CircuitLab & Op-Amps

Circuits Review

One of the requirements for your 401 project is it must include an integrated circuit (IC). Usually, this is an op-amp, a 555 timer, or a Raspberry Pi-Pico processor.

CircuitLab

CircuitLab is a circuit simulator, which is very similar to SPICE or PSPICE, and has a graphical front end. The graphical front end makes CircuitLab very easy to use.

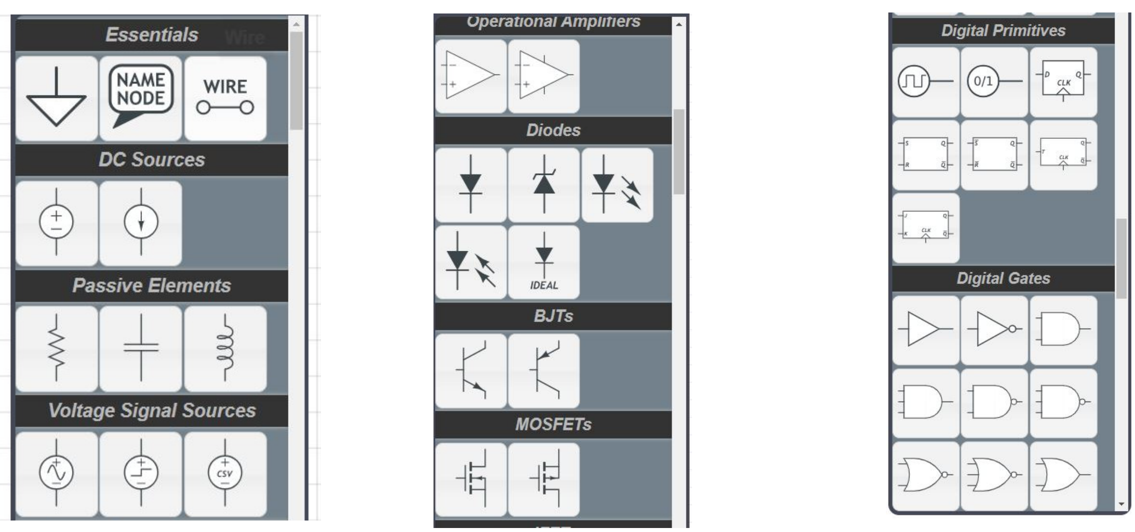
What CircuitLab does is it lets you check your design using a nonlinear circuit simulator. Typically, hand calculations make some approximations, such as diodes are ideal, op-amps are ideal, loading is insignificant, etc. With CircuitLab, you can test your design with a more accurate, more complex model. If you need to tweak your design slightly, it's really easy in CircuitLab.

Once you finalize your circuits, you can then build them on a breadboard to see if they really work in practice.

CircuitLab is capable of simulating

- Linear Circuits (Circuits II and II)
- Nonlinear Circuits (Electronics)
- Digital Circuits (Digital Systems)
- Dynamic Systems (Controls Systems)

Likewise, it's useful for many courses in ECE, including Senior Design.



CircuitLab has components useful for linear circuits (left), nonlinear circuits (center), and digital circuits (right)

Signing Up for CircuitLab

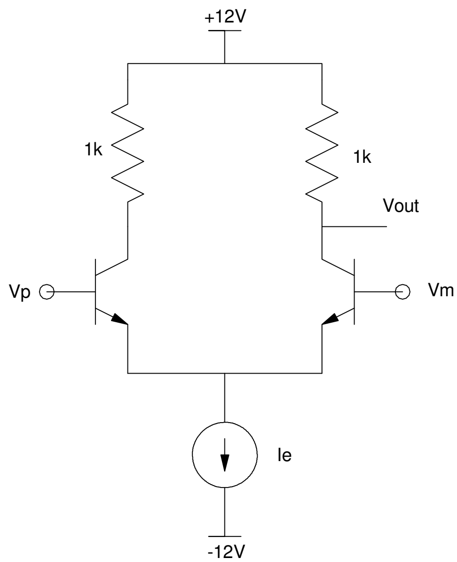
There are several ways you can use CircuitLab:

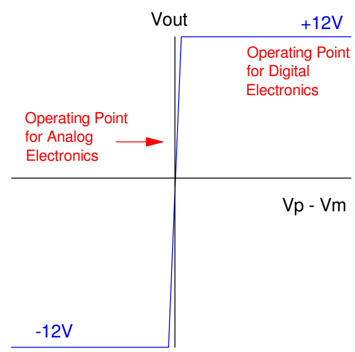
- Trial Version: If you don't register or sign in, you're using the trial version. This limits you to 1/2 hour per session and you cannot save your work.
- Free Version: Register with CircuitLab using your NDSU email address (@ndsu.edu). The ECE department pays for a site license - so all NDSU students can use CircuitLab for free. There is no time limit and you can save your work.
- Personal Version: Sign up with your personal email account at a cost of $24/year. Again, there is no time limit and you can save your work. Plus, you still have your work after you graduate.

Operational Amplifiers

Op-Amps (General Background)

Operational Amplifiers (Op-Amps) are high gain differential amplifiers. The heart of an op-amp is a pair of transistors implementing emitter-coupled logic:





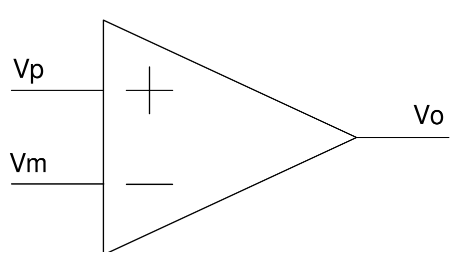
Op-Amps can be operated in one of two ways:

- Digital Outputs: The output is binary: either at the + power supply or the minus power supply
- Analog Outputs: The output is an analog voltage in-between the plus and minus power supplies

When operating in the high-gain region, an op-amp can be modeled as a 2-input device with

$$V_o \approx k(V^+ - V^-)$$

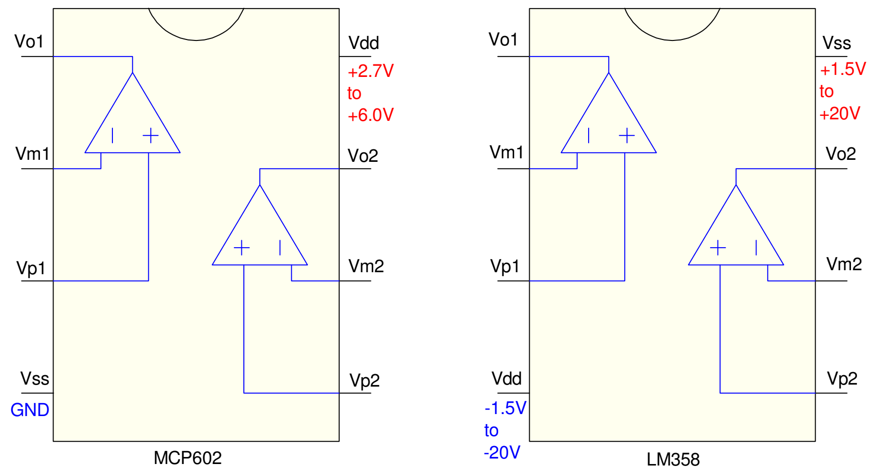
where k is a large number. For short, the following symbol is used for an differential amplifier:



