

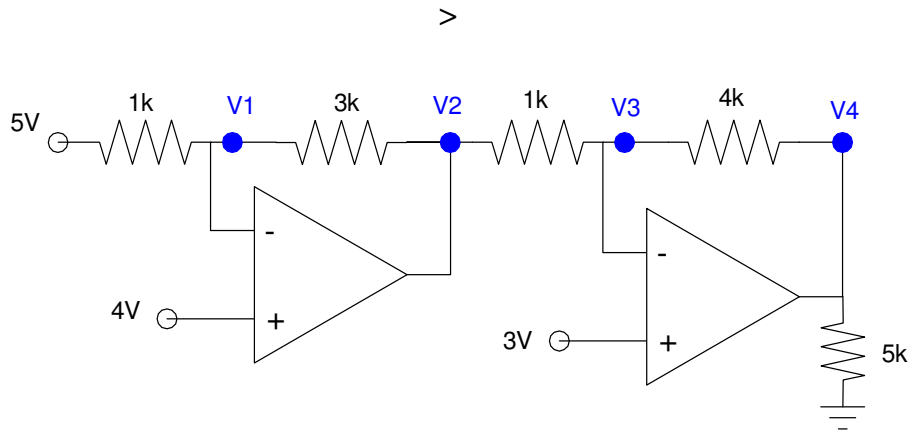
ECE 211: Homework #5

Ideal Op-Amps, Amplifiers, Comparitors, & Schmitt Triggers

Ideal Op-Amps

1) Write the voltage node equations for the following op-amp circuit. Assume ideal op-amps.

- Solve for V_1 , V_2 , V_3 , and V_4



Start with the easy ones ($V_p = V_m$)

$$V_1 = 4V$$

$$V_3 = 3V$$

Write the node equations at node V_1 and V_3

- you can't write the node equations at nodes V_2 and V_4 since you don't know the current from the op-amp*
- node V_1

$$\left(\frac{V_1 - 5}{1k} \right) + \left(\frac{V_1 - V_2}{3k} \right) = 0$$

node V_3 :

$$\left(\frac{V_3 - V_2}{1k} \right) + \left(\frac{V_3 - V_4}{4k} \right) = 0$$

That gives four equations and four unknowns. To solve, group the terms

$$V_1 = 4$$

$$V_3 = 3$$

$$\left(\frac{1}{1k} + \frac{1}{3k} \right) V_1 - \left(\frac{1}{3k} \right) V_2 = \left(\frac{1}{1k} \right) 5V$$

$$-\left(\frac{1}{1k} \right) V_2 + \left(\frac{1}{1k} + \frac{1}{4k} \right) V_3 - \left(\frac{1}{4k} \right) V_4 = 0$$

place in matrix form

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \left(\frac{1}{1k} + \frac{1}{3k}\right) & \left(\frac{-1}{3k}\right) & 0 & 0 \\ 0 & \left(\frac{-1}{1k}\right) & \left(\frac{1}{1k} + \frac{1}{4k}\right) & \left(\frac{-1}{4k}\right) \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} 4 \\ 3 \\ \left(\frac{5}{1k}\right) \\ 0 \end{bmatrix}$$

solve using Matlab

```
>> a1 = [1,0,0,0];
>> a2 = [0,0,1,0];
>> a3 = [1/1000+1/3000,-1/3000,0,0];
>> a4 = [0,-1/1000,1/1000+1/4000,-1/4000];
>> A = [a1;a2;a3;a4]
```

```
1.0000      0      0      0
      0      0  1.0000      0
0.0013  -0.0003      0      0
      0  -0.0010  0.0013  -0.0003
```

```
>> B = [4;3;5/1e3;0]
```

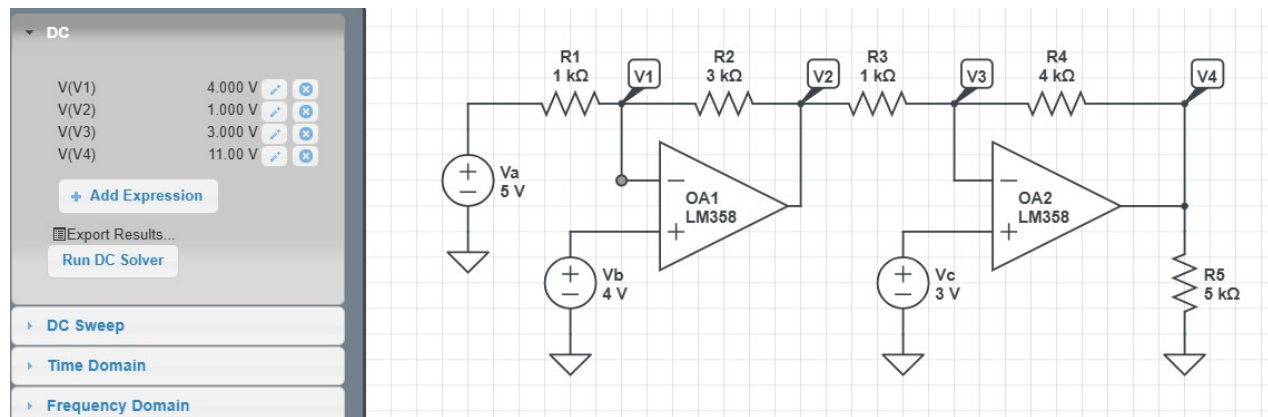
```
4.0000
3.0000
0.0050
      0
```

```
>> V = inv(A)*B
```

```
v1      4
v2      1
v3      3
v4     11
```

