFTER doing this experiment: (Students will be able to)

- Find the current-voltage characteristic of a device using the Source Measure Unit.
- Define a linear component (resistor) and a non-linear component (light emitting diode).
- Use nodal analysis to solve for voltage and current in a linear resistive circuit.
- Use matrix math to solve a set of linearly independent equations.
- Identify different operational amplifier (Op amp) configurations to do math or make a decision.
- Discuss the idea of a transfer function at a high level.
- Articulate a series of questions posed about simple circuits and answer the questions using data obtained from physical experiments.
- Demonstrate to themselves and others the difference between tinkering and engineering by answering the question “Is this right?” through documenting the comparison of mathematical analysis, simulation and experiment to prove a concept or an idea!

Software and Equipment Required:

- LTSpice
- MATLAB Simulink
- ADALM1000 (M1K) board with Alice Source-Meter tool or ADALM2000 (M2K) board with Scopy or Analog Discovery with Digilent Waveforms
- Several different Resistors and wires from the ADALP2000 Parts Kit
- Light Emitting Diodes (LEDs)
- Operational Amplifiers (OP484 or OP482) LTSpice use “universal opamp2”
- Omega Exploration Optional: Resistive Sensors, Arduino, Push buttons or switches, Op Amps
- Protoboard

Learning from Proof of Skills applied to this lab:

Professional Accountability: I **can clearly document and compare a calculated, simulated, and experimental result** to answer the question “Is this right?” for myself

Circuit Simulation (LTSpice or equivalent): Nodal Voltages

I **can label and identify Nodal Voltages** in a circuit. (creating a well labeled schematic!!)

I can use **transient analysis with a sinusoidal source** to measure voltage across ONE resistor in a resistive circuit (**Total resistor count in the circuit must be two or more**)

I can step through parameters with **parametric analysis** to repeatedly measure voltages as I vary my resistance over a range of values

Experimental Measurement and Personal Instrumentation: I can use my instrumentation board’s function generator to **create a DC, sinusoid, and pulsed signal** and measure with its oscilloscope directly (*hint: no circuit necessary but need external wires!*)

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I can **build a resistive circuit** and **measure dc voltage across ONE resistor using a dc input source** and vary dc voltage at least 3 times (-5,+5 and any voltage in between) (**Must be two or more resistors**, hint: to do something useful to you, try to simulate a homework or class problem!)

I can **build a resistive circuit** and **measure the dc current through ONE resistor using a dc source** (OR find another way if needed depending on board!) (**Must be two or more resistors**, hint: to do something useful to you, try to simulate a homework or class problem!)

I **can use my cursor function** to show specific voltage and time points.

MATLAB and Simulink Basics: I **can analytically determine the amplitude, frequency, period and phase shift of a sinusoid** (hint: for phase shift you will need a reference point which could be two different sinusoids plotted together!)

I **can find the solutions for linearly independent equations using the matrix function** on my personal calculator (TI-XX) and compare it to the calculation in MATLAB

I **can import simulation data** (from LTSpice or equivalent) **to MATLAB** and plot the function

I **can use a regression** in MATLAB to help define my function

PART A – Defining Linear and Non-linear Devices with Current-Voltage Characteristics

Material covered: I-V characteristics of Resistors and LEDs

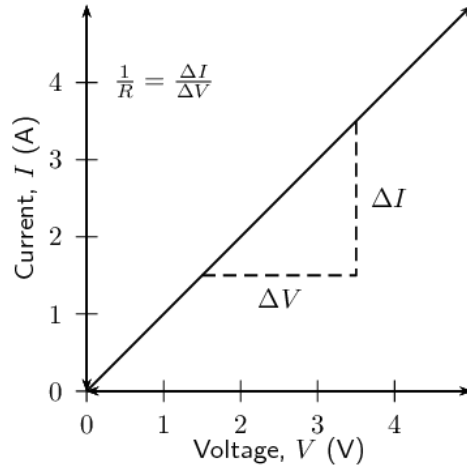
I-V Characteristics of Resistors and Light Emitting Diodes Background:

I-V Characteristic of Resistors: The relationship between current and voltage in a resistor is defined by Ohm's Law, $V = IR$ (Voltage = Current*Resistance). This equation is a linear relationship, following the classic expression, $y = mx+b$, where m is the slope of the line and b is the y-intercept. When considering Ohm's Law, we can say the y-variable is the voltage, V , and the x-variable is the current, I . The slope of the line is then the resistance, with the y-intercept being zero.

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Note: In your experiments and simulation below, the x axis is current (I) and the y axis is voltage (V). This makes the slope R instead of 1/R!

Figure 1: I-V characteristic of a resistor. Ohm's Law. <https://www.siyavula.com/read/science/grade-11/electric-circuits/11-electric-circuits-02>

I-V characteristic of a Light Emitting Diode: In order to understand how a diode functions, it is useful to look at a plot of the voltage across the diode vs. the current through the diode. We call this type of curve an I-V characteristic curve. If we were to create an I-V curve of a resistor, where the current is directly proportional to the voltage ($V=IR$), we would see a straight line with a constant slope of R^{-1} . When we plot the characteristic curve of an ideal diode (that switches on when the voltage across it goes above zero), we see zero current when v_D is negative and infinite current as soon as v_D tries to go positive. This is shown in Figure 2. Note that, when an ideal diode turns on, it is a short circuit and, therefore, the voltage across the ideal diode when it is on is always zero.

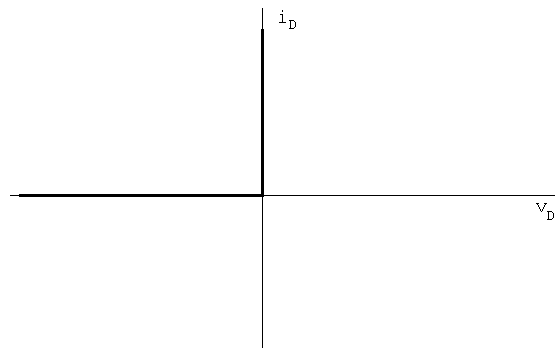


Figure 2: I-V characteristic for an ideal diode

I-V curve of a diode: In comparison, Figure 3 shows typical characteristics of a real diode.