Symbol for an operational amplifier (op-amp)

Operational Amplifier Characteristics

Op-Amps usually come with two op-amps in an 8-pin package:



Pin Layout for two common op-amps: MCP602 and LM358

If you look up the data sheets for these, you get something like the following:

	MCP602	LM2904 / LM358	Ideal
Input Resistance	1e13 Ohms	4G Ohm	infinite
Current Out (max)	25mA	40mA	infinite
Operating Voltage	2.7V - 6V	+/- 1.5V .. +/- 20V	any
Differential Mode Gain	500,000	140,000	infinite
Common Mode Gain	0.00003	0.00002	0
Slew Rate	2.3V/us	0.3V/us	infinite
Gain Bandwidth Product	2.8MHz	1.2MHz	infinite
Operating Range	-40C to +85C	-40C to +85C	infinite
Price (qty 100)	$0.61	$0.12	-

The main two things you care about are:

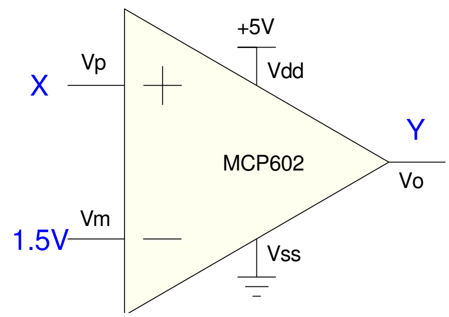
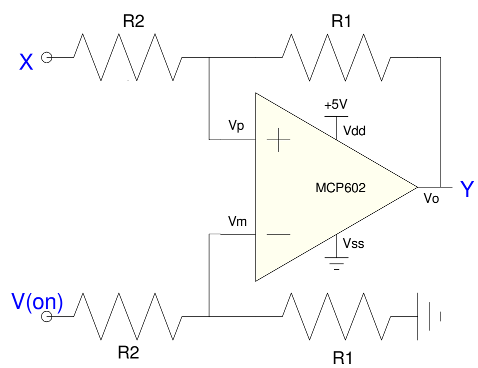
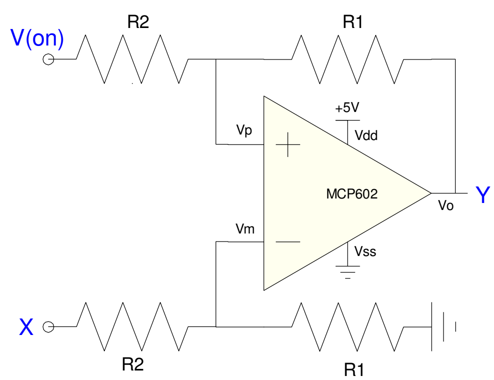
- Current Output (MCP602): How much current the op-amp can source or sink. 25mA means you can't drive an 8 Ohm speaker directly with these op-amps.
- Differential Mode Gain: This isn't infinity - meaning that if the output is between the power supply limits, there is a *small* difference in voltage between Vp and Vm. If you don't care about a micro-volt, the gain is essentially infinity.
- Gain-Bandwidth Product (MCP602): This op-amp can have
  - A gain of one out to 2.8MHz
  - A gain of ten out to 280kHz
  - A gain of 100 out to 28kHz
- Operating Voltage:
  - Use an MCP602 when operating at 0V/5V (usually digital circuits)
  - Use an LM358 when operating at +/- 9V (usually analog circuits)

Op-Amp Circuits with Digital Outputs

Op-Amp circuits are kind of like legos: there are a bunch of different circuits you can plug into your circuit for different functions. For these circuits, the power supply is important

- Vdd determines logic level 1
- Vss determines logic level 0

Some of the common circuits with digital outputs are:

Name	Description	Circuit
Comparitor - Level Shifter (convert 0V/3.3V logic to 0V/5V logic)	Y = (X > 1.5) 5V = true 0V = false	
Schmitt Trigger Von > Voff	Set: X > Von Clear: X < Voff	
Schmitt Trigger Von < Voff	Set: X < Von Clear: X > Voff	

Example 1: Night Light (Comparitor)

Design a circuit so that a Pi-Pico can determine when a room is dark. Assume you have a light sensor with

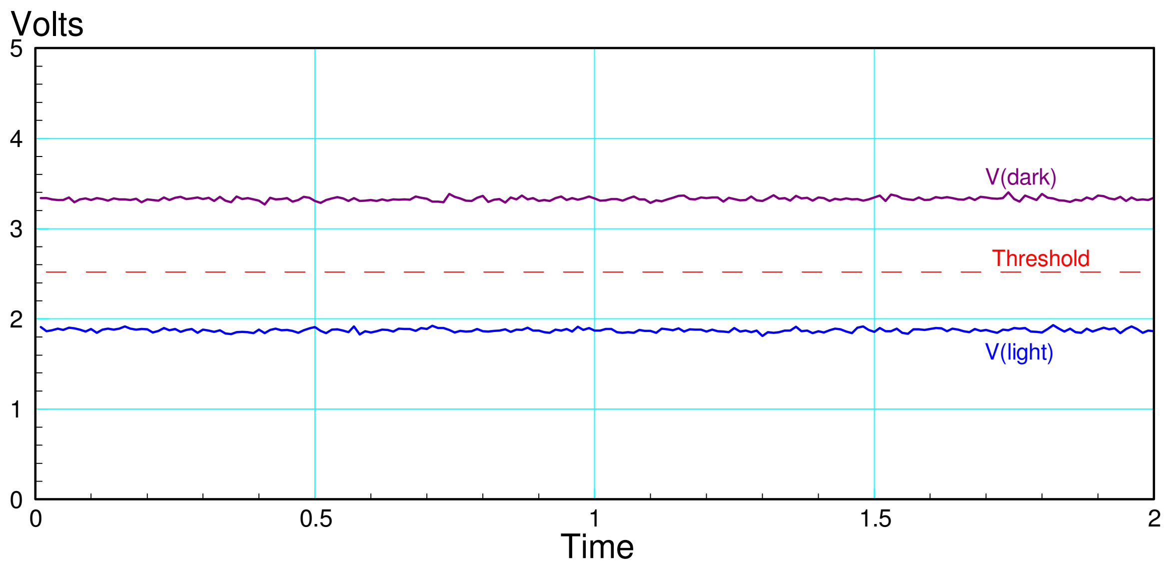
- R = 3k Ohms (room lights on)
- R = 10k Ohms (room is dark)

Solution: Convert resistance to voltage using a voltage divider. Assume a 5k resistor.