2) Check your answers using CircuitLab

- Assume LM394 op-amp (doesn't really matter)



Comparing

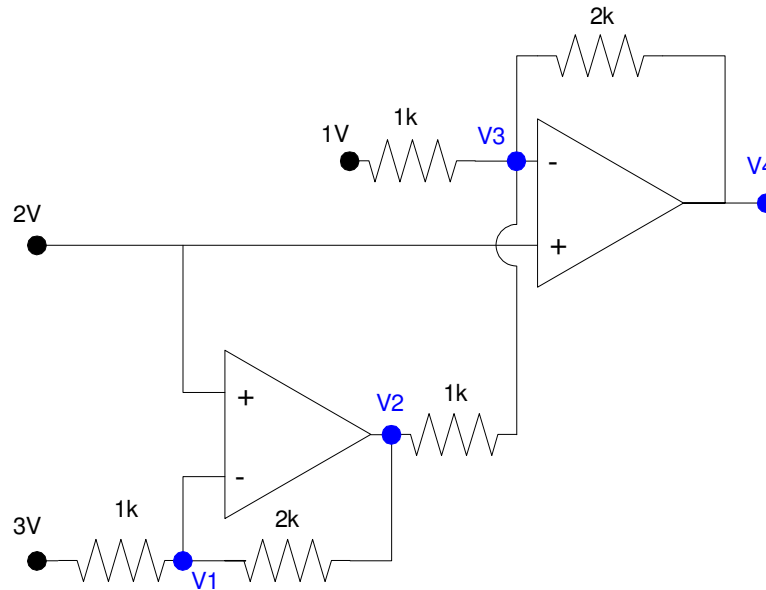
	V1	V2	V3	V4
ideal op-amp	4.0000	1.0000	3.0000	11.0000
CircuitLab	4.0000	1.0000	3.0000	11.0000

The ideal op-amp model is slightly off.

- The results are very close
- The circuit is a *lot* easier to analyze using ideal amp approximations

3) Write the voltage node equations for the following op-amp circuit. Assume ideal op-amps.

- Solve for V_1 , V_2 , V_3 , and V_4



Start with the easy ones ($V_p = V_m$)

$$V_1 = 2V$$

$$V_3 = 2V$$

Write the node equation at V_1

$$\left(\frac{V_1 - 3}{1k} \right) + \left(\frac{V_1 - V_2}{2k} \right) = 0$$

Node equation at V_3

$$\left(\frac{V_3 - 1}{1k} \right) + \left(\frac{V_3 - V_2}{1k} \right) + \left(\frac{V_3 - V_4}{2k} \right) = 0$$

That gives four equations for four unknowns. To solve, group the terms

$$V_1 = 2V$$

$$V_3 = 2V$$

$$\left(\frac{1}{1k} + \frac{1}{2k} \right) V_1 - \left(\frac{1}{2k} \right) V_2 = \left(\frac{3V}{1k} \right)$$

$$-\left(\frac{1}{1k} \right) V_2 + \left(\frac{1}{1k} + \frac{1}{1k} + \frac{1}{2k} \right) V_3 - \left(\frac{1}{2k} \right) V_4 = \left(\frac{1V}{1k} \right)$$

Place in matrix form

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \left(\frac{1}{1k} + \frac{1}{2k}\right) & \left(\frac{-1}{2k}\right) & 0 & 0 \\ 0 & \left(\frac{-1}{1k}\right) & \left(\frac{1}{1k} + \frac{1}{1k} + \frac{1}{2k}\right) & \left(\frac{-1}{2k}\right) \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} 2 \\ 2 \\ \left(\frac{3}{1k}\right) \\ \left(\frac{1}{1k}\right) \end{bmatrix}$$

Solve using Matlab

```
>> a1 = [1,0,0,0];
>> a2 = [0,0,1,0];
>> a3 = [1/1000+1/2000,-1/2000,0,0];
>> a4 = [0,-1/1000,1/1000+1/1000+1/2000,-1/2000];
>> A = [a1;a2;a3;a4]
```

```
1.0000      0      0      0
      0      0      1.0000      0
0.0015  -0.0005      0      0
      0  -0.0010      0.0025  -0.0005
```

```
>> B = [2;2;3/1000;1/1000]
```

```
2.0000
2.0000
0.0030
0.0010
```