Ideally, a diode is a device that allows current to flow in one direction only. In practice, diodes allow large amounts of forward current to flow when the positive voltage across them reaches a small threshold. They also have a small “saturation” current, which flows in the opposite direction when the voltage across the diode is negative, and a “breakdown” region in which a large amount of current will flow in the opposite direction when a large negative voltage is applied. In small signal diodes, the forward current will typically be up to a few tens of mA at a forward voltage of about 1V. The reverse-breakdown voltage might be about 100V, and the saturation current I_s may be of the order of 1nA. Power diodes may allow forward currents up to many amps at forward voltage drops of 0.6 to 1.5V or so, depending on the type of diode. The reverse-breakdown voltage of power diodes may range from as low as 50V up to 1000V or even much more.

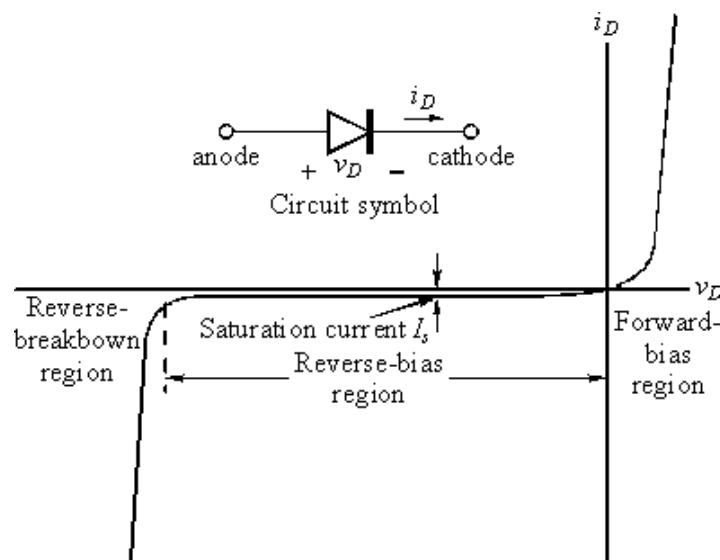


Figure 3: I-V characteristic of a real diode

The diode equation: The equation below gives a reasonably good representation of the I - V characteristics of a diode.

$$i_D = I_s \left(e^{v_D / n V_T} - 1 \right)$$

I_s is the saturation current usually measured in microamps, or nanoamps. V_T is the Thermal Voltage where $V_T = kT/q = 0.0259V$ at 300K and n is a somewhat arbitrary parameter that depends on how the diode is constructed and usually lies between 1 and 2. Note that this equation characterizes the basic features of the diode I - V curve, but leaves out some details like reverse breakdown, junction capacitance, etc.

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ECSE-1010

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Important: The description of the Alice Meter-Source tool and how to setup the channels to make measurements while sourcing voltages is discussed in this video. Watch and listen carefully before doing this experiment.

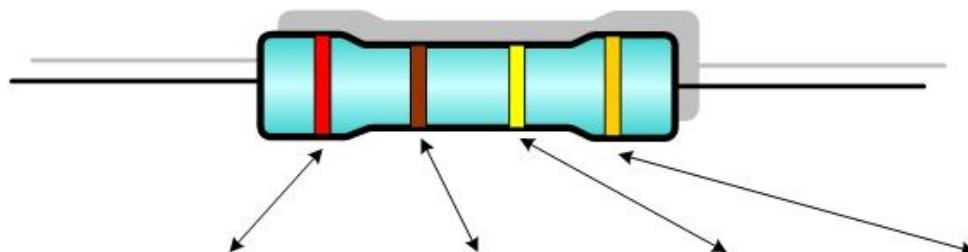
<https://youtu.be/y-Tl-tksPnk>

Determining Resistor Values

Select any resistor from your parts box. (It is a good idea to pick a resistor smaller than $1\text{M}\Omega$, $10^6\Omega$. The reason for this will be discussed in the next laboratory.)

- 1) Write down the four-color code for any resistor you choose in your Proof of Concept document.
- 2) Using the following table, determine the resistance of the resistor you selected.

4-band Resistor



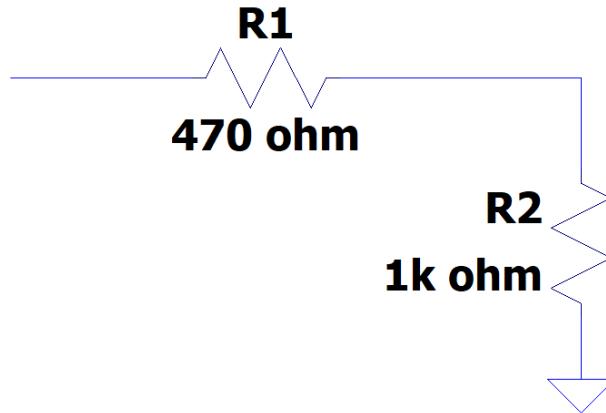
Color	1 st band value	2 nd band value	Multiplier	Tolerances
Black	0	0	$\times 1$	
Brown	1	1	$\times 10$	$\pm 1\%$
Red	2	2	$\times 100$	$\pm 2\%$
Orange	3	3	$\times 1000$	$\pm 3\%$
Yellow	4	4	$\times 10,000$	$\pm 4\%$
Green	5	5	$\times 100,000$	$\pm 0.5\%$
Blue	6	6	$\times 1,000,000$	$\pm 0.25\%$
Violet	7	7	$\times 10,000,000$	$\pm 0.10\%$
Grey	8	8	$\times 100,000,000$	$\pm 0.05\%$
White	9	9	$\times 1,000,000,000$	
Gold			$\times 0.1$	$\pm 5\%$
Silver			$\times 0.01$	$\pm 10\%$
No band				$\pm 20\%$

You can use an online resistor calculator to verify your calculation, a nice reference can be found at All About Circuits using the following link.

<https://www.allaboutcircuits.com/tools/resistor-color-code-calculator/>

I-V Characteristics of Resistors and Light Emitting Diodes Experiment:

I-V Characteristic of Resistors



**You can choose ANY values for R1 and R2
as long as they are different (and less than 1 Mohm)**

Figure 4: Set of two resistors for I-V measurements.