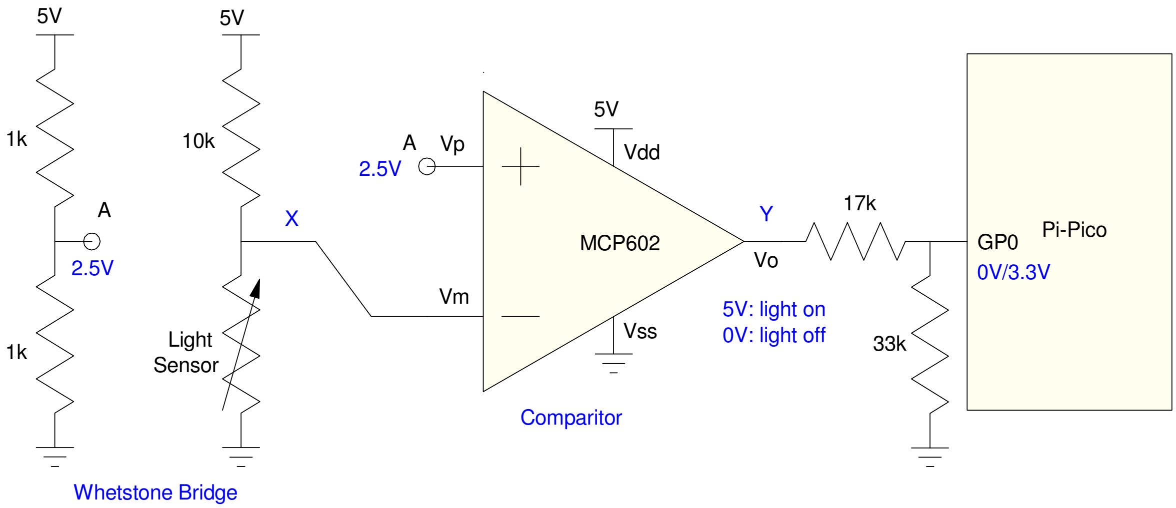
$$V_{on} = \left(\frac{3k}{3k+5k}\right)5V = 1.875V$$

$$V_{off} = \left(\frac{10k}{10k+5k}\right)5V = 3.33V$$

Pick a voltage in-between, such as 2.50V



A circuit which will allow a Pi-Pico to detect if a room is light or dark is as follows. Note that the output needs to be dropped from 5V to 3.3V (logic level 1 for a Pi-Pico). You could also do this by changing the power supply to the Op-Amp to 3.3V.

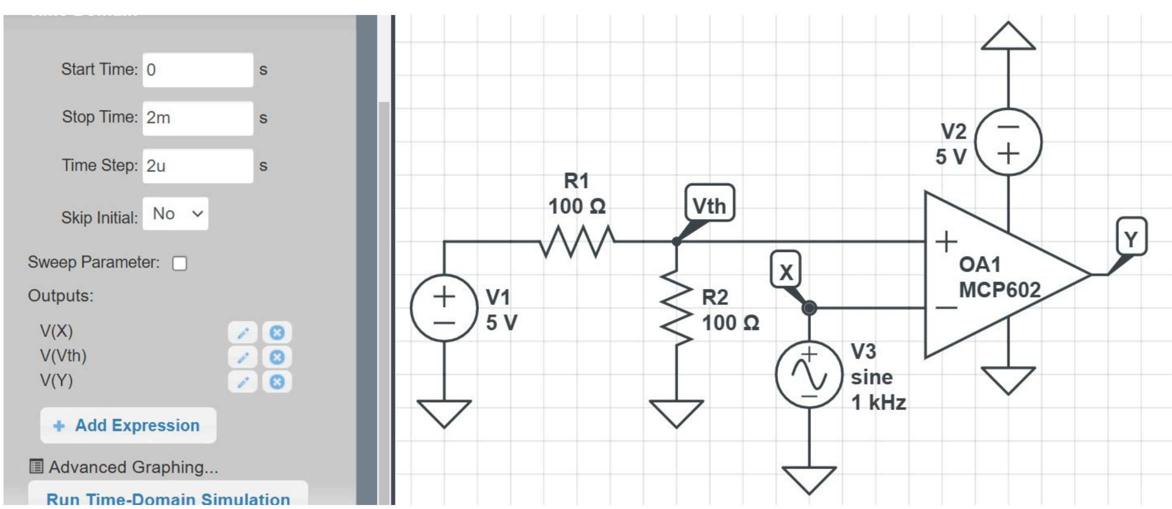


Comparitor Circuit for a Night Light

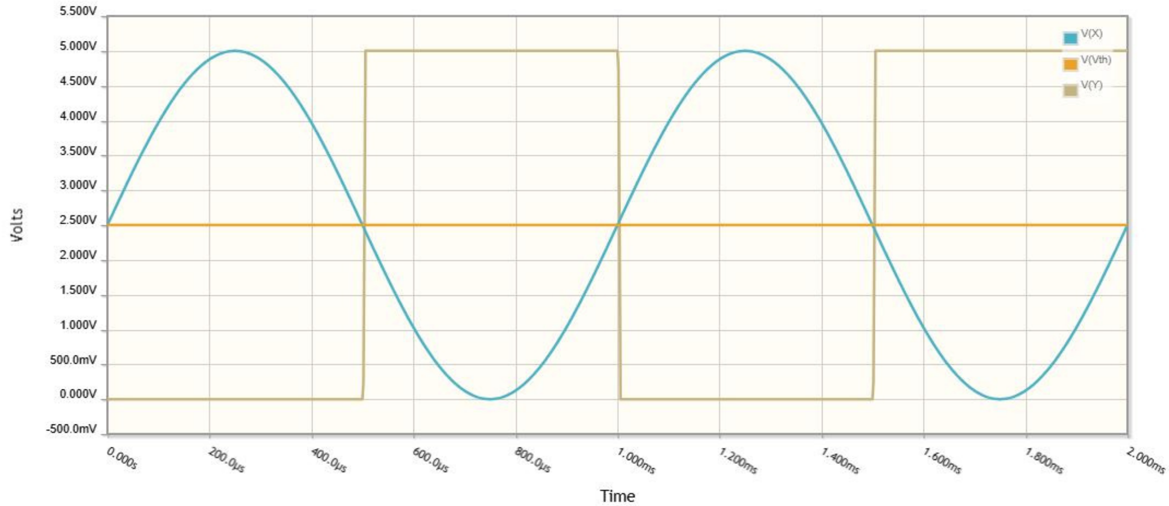
CircuitLab: There are several ways to check your design in CircuitLab

- You could plug in different resistors for the light sensor and verify that
  - At 3k Ohms (light), the output is 3.3V
  - At 10k Ohms (dark), the output is 0V
- You could apply a sine wave at X and verify that
  - The op-amp turns on (5V) when Vx < 2.5V
  - The op-amp turns off (0V) when Vx > 2.5V

Using the latter, the CircuitLab schematic is:



A time-domain simulation shows the on-off voltage



Note that

- The on voltage is 2.50V,
- The off voltage is 2.50V, and
- The output is on (5V) when the input is less than 2.5V

The circuit is working as expected.