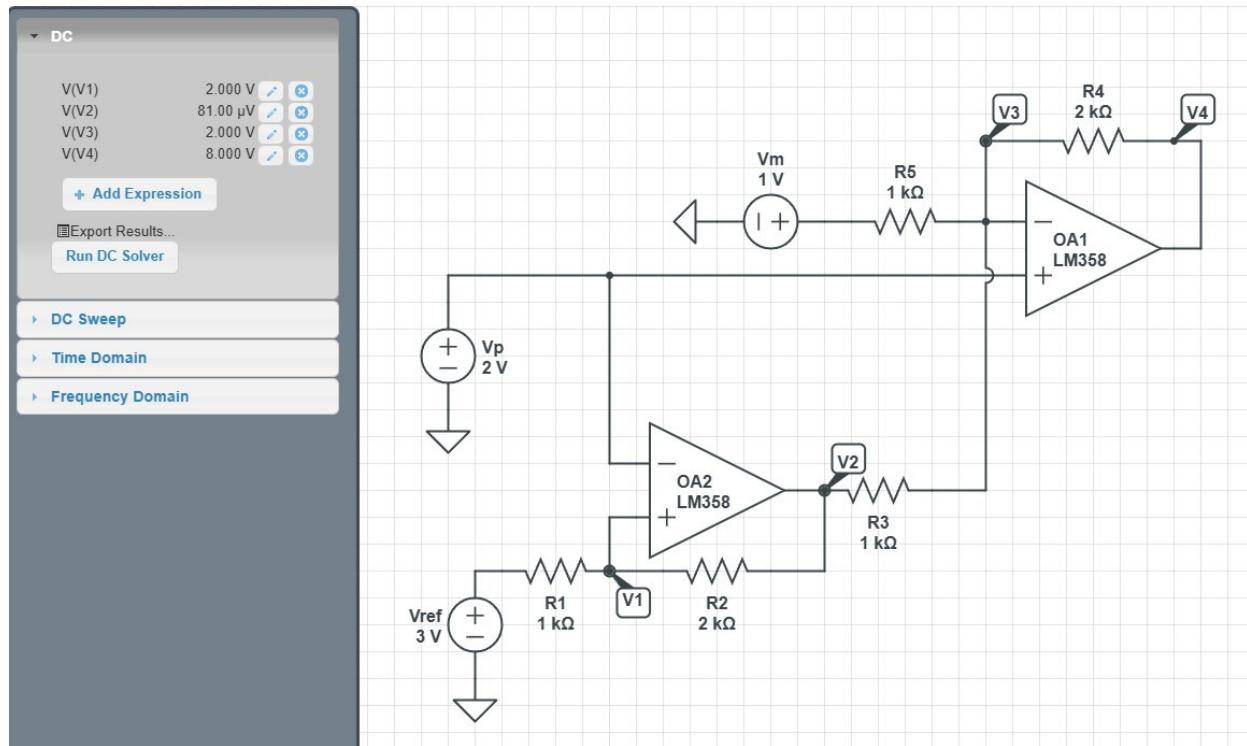
```
>> V = inv(A)*B
```

```
v1      2.000
v2      0.000
v3      2.000
v4      8.000
```

The voltages normally don't come out so nice...

4) Check your answers using CircuitLab

- Assume LM394 op-amp (doesn't really matter)



Note:

- CircuitLab uses a more complex model similar to homework #4
- The ideal op-amp model is slight off, but really close

	V1	V2	V3	V4
ideal op-amp	2.0000	0.0000	2.0000	8.0000
CircuitLab	2.0000	80uV	2.0000	8.0000