Analysis

1. Draw the I-V characteristics of the resistor above by hand!
2. Rock out to this ~1 minute video to learn how... <https://youtu.be/ZDAltCd1M-U>
3. Make the chart for R1 and R2 and plot them together on the same x-y axis (current-voltage axis respectively) ...you may use excel if you'd like or draw by hand. Either one is fine.

Simulation (LTSpice)

1. Simulate the I-V characteristic of a resistor using parametric analysis
2. See <https://iexploresiliconvalley.com/2019/02/03/ltspice-lesson-1-generating-iv-curves/>

Measurement (M1K or M2K or Analog Discovery Board)

Only instructions for M1K are shown below..please see the [Self-Directed Skills Development Document](#) for introductory level instructions for the other instrumentation boards...

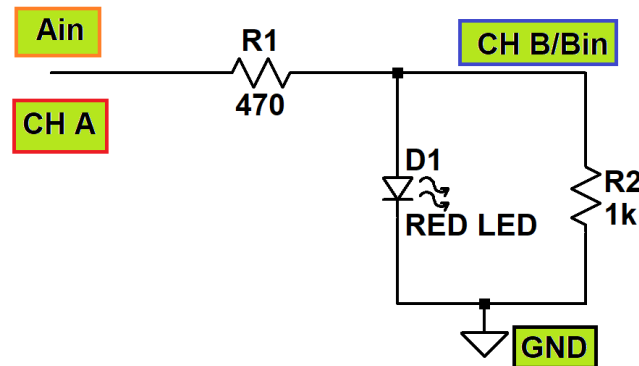


Figure 5: Set of resistors for experiment with optional LED. Note: 470 ohm is a current limiting resistance. If you change it significantly, it will alter the current to the diode....and might not light up!

1. Using the process described in the video titled "[Source and Measure DC Voltages](#)", configure Channel A (CH A) as a variable DC voltage source and the Ain pin as the DC voltmeter. The value of the DC voltage source will be adjusted to make multiple measurements. **Note, here CH A needs to be in Split I/O mode.** [Watch video for the details.](#)
2. The source part of the circuit shown above is built using the M1K Board connections. The CH A pin on the M1K board should be connected to resistor R1 using a wire as shown above. You should build your circuit and make connection on the Protoboard.
3. The DC voltage source can produce voltages between 0V and +5V. The source also needs a reference. We will use the GND pin on the M1K to provide this reference and connect it to one end of LED and R2 as indicated in the above circuit diagram.
4. To measure the voltage across the resistor R1, connect the Ain pin to one side of the resistor and the CH B (or Bin) pin to the other side of the resistor using wires. CAV – CBV will give us this value.
5. Once you build your circuit, launch the Alice Meter-Source tool, put CH A in Split I/O mode, turn on CH A, and "run" the meter source unit. Vary the DC voltage of CH A from 0V to 3V in 0.5V increments. For each source voltage increment, record the voltage measured across resistor R1. Apply Ohm's Law to determine the current through the resistor

Intro to ECSE Laboratories: Alpha Experiments and Omega Explorations

ECSE-1010

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CH A Voltage (V)	Channel A voltage measured on Ain pin, V	Channel B voltage measured on CH B/Bin pin, V	Resistor R1 Voltage, V	Resistor Current, I
0				
0.5				
1				
1.5				
2				
2.5				
3				

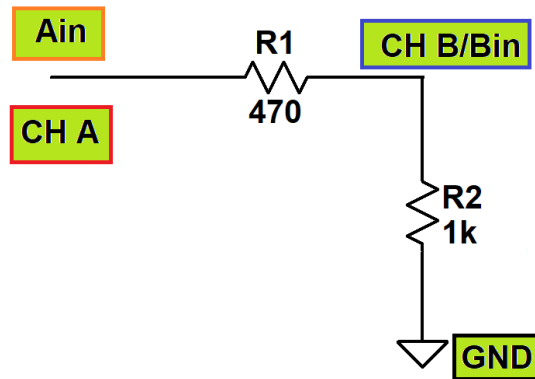
6. Plot the resistor current I (x-axis) vs the resistor voltage V (y-axis). From the slope of your plot, verify that Ohm's Law results in a linear relationship with a slope determined by the resistance value.

Note, the resistor current will have a linear relationship with the resistor voltage. However, the resistor current will not have a linear relationship with the CH A source voltage. You might want to verify that yourself on a separate plot, but it is not required for the laboratory.

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ECSE-1010

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1. Remove the LED from the circuit.
2. Now we will also measure voltage across R2. To measure the voltage across the resistor R2, connect the CH B (or Bin) pin to one side of the resistor R2 and the GND pin to the other side of the resistor using wires. These connections should have already been made for Part 1. CBV – GND (or simply CBV) will give us the value of resistor R2's voltage.
3. As in the previous part, step the CH A source voltage from 0.0 to 3.0V in 0.5V increments.
4. Using voltage measurements CAV and CBV (using the Ain and CH B/Bin pins), measure the voltage across R1 and R2. For each voltage, use Ohm's Law to determine the current.
5. You may export this data to excel or MATLAB and fit a linear regression curve to it. [LTSpice to MATLAB](#), [Experimental Data to MATLAB](#), [Linear regression in MATLAB](#)

CH A Voltage (V)	R1 Voltage (measured)	R1 Current (calculated)	R2 Voltage (measured)	R2 current (calculated)
0				
0.5				
1				
1.5				
2				
2.5				
3				

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ECSE-1010

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For both resistors, plot the V-I curves (voltage vs. current) on the same graph. From the slopes of your plots, verify that Ohm's Law results in a linear relationship with a slope determined by the resistance value. Does the plot of the larger resistor have a steeper slope, as would be expected?

We can experimentally find the exponential I-V curve using the Figure 6 circuit (drawn below).

- Set Channel A source to a triangle wave that varies from 0V to 4V. Choose a source frequency of 200 Hz. Measure the voltage across the diode (using math channel CA V – CB V) and resistor (CB V).

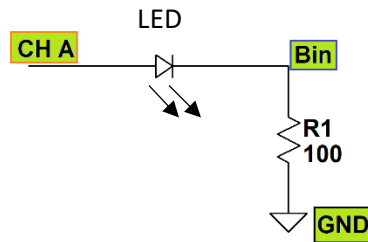


Figure 6: LED with current limiting resistor in series for I-V characteristic measurements.