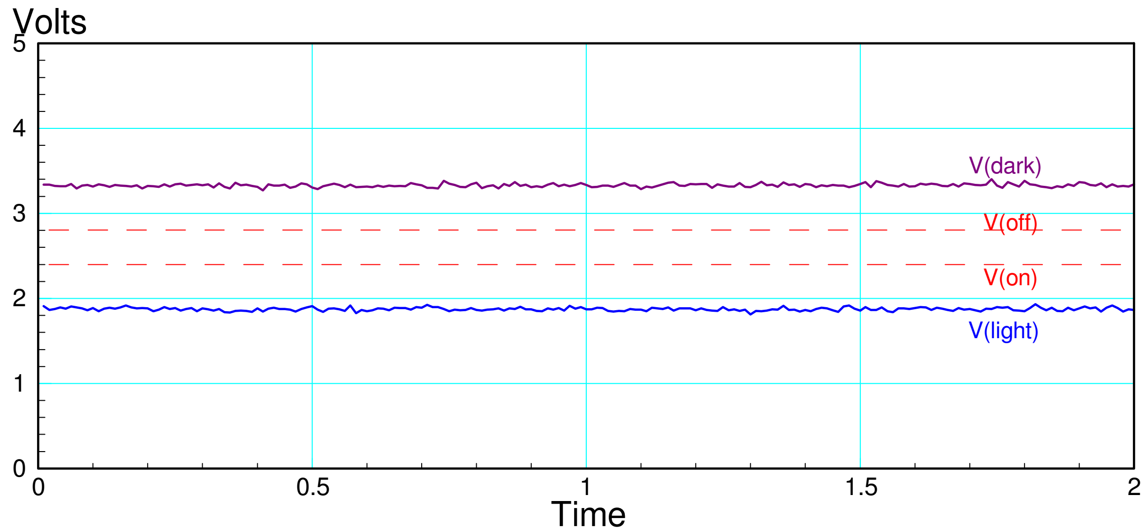
Example 2: Night Light (Schmitt Trigger)

In the previous example, the on voltage (2.5V) is equal to the off voltage (2.5V). This can create chatter or multiple counts when the voltage at Vm hovers around 2.5V.

To prevent this, a Schmitt Trigger can be used. With a Schmitt trigger, the on and off voltages differ, creating hysteresis. This helps to avoid chatter and multiple counts on 1/0 or 0/1 transitions.

Let the on-off voltages be

- V(on) = 2.4V
- V(off) = 2.8V



In this case,

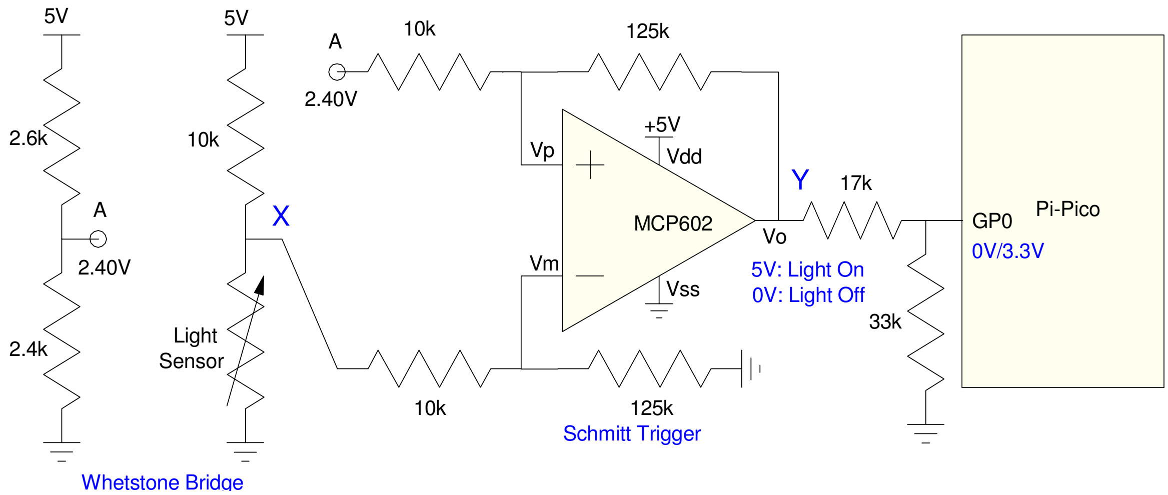
- Since V(on) < V(off), choose the Schmitt trigger circuit with the input going to the minus input.
- Set the plus input equal to V(on) (2.4V).

Make the gain equal to

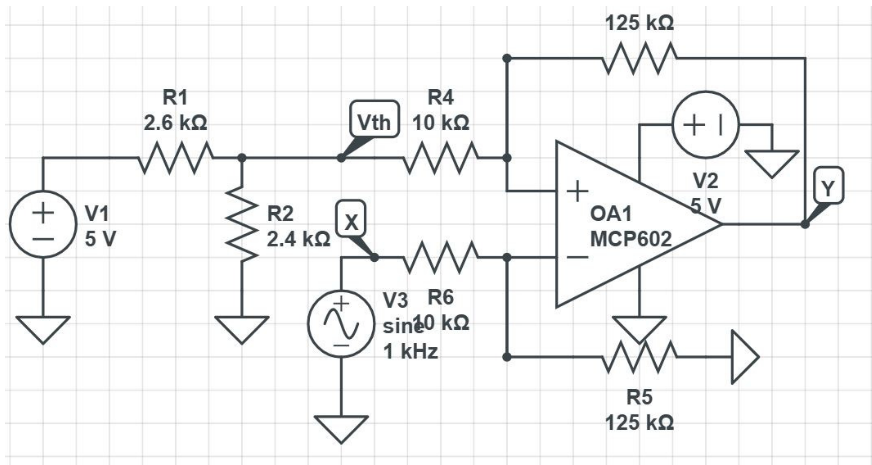
$$gain = \left(\frac{\text{change in output}}{\text{change in input}}\right)$$

$$gain = \left(\frac{5V - 0V}{2.8V - 2.4V}\right) = 12.5$$

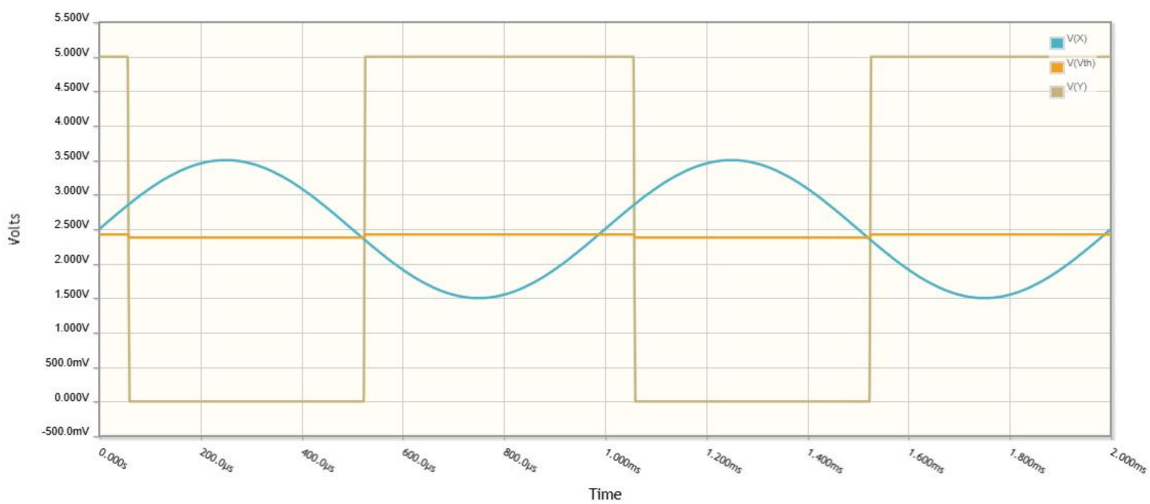
Set the resistor ratio to 12.5 : 1



Checking this design in CircuitLab is a little trickier due to the hysteresis. Using a sine-wave input lets you check the on and off voltages



Running a time-domain simulation lets you see where the output turns on and off



Note that

- V(on) = 2.40V as expected. When Vx (blue line) drops below 2.40V, the output turns on.
- V(off) = 2.80V as expected. When Vx goes above 2.80V, the output turns off

The circuit is working as expected.