Amplifiers

5) Design an op-amp circuit to implement

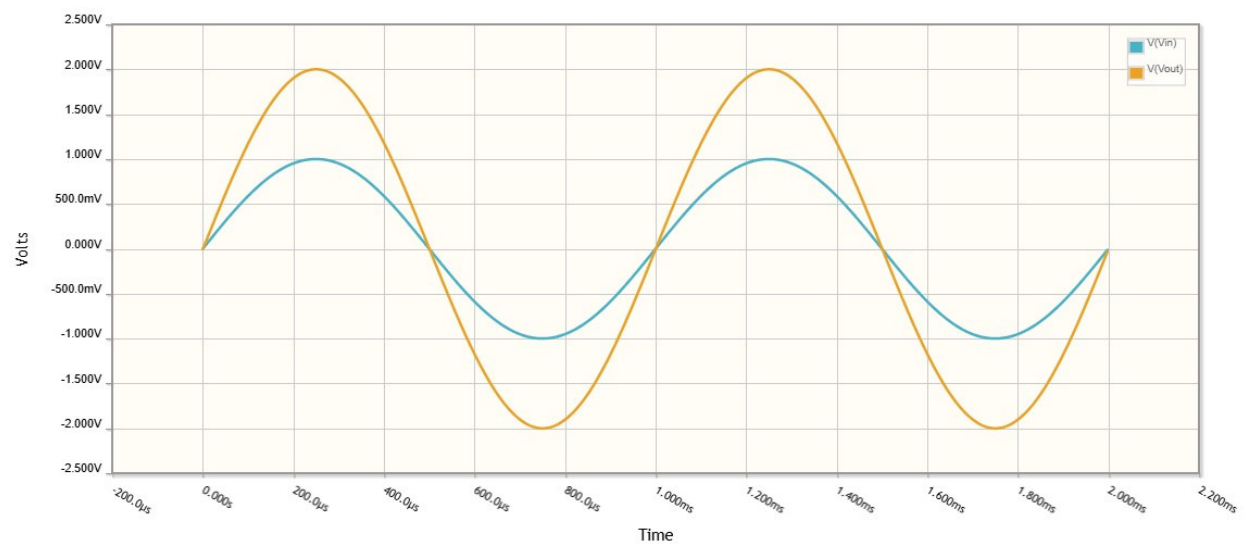
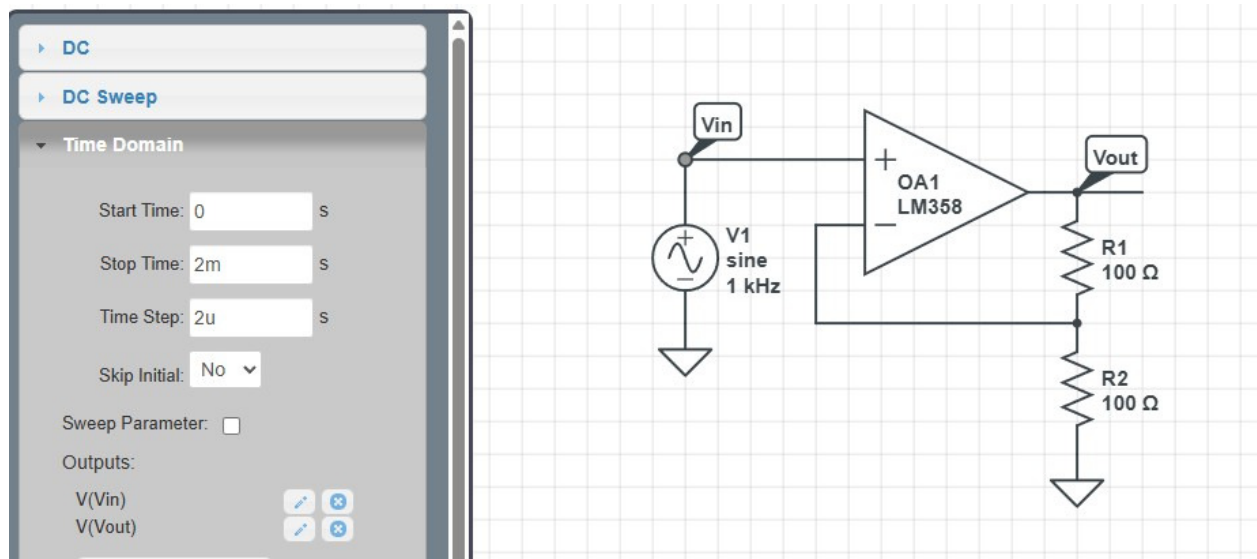
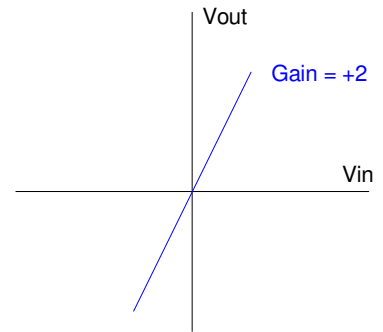
$$Y = 2X$$

Simulate this circuit in Circuitlab with

- $x(t) = 1V_p$, 1kHz sine wave

Note:

- Y (orange) = $+2 \cdot X$ (blue)