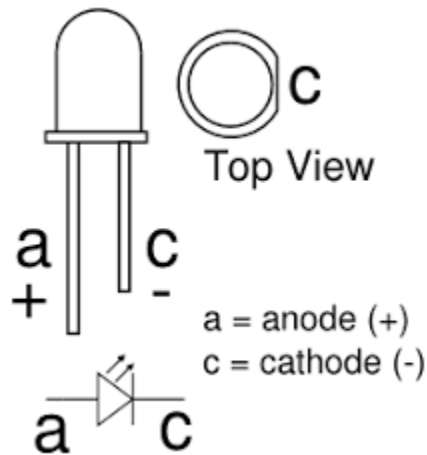


Figure 7: LED configuration for anode and cathode. You might align this correctly for the LED to turn on!

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ECSE-1010

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Once you have at least two time periods of diode and resistor voltages being displayed on the Oscilloscope, follow these steps to sketch the I-V characteristics.

1. Click on X-Y plot option in Alice Desktop.
2. This should bring up "X-Y Plot" window on which you can sketch one measurement versus another measurement.
3. Choose Math for X-Axis. This will set the diode voltage as your horizontal axis.
4. Choose CB-V for Y-Axis. This will set the resistor voltage as your Y-Axis. The resistor current is $CB-V/100$ and is the same as the diode current (series elements). Since we are interested in observing the exponential relationship, using a value 100 times larger for the y-axis should just be a scaling issue and will not change the shape of the current-voltage characteristics of the diode.
5. Take a screenshot of X-Y plot and include in report.
6. Can you import this data to MATLAB and fit an exponential curve to it? Try it out!
7. Pick a range of voltages and their corresponding currents at different points of the I-V curve. Find the differential resistances along this curve and comment on how it changes?

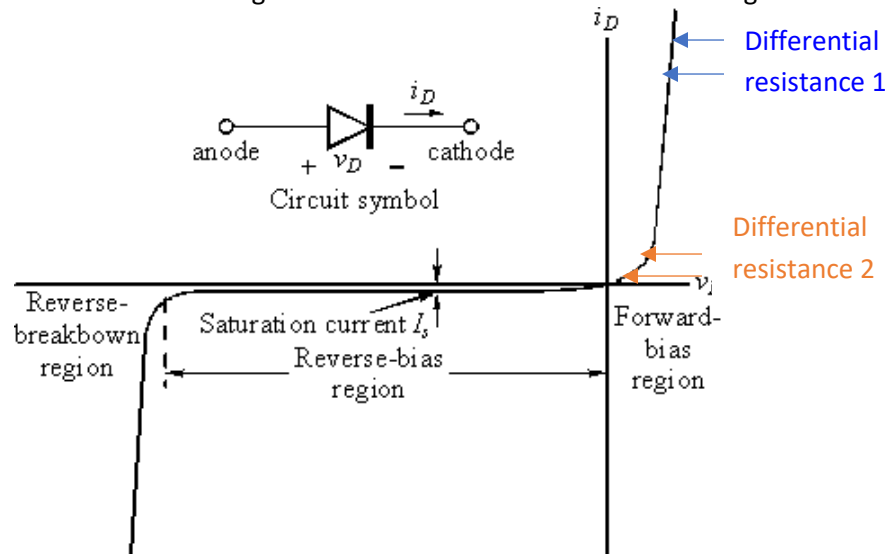


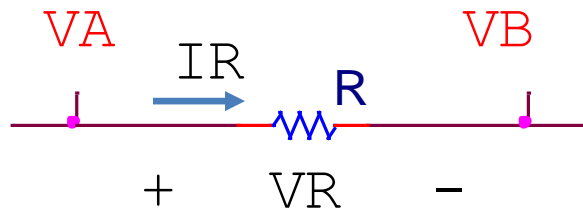
Figure 8: Differential resistance in a real light emitting diode I-V characteristic

Part A: Proof of Concepts List

1. Prove that the slope of an I-V curve corresponds with ohm's law for two different resistor values.
2. Prove the non-linear I-V curve for a light emitting diode.
3. Show/demonstrate that the differential resistance changes in different regions in the diode I-V curve.

Part B – Solving a Linear Resistive Network using Nodal Analysis and Linear Algebra (Matrix Math)*Material covered: Nodal Analysis, Linear Independent Equations and Matrices***Nodal Analysis and Linear Algebra Background:**

Nodal Analysis Mechanics with Voltage Differences and Ohm's Law: In previous experiments we have discussed the relationship between voltage and current in a resistor (Ohm's Law). In the last experiment we used nodal analysis to determine the voltage across a resistor (or combination of resistors). The voltage we use in Ohm's Law is always a voltage difference, i.e. the voltage on one side of the resistor minus the voltage on the other side of the resistor.

*Figure 9: Voltage of resistor between nodes VA and VB*

In Figure 9, the voltage across the resistor is $V_R = V_A - V_B$, as we saw in the previous laboratory. Likewise, the current through the resistor is $I_R = V_R / R$. We can then use the voltage difference expression and rewrite the current through the resistor as, $I_R = \frac{V_A - V_B}{R}$. This form of the equation is used to set up a system of equations to find the voltage at every node in a circuit. Review: [What is a node?](#)

Important note: Current in a resistor has direction and will always flow from a higher voltage node to a lower voltage node. In Figure 9, the '+' side of the resistor is assumed to be a higher voltage, indicating that current will flow to the 'right'. These designations are called the **polarity** of the voltage and current. It is possible that VB is a higher voltage than VA, which would result in VR being negative (using the expression $V_R = V_A - V_B$). If the voltage across a resistor is negative, then the current will also be negative since we always use the same polarity designations.