Op-Amp Circuits with Analog Outputs (Amplifiers)

When you want an analog output, dozens of op-amp circuits are available to plug into your design. These circuits tend to use +/- power supplies and an LM2904 or LM358 op-amp.

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<tr><th>Name</th><th>Description</th><th>Circuit</th></tr>
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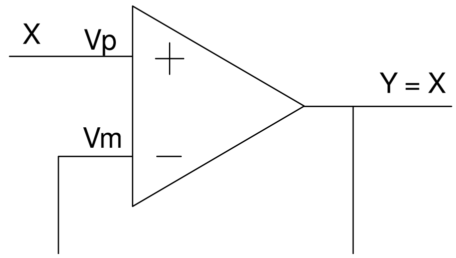

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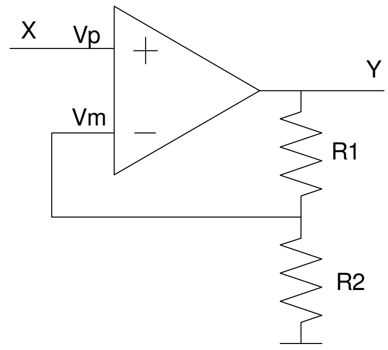
<tr><td>Non-Inverting Amplifier</td><td></td><td>


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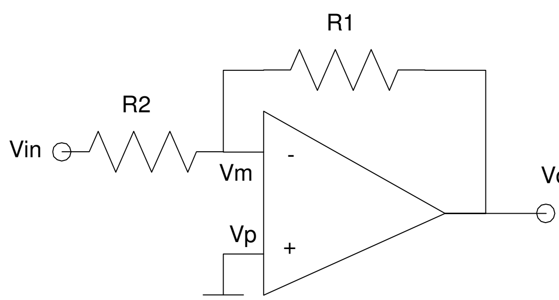
<tr><td>Inverting Amplifier</td><td></td><td>


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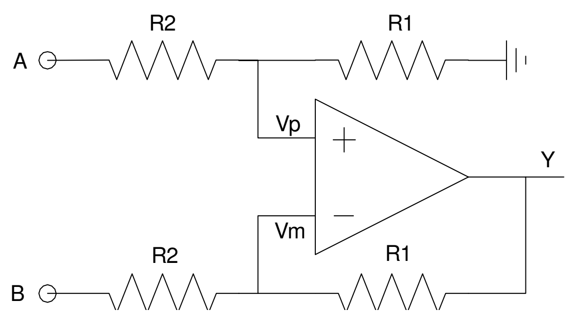

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Voltage Node Equations for Op-Amp Amplifiers:

Voltage nodes tends to work best when trying to write the equations for op-amp amplifiers. There is one trick when writing these equations, however. The node equation at the output of the op-amp is

Vp = Vm

This comes from operating in the linear region where

$$V_0 = k(V_p - V_m)$$

and k is the op-amp's gain (140,000 in the case of a LM298 op-amp.) Assuming Vo is finite

$$V_p - V_m = \left(\frac{V_o}{k}\right)$$

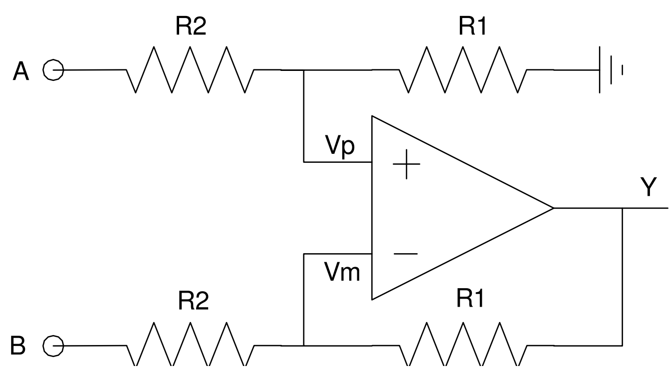
As k goes to infinity (ideal op-amp assumption)

$$V_p - V_m \to 0$$

or

$$V_p \approx V_m$$

For example, write the voltage node equations for the following op-amp circuit:



Instrumentation Amplfier: Write the voltage node equations

This circuit has three unknown voltages (Vp, Vm, and Y). This means you need to write three equations to solve for three unknowns. At nodes Vp and Vm, you can write the voltage equations

Vp: $\left(\frac{V_p - A}{R_1}\right) + \left(\frac{V_p}{R_2}\right) = 0$

Vm: $\left(\frac{V_m - B}{R_1}\right) + \left(\frac{V_m - Y}{R_2}\right) = 0$

The third equation is

$$V_p = V_m$$

With a little algebra, this simplifies to

$$Y = \left(\frac{R_2}{R_1}\right)(A - B)$$

note: As much as you'd like to write the voltage node equation at Y, you can't. The current from the op-amp can be anything - making it impossible to write the voltage node equation at Y. Instead, the third equation is simply Vp = Vm.

Example 1: Current Sensor

Problem: Measure the current going to a circuit. Assume

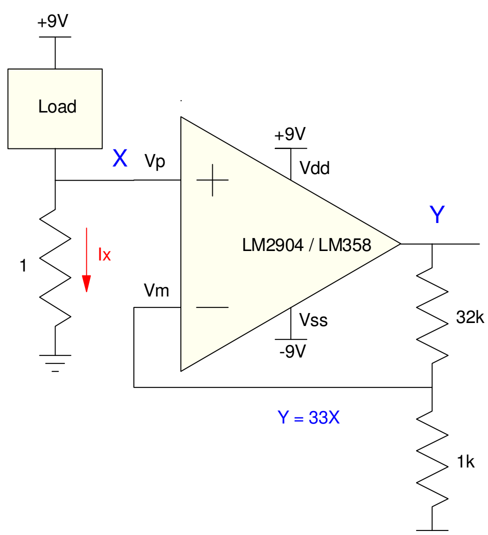
- The current is in the range of 0 - 100mA
- The output should be in the range of 0-3.3V (analog input to a Pi-Pico)

Solution: Convert current to voltage using a 1 Ohm resistor. This does change your circuit (it adds one ohm in series with your circuit). If that's a problem you could use a 0.1 Ohm resistor.