6) Design an op-amp circuit to implement

$$Y = -2X$$

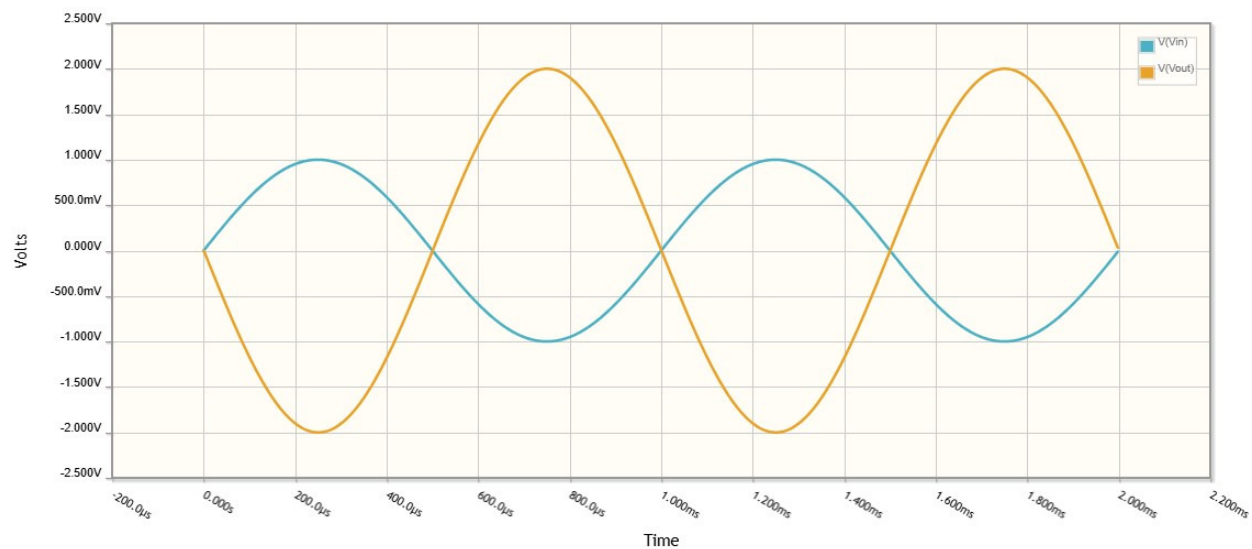
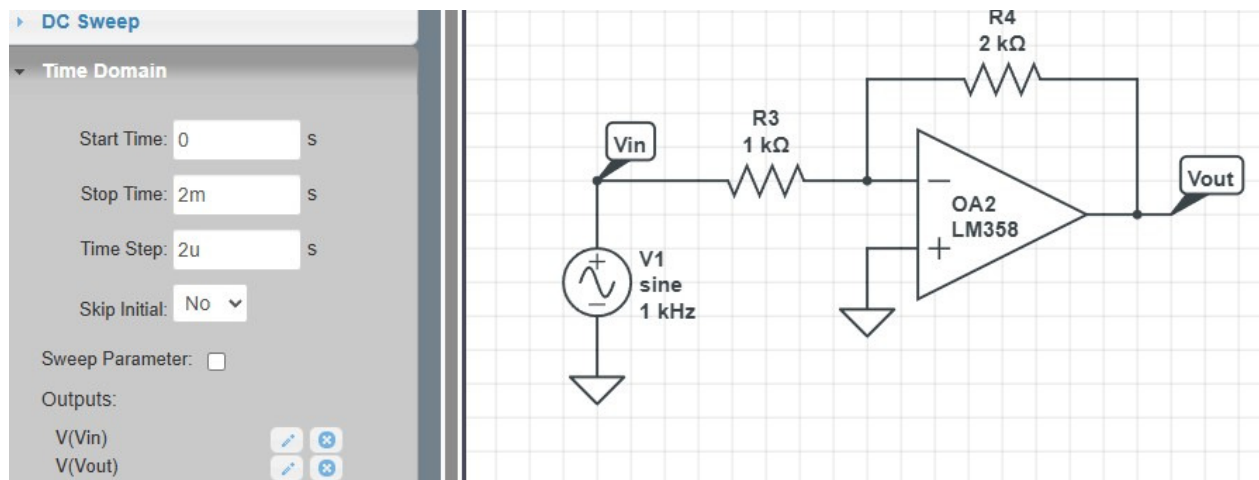
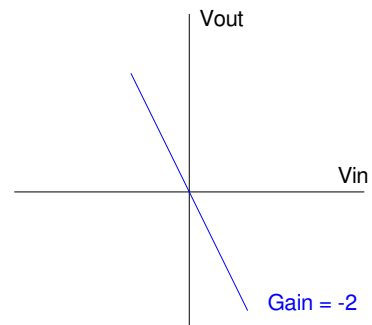
Simulate this circuit in Circuitlab with

- $x(t) = 1\text{Vp}$, 1kHz sine wave

Is Y two times X and 180 degrees out of phase?

note:

- V_{out} (orange) is 2x V_{in}
- 180 degrees out of phase



7) Design an op-amp circuit to implement

$$Y = 2X - 1$$

Simulate this circuit in Circuitlab with

- $x(t) = 1V_p$, 1kHz sine wave

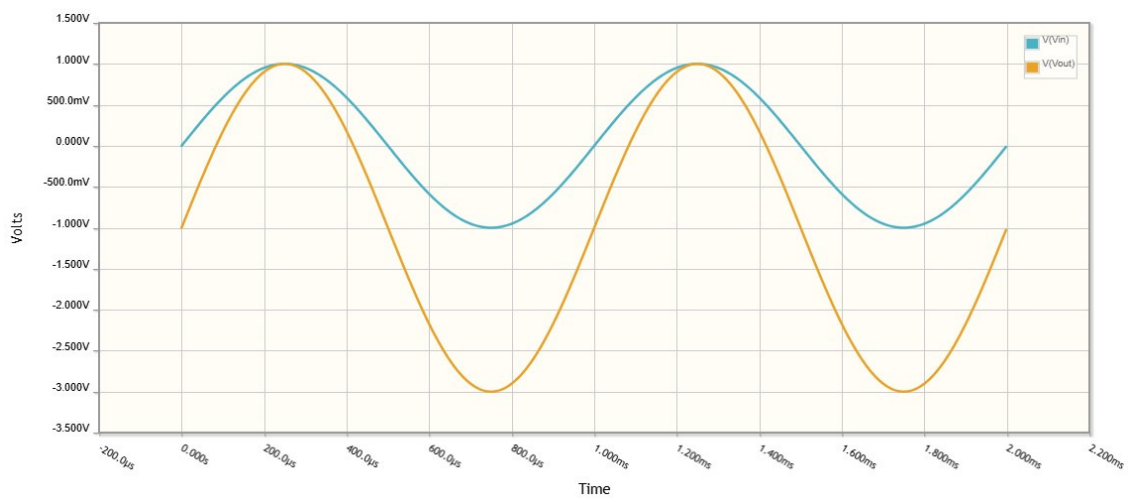
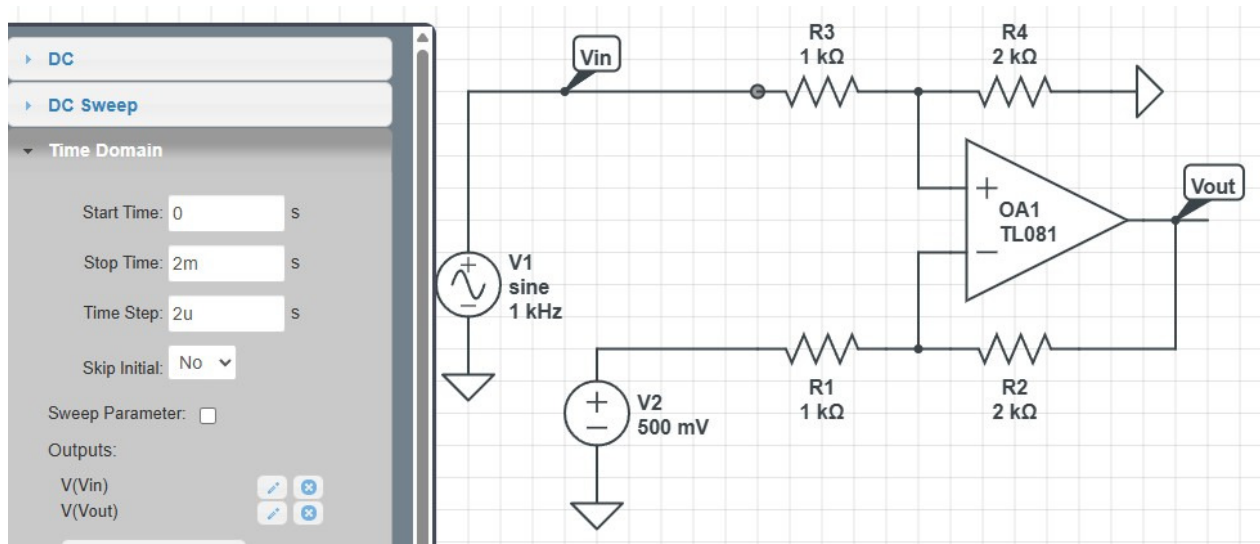
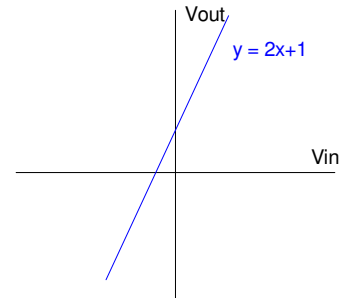
Is Y two times X, in-phase, and shifted down by 1V?

Rewrite as

$$y = 2\left(x - \frac{1}{2}\right)$$

note:

- $V_{out} = 2x V_{in}$
- Plus a 1V offset



Comparitors & Schmitt Triggers

8) Using your light sensor, measure the resistance

- When the lights in your room are turned on
- When the lights in your room are turned off

Results

- Light: 3.526k Ohms
- Dark: 143.92k Ohms



Design a voltage divider to convert this resistance to a voltage.

Pick something in the middle - like 30k. This should result in

$$V = \left(\frac{R}{R+30k} \right) 5V$$

Calculated Values

- Light: 0.5259V
- Dark: 4.1375V

Measured Values:

- Power: 5.005V
- Light: 0.464V
- Dark: 3.594V

9) (Comparator) Pick a voltage between V(light) and V(dark).

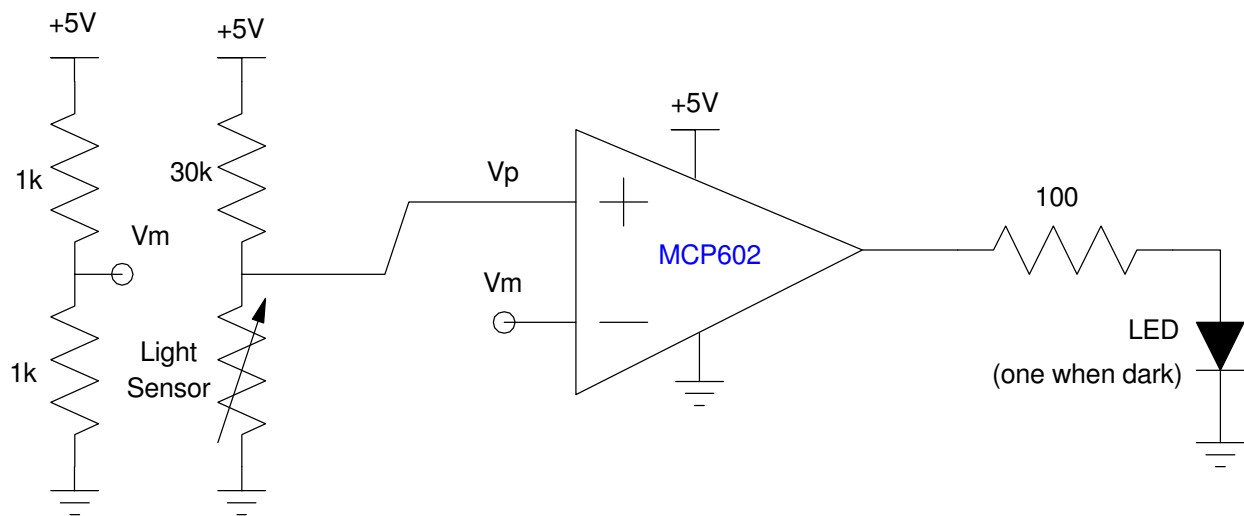
- 2.50V works pretty well

Design a circuit which turns on and off at this voltage:

- 0V when the lights are turned on, and
- 5V when the lights are turned off

Use a comparator circuit with

- Sensor going to V_p (on when dark)
- 2.5V going to V_m (threshold in between 0.464V and 3.594V)



10) (Schmitt Trigger) Pick two different voltages between V(light) and V(dark). Design a circuit which outputs

- 0V when voltage goes below V(off) and
- 5V when the voltage goes above V(on)

Let

- V(on) = 2.00V
- V(off) = 1.50V

Connect the sensor to Vp

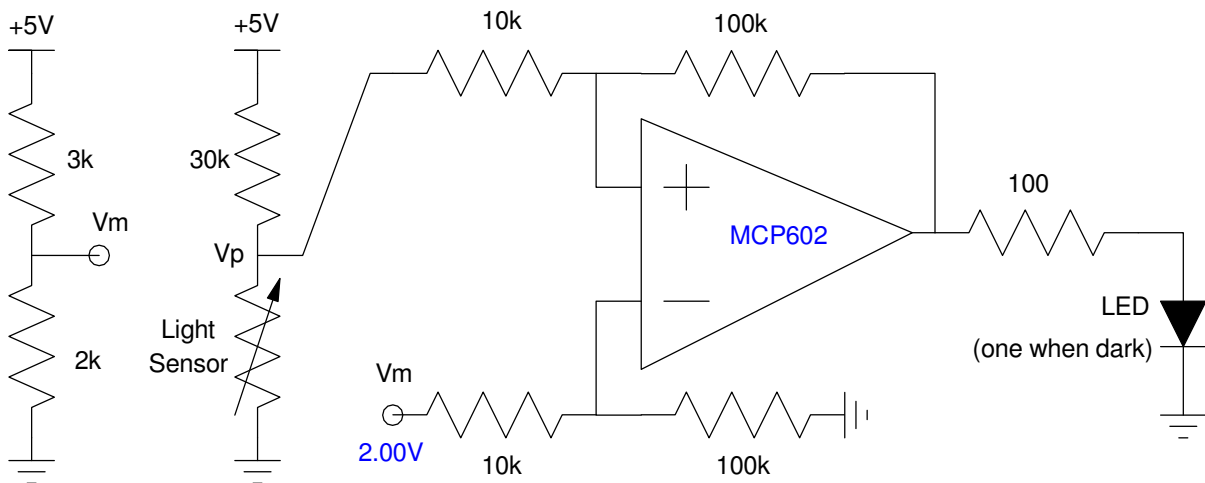
- V(on) > V(off)

Set Vm = 2.00V

- Use a voltage divider

Set the gain to 10

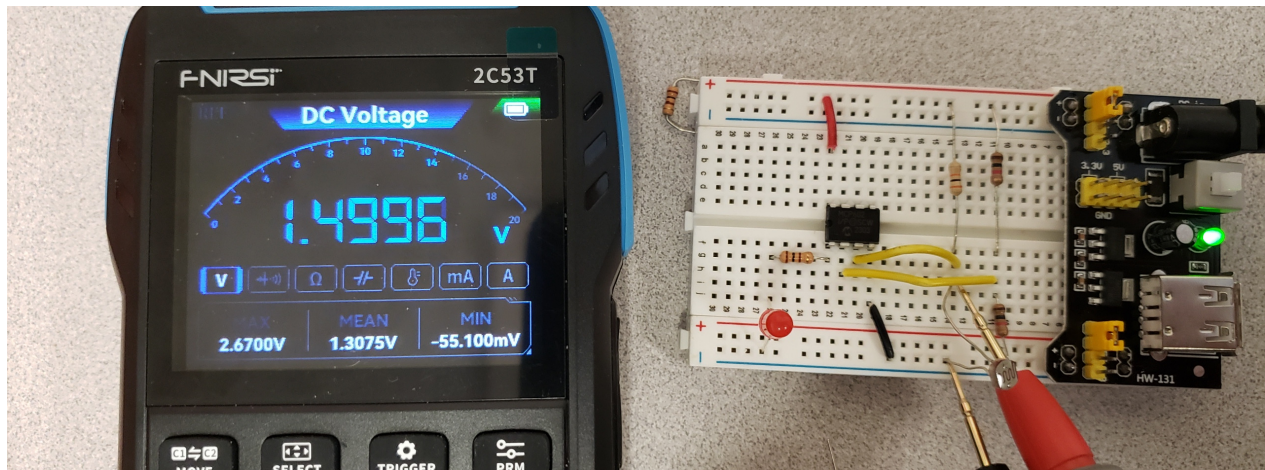
$$gain = \left(\frac{\text{change in output}}{\text{change in input}} \right) = \left(\frac{5V - 0V}{2.00V - 1.50V} \right) = 10$$



Lab

11) Build the comparitor on your breadboard

- Include a photo of your finished breadboard circuit



12) Collect measurements to verify the operation of your circuit

Measure V(on)