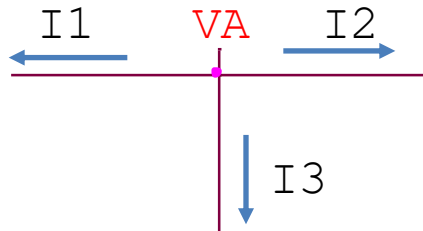


Figure 10: Currents leaving node VA

Kirchoff's Current Law (KCL): In words, KCL indicates that the total amount of current entering a node must be equal to the total amount of current leaving a node. In other words, there is no accumulated charge (electrons) at a node. Visually, we can represent that concept in Figure A-2. Node VA has three paths (connections to various components). If we draw currents leaving the node, as shown in the figure, we can express KCL mathematically as,

$$I_1 + I_2 + I_3 = 0$$

In this expression, we notice that at least one of the currents must be negative. In other words, at least one of the currents must be entering the node. As mentioned above, a negative current just means we 'guessed' the wrong direction when we drew the arrow.

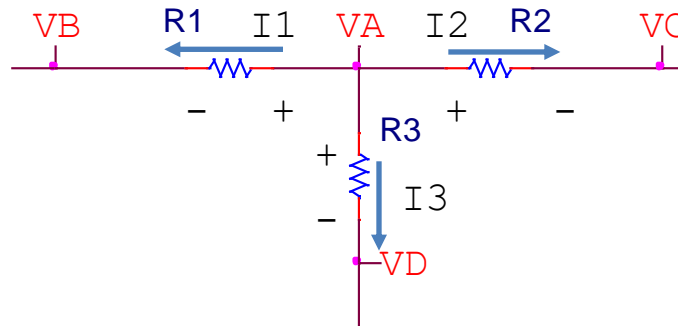


Figure 11: KCL applied at node VA with current leaving node

We can apply KCL to a node connected to resistors, as shown in Figure A-3. Again, we assume currents are leaving the node. Based on that current polarity, we must assign a consistent voltage polarity, with the + side on the VA side of each resistor and the - side on the other node for each resistor (VB for R1, etc.). Applying KCL, we get the same expression as seen on the previous page,

$$I_1 + I_2 + I_3 = 0$$

We can now apply Ohm's Law to each of those currents and use voltage difference concepts to include the nodal voltages,

$$I_1 = \frac{V_A - V_B}{R_1}$$

$$I_2 = \frac{V_A - V_C}{R_2}$$

$$I_3 = \frac{V_A - V_D}{R_3}$$

We can substitute these Ohm's Law expressions back into the KCL expression, to obtain an equation

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$$\frac{V_A - V_B}{R1} + \frac{V_A - V_C}{R2} + \frac{V_A - V_D}{R3} = 0$$

We now have one equation with four unknowns (V_A , V_B , V_C , and V_D). In order to find the values of each of those nodal voltages, we would need three more **linearly independent** equations.

Summarizing Nodal Analysis:

To solve for the voltages at the nodes of a circuit, a summary of the process is as follows.

- 1) Label all the nodes in the circuit.
- 2) Pick a node to be common ground and set the voltage at the node to be zero.
- 3) For each voltage source, use voltage differences to find the voltage at another node (note, the voltage source needs to be connected to ground).
- 4) At each of the remaining unknown nodal voltage, apply KCL to get an equation
- 5) Implement the system of equations as a matrix expression, $Ax = b$. Need a review? See [Proof of Skills Find solutions for linear independent equations using the matrix function](#)
- 6) Solve the matrix expression

Nodal analysis design problem

In many design problems, we can find there is tremendous flexibility. Often there will be more variables than constraints, leaving many choices to the designer. For example, in the circuit shown in Figure 12, if the only constraint is that the voltage at A must 2V, then an infinite number of circuits are possible. There are three design choices to make, the voltage of V_1 and the resistance values of the two resistors R_1 and R_2 . We do recognize some additional design restrictions, for example, we know that the voltage source must be greater than 2V since the voltage divider always results in a 'step down' in voltage. Additional, once we pick a source voltage, we know the voltage divider expression determines a relationship between R_1 and R_2 , $V_A = \frac{R_2}{R_2 + R_1} V_1$. For example, we could pick $V_1 = 4V$, leading to the relationship $R_1 = R_2$.

There are still an infinite number of possibilities, even though the source voltage has been chosen. Some practical considerations now emerge. Picking resistors that are too small can be problematic since we have verified that voltage sources have an internal resistance that we tend to neglect. If we chose resistance values, $R_1 = R_2 = 1\Omega$, simulation results would give us $V_A = 2V$, however, experimental results would likely produce a very different result. Another practical consideration with resistors is choosing a resistor value that is easy to locate (i.e. in our parts kit). Choosing $R_1 = R_2 = 6k\Omega$ would require using other resistors in series and parallel to obtain that value.

In our design process, we may wind up with a resistor value that is not a standard or readily available. That is fine, but let that be a single resistor value where we need to design a small resistor network (parallel and series) to implement that single value.

As you approach the design problems on the following page, you might

- 1) Lay out a basic circuit that meets the provided constraints
- 2) Assign voltage values that you feel will be sufficient to meet the goals
- 3) Assign values to some (not all) of the resistor values based on what is available in your parts kit.
- 4) Apply circuit analysis to any remaining resistors, determining a value that meets the requirements

(Note you can approach from another direction by assigning resistors values first and then choosing voltage source values that meet the requirements.)

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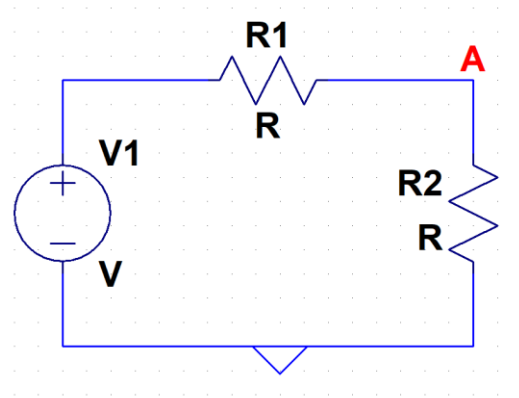