With a 1 Ohm resistor, the voltage range at X is 0 - 100mV. To get this to 3.3V, add a non-inverting amplifier with a gain of 33.

Note that since the voltage never goes negative, you could use

- An LM2904 or LM353 op-amp with +/- 9V power supplies, or
- An MCP602 with 0V / 5V power supplies.

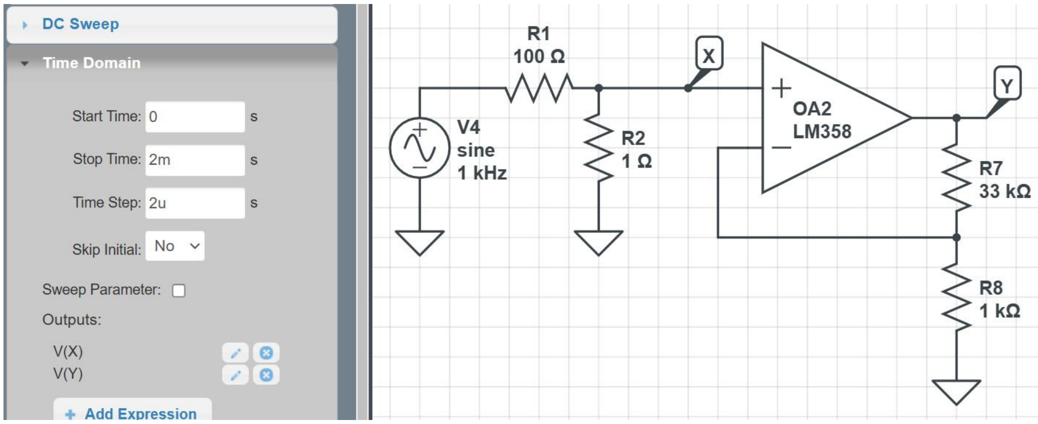


Current Measurement Circuit with a Non-Inverting Amplifier. 100mA = 3.3V out

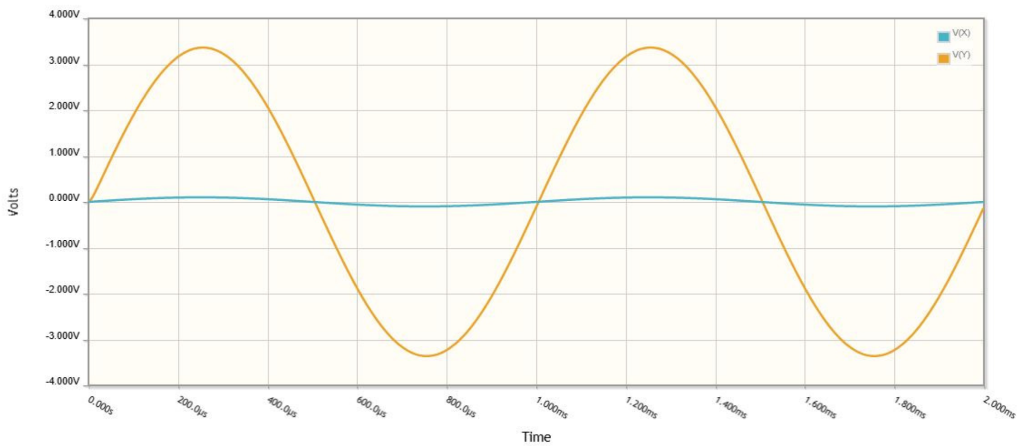
To check this in CircuitLab, you want to see that

- Y is proportional to X (as X goes up and down, Y goes up and down as well), and
- 100mA produces 3.3V at the output.

To do this in CircuitLab, make the source a 10Vp sine wave going through a 100 Ohm resistor (giving +/- 100mA of current). The voltage at Y should then go from -3.3V to +3.3V



CircuitLab schematic of a current sensor circuit



CircuitLab Time Domain Simulation: Y (orange) is a sine wave, telling you the amplifier is working

As expected,

- When the input is a sine wave, the output is a sine wave (this is an amplifier)
- The output is 3.3V when the current is 100mA (10V across 100 Ohms).

The 1 Ohm resistor does affect the circuit a little (it's actually 101 Ohms total).

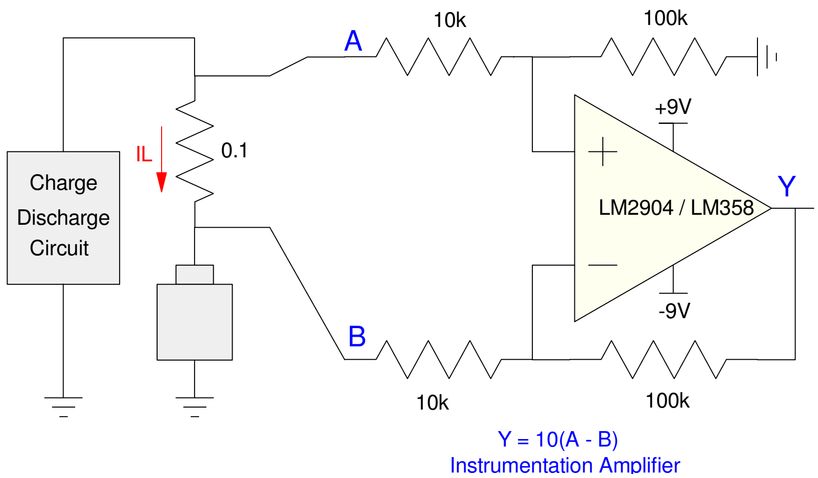
Example: Current Sensor (take 2)

Measure the current going to a lithium battery. Assume

- The current can be in the range of -2A to +2A.
- The output voltage should be -2V to +2V

Solution: Again, use a current sensing resistor. To keep the losses down, use a 0.1 Ohm resistor.

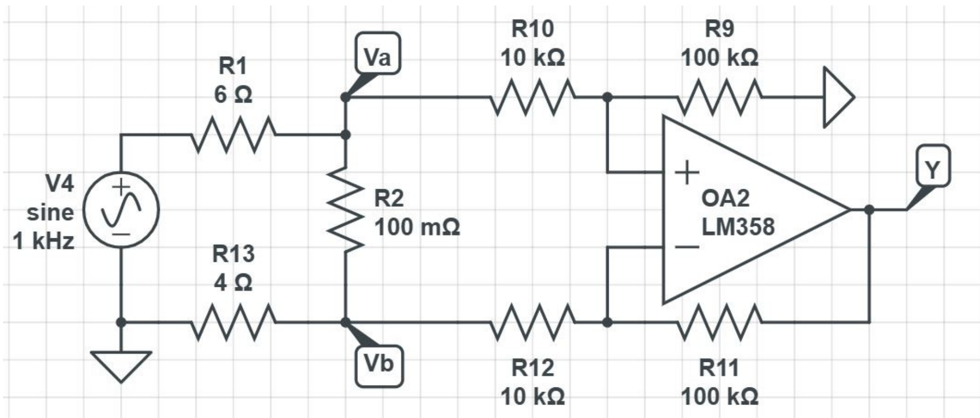
Use an instrumentation amplifier to cancel out the offset due to the lithium battery's voltage. Set the gain of the amplifier to 10