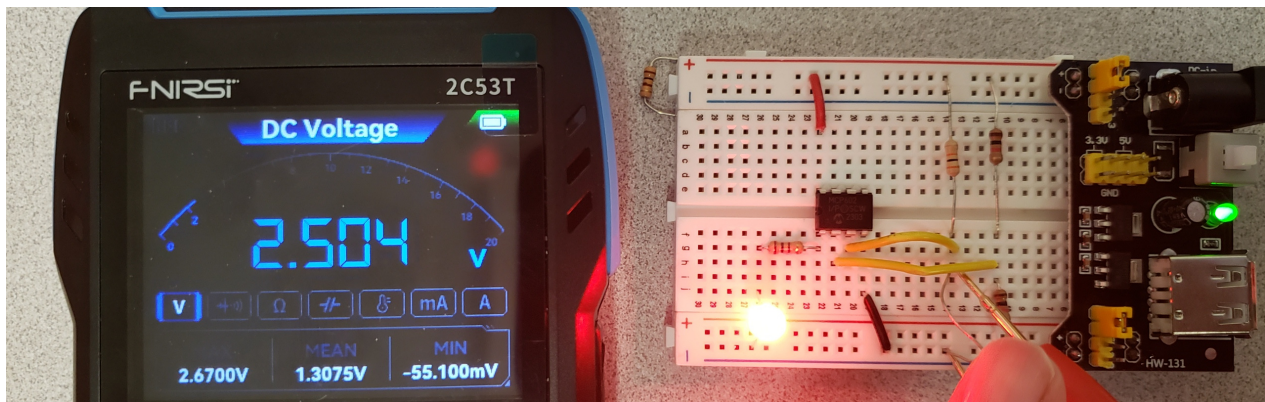
- Turns on at 2.504V

Measure V(off)

- Turns off at 2.498V

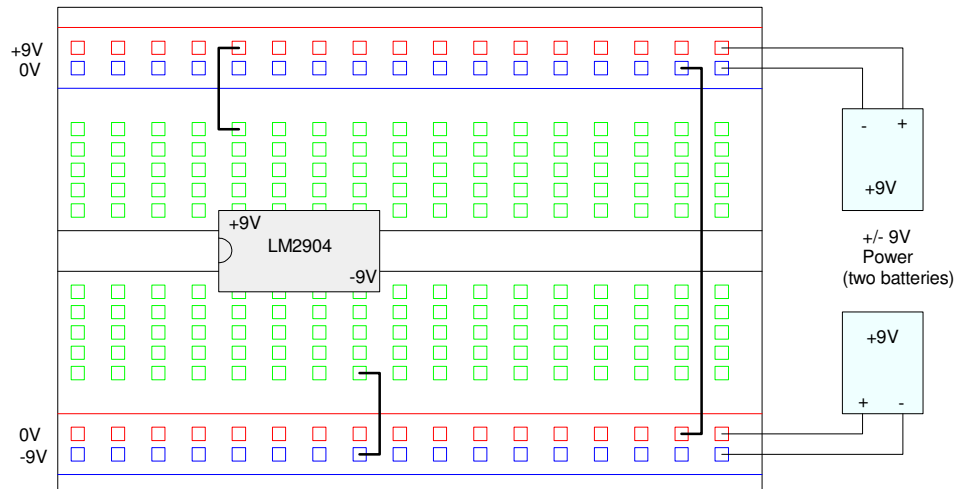
Measure the current to the diode when on

- 1.5028V across the 100 Ohm resistor
- $I_d = 15.028\text{mA}$



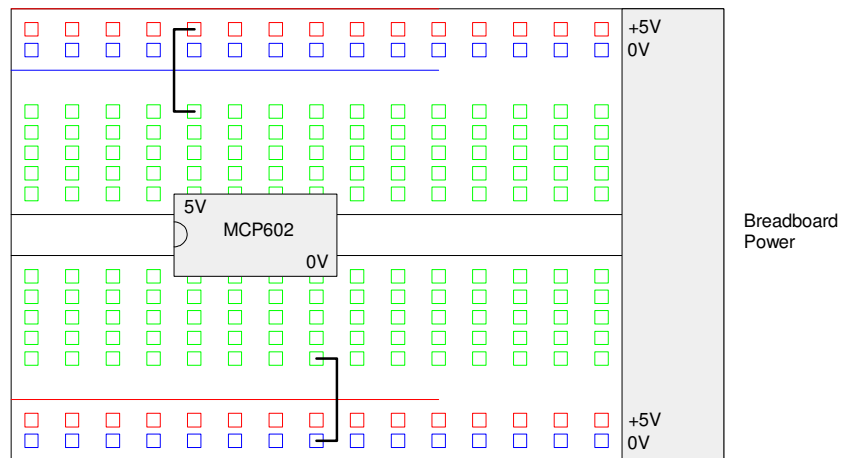
12) Collect measurements to verify the operation of your circuit

note: If building an amplifier, use an LM2904 o-amp (or equivalent) with two 9V batteries



Breadboard power for an amplifier circuit ($y = 2x$, $y = -2x$, $y = 2x - 1$)

If building digital logic, use an MCP602 op-amp with a 5V powered breadboard



Breadboard & power for a digital circuit (comparator & Schmitt trigger)