Figure 12: Voltage Divider with Node A

Nodal Analysis and Linear Algebra Experiment

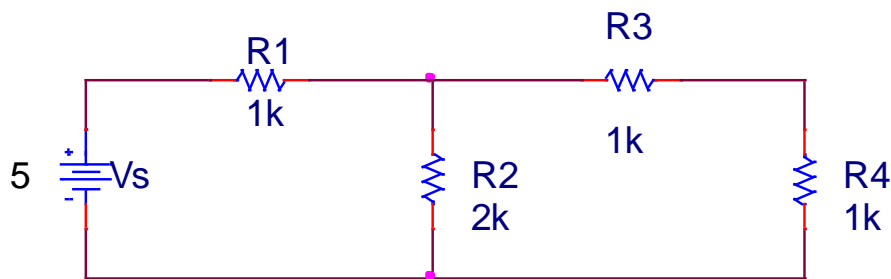


Figure 13: Four node circuit

- 1) In your Proof of Concepts, (Building Block) include the circuit schematic with each node labelled. You may choose any resistor values you want. You can also change the input voltage if you'd like.
- 2) Identify a ground node (it is best to pick a node connected to the source)
- 3) Use the source to identify the voltage at one of the labelled nodes. Which node and what voltage?
- 4) How many unknown voltages are left?
- 5) Apply KCL to each of those unknowns. Include the expressions in your report.
- 6) Combine your simultaneous equations into matrix form, filling in values for the matrix A and vector b .
- 7) Solve the matrix 'by hand'.
- 8) Verify your solution using Matlab for the matrix mathematics (take screen shots of your process and include them in your report).
- 9) Simulate the circuit in LTspice and check your answers. (Comparing calculations and simulations is a frequent part of engineering.)
- 10) Build the circuit and confirm your findings in your Proof of Concepts.

Design Challenges with Nodal Analysis

Choose one of the design challenges and include in your Proof of Concepts document:

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ECSE-1010

*One Gradescope submission
per group of 2 or 3 (add names)*

Design Challenge 1:

Design a circuit with a node that has 2V (not the source node). Your circuit should consist of one voltage source and three equivalent resistors*. The resistors cannot be in series. Two of the resistors may be in parallel.

Design Challenge 2:

Design a circuit with a node that has 2V (not the source node). Your circuit should consist of two voltage sources and three equivalent resistors*. None of the resistors should be in parallel or series. The voltage sources should have a difference of at least 1V.

Design Challenge 3:

Design a circuit with one node at 2V and one node at 3V (neither are source nodes). Your circuit should consist of two voltage sources and resistors as needed. None of the resistors should be in parallel or series. The voltage sources should have a difference of at least 1V.

*equivalent resistors – resistor values that can be (but don't have to be) constructed by using resistors in parallel and/or series configurations available in the parts kit

Part B: Proof of Concepts List

4. Prove that nodal analysis solves unknown nodal voltages in a circuit.

5. Prove/demonstrate your approach to designing a circuit using nodal analysis.

Part C – Operational Amplifiers

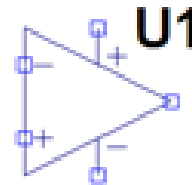
Material covered: Operational Amplifiers and MATLAB Simulink

General Operational Amplifier Basics

The op amp is another non-linear device that we treat as a black box. It is an amplifier with properties that are important for circuit isolation, amplification, mathematical operations, and binary decision making. There are hundreds, if not thousands of different types of op amps. All have datasheets and different specifications to meet needs.

The circuit schematic symbol of the connections for op amps are below. You can find this component in LTSpice “UniversalOpamp2” :

- input, - (left), inverting input
- input, + (left), non-inverting input
- -(bottom), V-: Negative power, -9 V
- +(top), V+, Positive power, 9V
- Right node: Vout, output voltage



In this lab, we introduce the fundamental idea and give you a chance to build and test an op amp circuit and/or represent its **transfer function** in Simulink. A transfer function is how a circuit or component affects an input to create an output. In fact, Transfer Function = $H = V_{out}/V_{in}$. It is the ratio of V_{out} to V_{in} . The idea of a **transfer function is a universal engineering concept**.



Operational Amplifier Applications

Content style modified from <http://site.iugaza.edu.ps/yyazji/files/lab-51.pdf>. All example output signals are referenced to this document.

Decision Making Op Amps

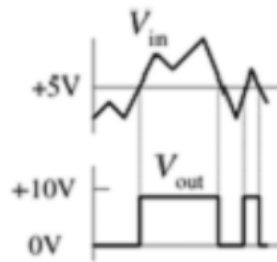
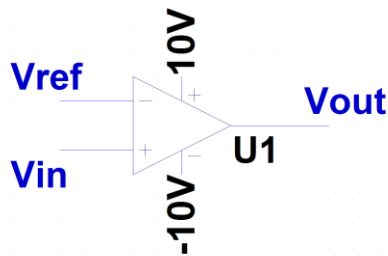
1. Non-inverting Comparator

Vref is a voltage you set, usually by a voltage divider with your source or just your source

Vin is the input that you want to compare to Vref.

If input is above Vref saturate positive.

If input is below Vref saturate negative.



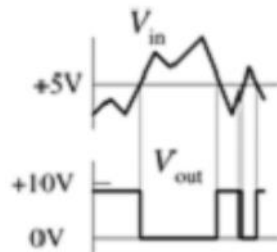
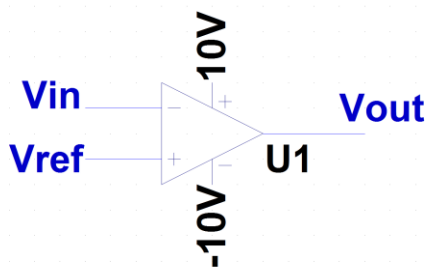
2. Inverting Comparator

Vref is a voltage you set, usually by a voltage divider with your source or just your source

Vin is the input that you want to compare to Vref.

If input is below Vref saturate positive.

If input is above Vref saturate negative.