Circuit to measure current (take 2). 1 Amp produces 1V output

In CircuitLab, simulate this by

- Using a 10Vp sine wave going across 10 Ohms
- Split the 10 Ohms as 6 and 4 Ohms to illustrate that the DC offset at the 0.1 Ohm current sensing resistor doesn't matter

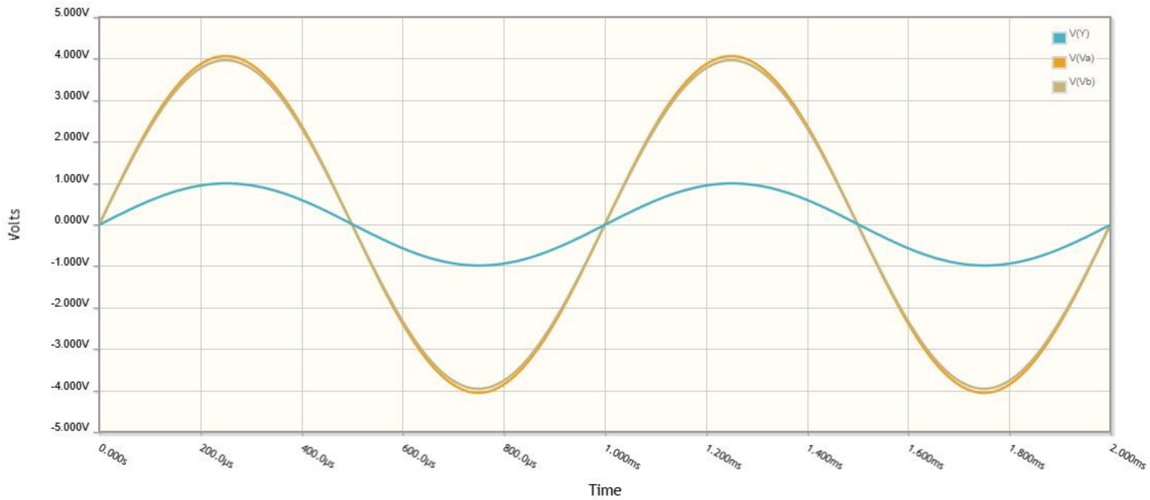


CircuitLab schematic to test the design. V4 is a 10Vp sine wave (max current is 1A)
R1 and R13 add a DC offset to Va and Vb

Running a time-domain simulation shows

- Va and Vb have a large offset,
- Vy is a clean sine wave (it's an analog output),
- Vy only shows the difference between Va and Vb, and
- The peak at Vy = 1V as expected (1A = 1V).

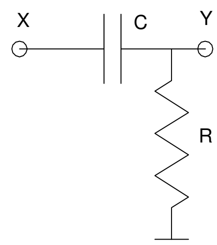
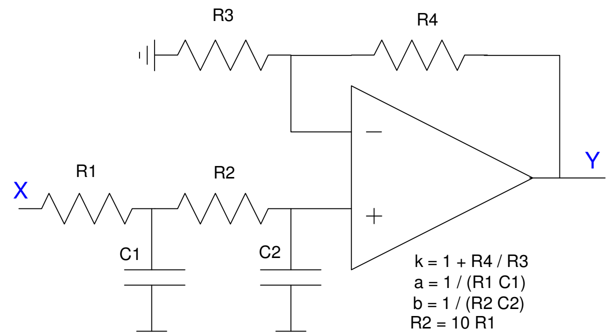
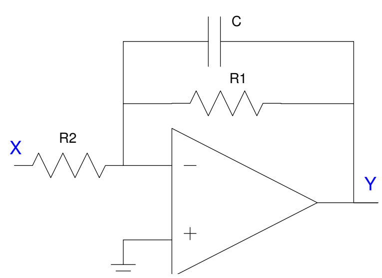
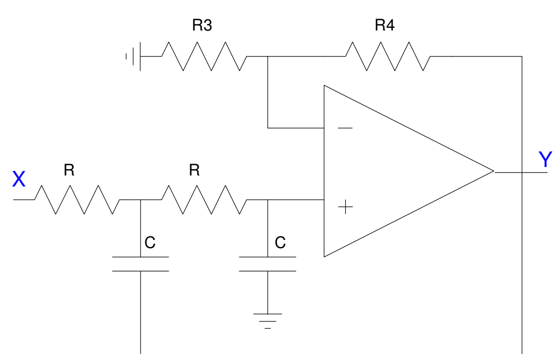
The circuit seems to work



CircuitLab time domain simulation. The output (blue) is a sine wave with a peak at 1V (for 1A)

Analog Filters

Finally, op-amps can be used to build various types of filters. The circuit used depends upon whether the poles are real or complex. There are other circuits with zeros as well (not included here).

Filter	G(s)	Circuit
DC Block	$\left(\frac{as}{s+a}\right)$ $a = \frac{1}{RC}$	
Real Poles No Zeros DC gain > 1	$\left(\frac{kab}{(s+a)(s+b)}\right)$ $a = \frac{1}{R_1C_1}$ $b = \frac{1}{R_2C_2}$ $R_2 = 10R_1$ $k = 1 + \frac{R_4}{R_3}$	
Single Real Pole No Zeros	$\left(\frac{-a}{s+b}\right)$ $b = \frac{1}{R_1C}$ $\frac{a}{b} = \frac{R_1}{R_2}$	
Complex Poles No Zeros	$\left(\frac{ka^2}{(s+a\angle\theta)(s+a\angle-\theta)}\right)$ $a = \frac{1}{RC}$ $k = 1 + \frac{R_4}{R_3}$ $3 - k = 2\cos\theta$	

Example: Design a circuit to implement

$$Y = \left(\frac{50}{(s+2)(s+3)}\right) X$$

Solution: Use a circuit with real poles. Let

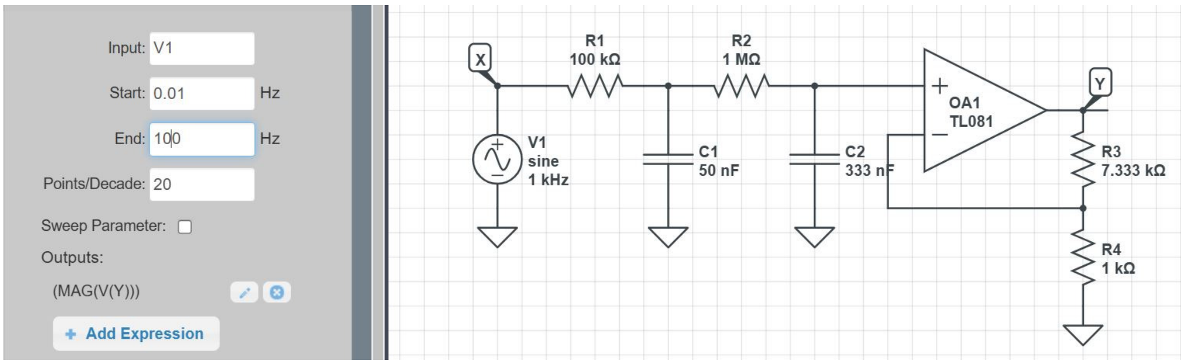
- R1 = 100k
- R2 = 1M

Then the capacitors are

$$\frac{1}{R_1 C_1} = 2 \qquad \Rightarrow C_1 = 50nF$$

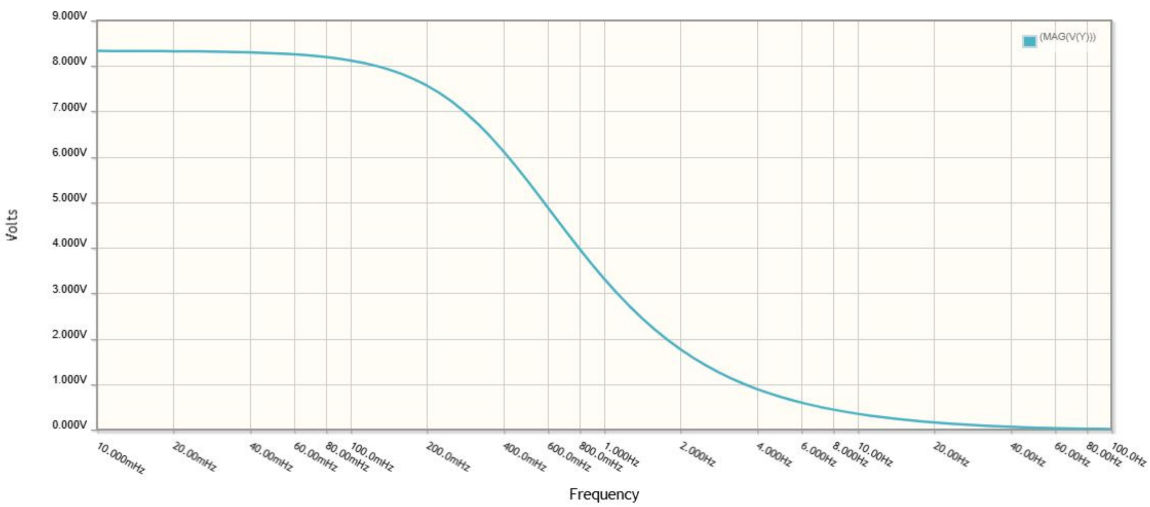
$$\frac{1}{R_2 C_2} = 3 \qquad \Rightarrow C_2 = 333nF$$

Add a non-inverting amplifier to make the DC gain 8.333



CircuitLab schamtic for a 2nd-order low-pass filter with two real poles.
Doesn't really matter which op-amp you use (LM2904, LM358, TL081)

In CircuitLab, you can sweep the frequency to see how this filter behaves



CircuitLab Frequency Domain Sweep showing this is a low-pass filter

Example: Design a circuit to implement

$$Y = \left(\frac{50}{s^2+2s+50}\right)X$$

Solution: Use a circuit with two complex poles. The poles are

$$s = -1 \pm j7$$

or in polar form

$$s = -7.071\angle \pm 81.87^0$$

If R = 100k, then

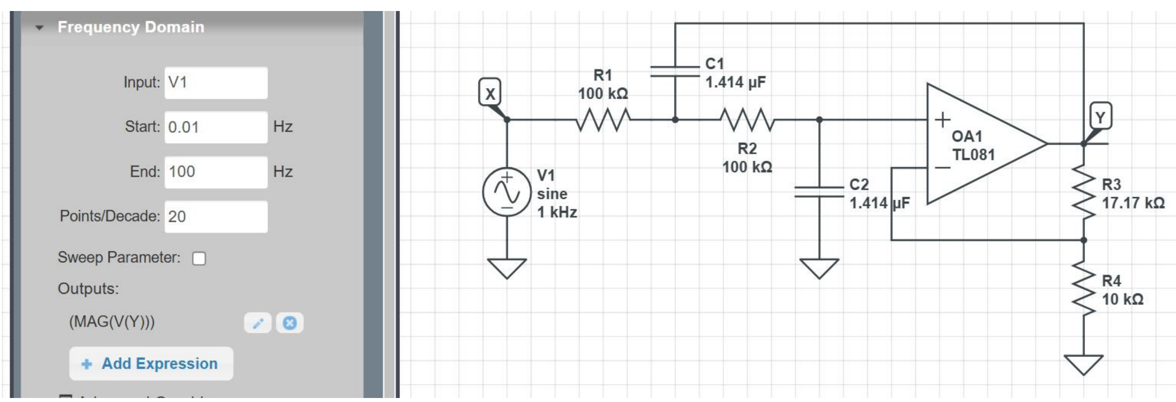
$$\frac{1}{RC} = 7.071 \qquad \Rightarrow C = 1.414\mu F$$

The gain to set the angle to 81.87 degrees is

$$3 - k = 2\cos\theta$$

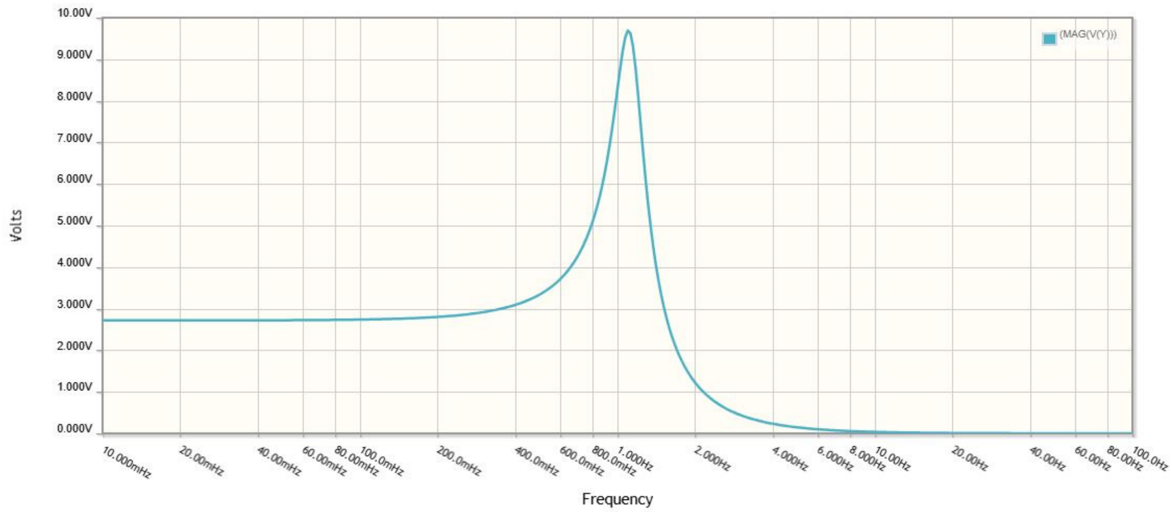
$$k = 2.717$$

The circuit is then



CircuitLab schematic for a low-pass filter with complex poles

With a complex pole, the circuit shows a resonance



CircuitLab frequency domain sweep showing a resonance due to the complex poles

Summary

Op-Amp circuits are kind of like legos: you build your project by piecing together op-amp circuits with different functions. CircuitLab then lets you check your design before you start breadboarding your circuit.