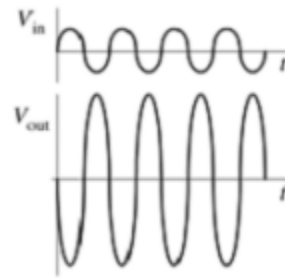
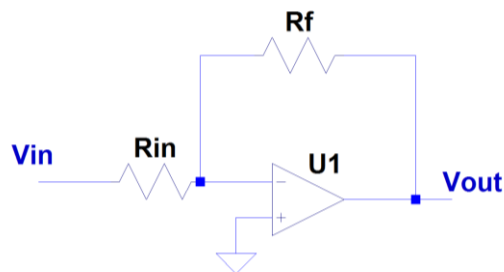


Mathematical Op Amps

1. The inverting amplifier: *Inverts a signal and amplifies it*

$$V_{out} = \frac{-R_f}{R_{in}} * V_{in}$$

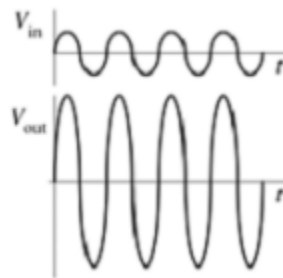
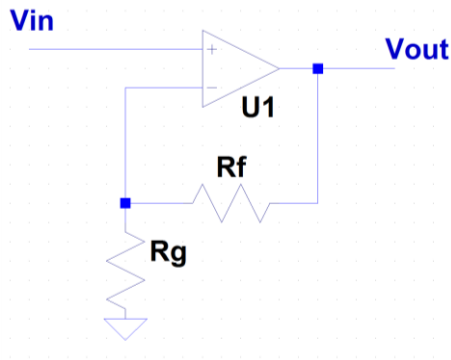
Inverting amplifier transfer function (also known as closed loop gain) = $\frac{-R_f}{R_{in}}$



2. The non-inverting amplifier: *Amplifies a signal*

$$V_{out} = \left(1 + \frac{R_f}{R_g}\right) * V_{in}$$

Non-inverting amplifier transfer function (also known as closed loop gain) = $\left(1 + \frac{R_f}{R_g}\right)$

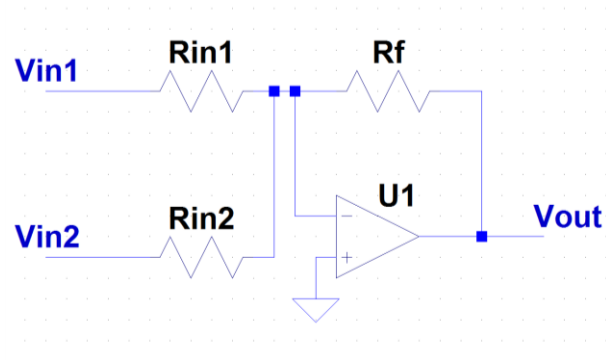


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ECSE-1010

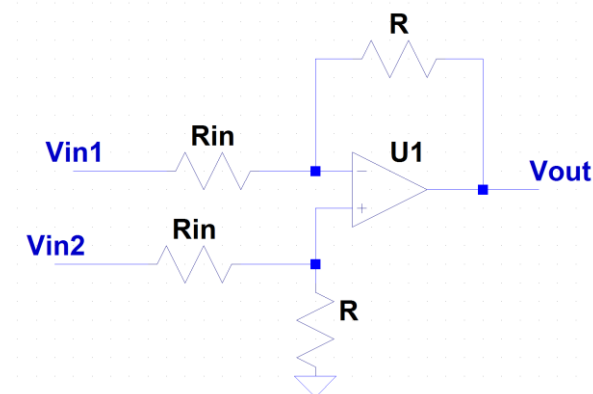
One Gradescope submission
per group of 2 or 3 (add names)

3. The Inverting Summer: *Adds signals together and amplifies as a weighted ratio and inverts the signal*



$$V_{out} = -\left(\frac{R_f}{R_{in1}} * V_{in1} + \frac{R_f}{R_{in2}} * V_{in2}\right)$$

4. The difference amplifier: *Subtracts signals*



$$V_{out} = \frac{R}{R_{in}}(V_{in2} - V_{in1}) \quad \text{note: } R \text{ is the same value in both places, } R_{in} \text{ in the same value in both places}$$

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One Gradescope submission
per group of 2 or 3 (add names)

Operational Amplifier and Transfer Function Experiment

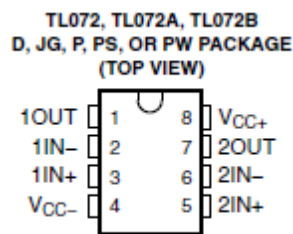
Decision Making Op Amp Circuit Experiment

- 1) In your Proof of Concepts, (Building Block) choose ONE Decision Making Op Amp circuit (either inverting or non-inverting comparator) and pick a reference that is NOT 5V. Like 1.3 or -2.7 or 3.6. (Use a voltage divider as your input! Make your schematic in LTSpice.
- 2) Simulate the function of your comparator using a changing input...triangle wave, sinusoid, ramp signal....any input that shows your output switching will work!
In LTSpice, you can use the "UniversalOpamp2" component or "opamp" component. The "opamp" component does not have power levels and is assumed ideal. It is useful for simplified drawings, but your simulations will not be the same as the experiments. As such, please use the "UniversalOpamp2" component, with LTSpice details shown below.
- 3) You may EITHER build the experiment with SIMULINK (find out how!) or build it with hardware on your protoboard. Use your M1K, M2K, or Analog Discovery Board function generator to provide an input that will show the function of your comparator. If you do both you get a bit of extra credit!
 - a. If building *a comparator with hardware use the TL072CP chip* (dual op-amp) which will be available at the front of the class or in lab...

The data sheet for the chip can be found online from any number of sites. One is provided below (it is long and contains several chips)

<http://www.ti.com/lit/ds/symlink/tl071.pdf>

A copy of the pin connections is shown below



- 4) There are two op-amps on the chip, indicated by the '1' and the '2' pin labels. For example, 1IN+ is the V+ and 1IN- is the V- of the first op-amp, with 1OUT being the Vout. Power connections are +Vcc at pin 8 and -Vcc at pin 4.

Math Op Amp Experiment

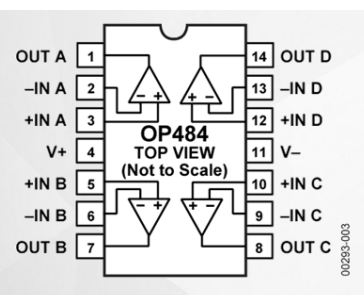
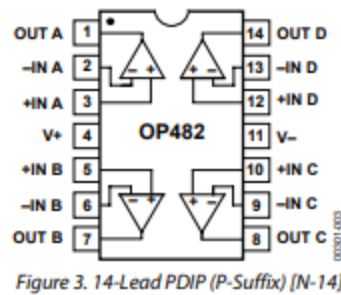
- 1) In your Proof of Concepts, (Building Block) choose ONE Mathematic Op Amp circuit. **Note: You can also try a differentiator or integrator** not shown in this document, there are more, absolute value op amp, non-inverting summer.....Make your schematic in LTSpice.
In LTSpice, you can use the "UniversalOpamp2" component or "opamp" component. The "opamp" component does not have power levels and is assumed ideal. It is useful for simplified drawings, but your simulations will not be the same as the experiments. As such, please use the "UniversalOpamp2" component, with LTSpice details shown below.

Intro to ECSE Laboratories: Alpha Experiments and Omega Explorations

ECSE-1010

*One Gradescope submission
per group of 2 or 3 (add names)*

- 2) Simulate the function of your comparator using a changing input...triangle wave, sinusoid, ramp signal....any input that shows the mathematical function of your op amp.
- 5) You may EITHER build the experiment with SIMULINK (find out how! Search online [just one example](#)) or build it with hardware on your protoboard. Use your M1K, M2K, or Analog Discovery Board function generator to provide an input that will show the function of op amp. If you do both you get a bit of extra credit!
 - a. If you are using hardware, use the OP482 ([datasheet here](#)) or OP484 ([data sheet here](#)) in your parts kit. The OP482 needs a positive and negative supply voltage (+9V and -9V power) while the OP484 is a single supply op amp that needs (+5V and ground). Both have four op amp chips in the same package!



Part C: Proof of Concepts List

6. Prove the function of an op amp comparator
7. Prove the function of a mathematical op amp.

Part D – Applications: Transfer Functions, Linear Algebra, and Control

Material covered:

1. Choose an application! (water quality monitor, sun tracker for solar panel, flex sensor for VR glove or body suit in gaming etc.)
2. Make high level building blocks with input and output that define your sensor system
3. Find Op Amps or other components that are functions in each building block

Choose Your Adventure! Alpha Experiments or Omega Exploration

Alpha Experiments

Sensors and Decisions

Choose an application of interest like a moisture sensor for an automated aquaponic system or a motion sensor for a smart traffic light.

1. Draw a high-level block diagram.
2. Simulate your application (must include at least one sensor and one op amp): You may simulate a sensor using a potentiometer find one in your kit!
3. Calculate the relationship from input to output for each part of your circuit. i.e. a non-inverting amplifier would amplify an input voltage by $(1+R_f/R_g)$ to get an output voltage. This is a transfer function!
3. Build your application (using hardware) and demonstrate its function. Compare.

Omega Exploration

Explore linear and non-linear concepts in an ECSE sub-discipline you are interested in!

- ☐ Design a sensor system for your application and create a circuit that makes a decision and triggers an alarm (light a diode or turn on a speaker). Find, simulate, build and discuss **at least one additional design** to do the same function and compare their performance! i.e. op amp vs. transistor, digital gate vs. analog, PWM vs. DC or sinusoidal...
- ☐ [Explore an Op Amp data sheet](#) and apply to YOUR design with knowledge from the data sheet. Why one Op Amp over another for your application?
- ☐ Explore how to make a diode, explain how it works (schedule clean room tour/visit) [Tour schedule sign up \(dates may change\)](#)
 - [Clean Room Diode Proof of Concept note/template](#)
- ☐ Linear Algebra and Computer Imaging [Instructions from Spring2022 Lab17-20 with datasets!](#)
- ☐ [PID controller \(MATLAB Simulink -> Op amps\)](#) how would you do it?

Part D: Proof of Concepts List

8. Alpha: Prove your sensor decision circuit. You may also amplify your signal if needed.
9. Omega: Prove the concept of transfer functions in your exploration.
And/OR
10. Omega: Prove the use of linear algebra in your exploration.

SUMMARY of Concepts

Concept List that must be accounted for in your Proof of Concepts

PART A:

1. Prove that the slope of an I-V curve corresponds with ohm's law for two different resistor values.
2. Prove the non-linear I-V curve for a light emitting diode.
3. Show/demonstrate that the differential resistance changes in different regions in the diode I-V curve.

PART B:

4. Prove that nodal analysis solves unknown nodal voltages in a circuit.
5. Prove/demonstrate your approach to designing a circuit using nodal analysis.

PART C:

6. Prove the function of an op amp comparator
7. Prove the function of a mathematical op amp.

PART D:

8. Alpha: Prove your sensor decision circuit. You may also amplify your signal if needed.
9. Omega: Prove the concept of transfer functions in your exploration.
And/OR
Omega: Prove the use of linear algebra in your exploration.
And/OR
10. Omega: I can describe how a diode works and connect this to some piece of equipment or procedure in the clean room.

How You'll Be Graded (with Standards Based Assessment):

You will be graded on the following Standards. Please ensure to achieve each standard. If you do not, you can resubmit to the missing standard to the end of the semester. **CLEARLY** mark the changes you make in you Proof of Concept submission by either Tracking Changes in Word or highlighting changes by writing comments in a different color and/or changing the color of the updated work.

Lab 02 Standards

1. I can create current voltage characteristics for a linear component.
2. I can create current voltage characteristics for a non-linear component.
3. I can solve a circuit's unknown voltages using nodal analysis.
4. I can design a circuit using nodal analysis.
5. I can demonstrate the function of a decision-making op amp.
6. I can demonstrate the function of a mathematical op amp.
7. Alpha: I can design and demonstrate a series of components with transfer functions (input, component, output) to make a larger circuit that makes a decision about something.
8. Omega: I can design and demonstrate a series of components with transfer functions (input, component, output) to make a larger circuit
9. Omega: I can use linear algebra to create an output I need for my system.
10. Omega: I can describe how a diode works and connect this to some piece of equipment or procedure in the clean room.
11. I can demonstrate "good failure" whenever applicable by providing accurate results in my experience and speculating what went wrong.
12. I can identify non-idealities or unexpected results and attempt to explain why they may exist.
13. I can answer for myself "Is this right?" by comparing mathematical calculations to simulation and experimental results.