Operational Amplifiers

Introduction

One of the more useful circuit elements are operational amplifiers, or op-amps for short. Op-amps are high-gain differential amplifiers. The symbol for an op-amp and its input / output relationship is presented in Figure 1.

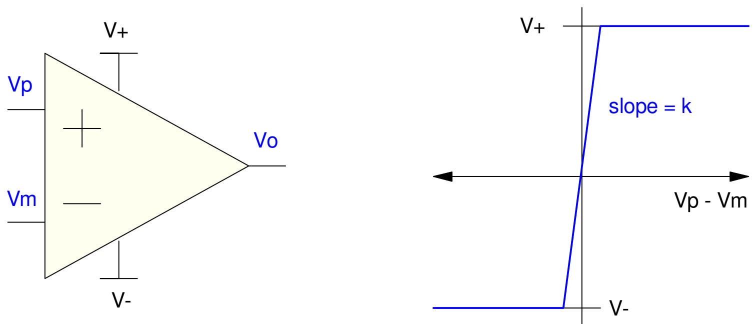

Figure 1: Op-Amps are high-gain differential amplifiers

When op-amps were released in 1967, they revolutionized electronics. They quickly became the core of many types of circuit including

- Amplifiers
- Competitors (digital logic)
- Schmitt Triggers (digital logic)
- Mixers
- Analog Computers, and
- Instrumentation Amplifiers

to name a few. Op-amps are not absolutely necessary: you *can* design these circuits without using op-amps. They do make the design of such circuits much simpler, however, and often with superior results.

In this lecture, we'll cover

- Two of my favorite op-amps, LM2904 and MCP602,
- Circuit models for these op-amps, and
- Three op-amp circuits: a buffer, a non-inverting amplifier, and an inverting amplifier.

Personal Favorites

One of the first commercial op-amps was the LM741, released in 1968 by Fairchild Semiconductor. Today, there are thousands of op-amps available. Digikey, for example, sells over 18,00 different op-amps.

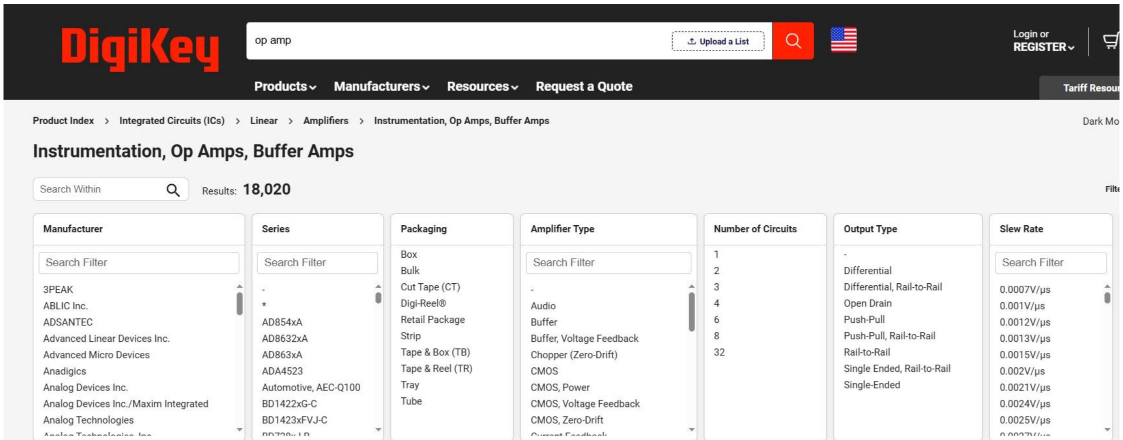

Figure 2: Digikey sells over 18k op-amps

Not surprisingly, there are a wide variety of options

The current per channel ranges from

- 50uA (LT1787: $12.56, cell phones) to
- 10A (OPA541: $29.28, motor controls)

The voltage supply span can vary from

- 0.9V (LMV951, $2.06) to
- 300V (HV256FG, $228)

The gain bandwidth product can vary from

- 400Hz (TLR1901GXZ, $1.54) to
- 20GHz (ASNT7113A: $1,350)

My personal favorites are the LM2904 and MCP602. These are the two op-amps you'll use in pretty much all of your courses - with a few exceptions.

	General Purpose		Digital	Power
	LM741 not a favorite	LM2904N LM358	MCP602	OPA2544
Voltage (min)	+/- 5V	+/- 2.5V	2.7V	+/- 10V
Voltage (max)	+/- 18V	+/- 20V	6.0V	+/- 35V
Current Out	25mA	50mA	22mA	4A
Gain-Bandwith	1.5MHz	700kHz	2.8MHz	1.4MHz
Package	DIP8	DIP8	DIP8	TO220-11
Price (ea)	$0.58	$0.16	$0.61	$21.70
CircuitLab?	yes	LM358	yes	OP07

Table 1: Select parameters for commonly used op-amps

Op-Amp Models

Each op-amp has several parameters that define its behavior. By-and-large, op-amps are interchangeable. If a circuit is designed for one op-amp, you can swap it with another and the circuit will work just fine. There are exceptions, however:

- An LM358 op-amp can take up to +/-20V whereas an MCP602 only accepts 0-6V. If you apply +/-20V to an MCP602, it smokes.
- An LM358 will operated down to +/- 2.5V whereas an LM741 needs a minimum of +/- 5V power. If you try to operate at +/- 2.5V, an LM358 will work but an LM741 won't.

As long as you keep within the limits of the op-amp, they're pretty much interchangeable.

If you go through the data sheets for an LM358, you can pull out the parameters given in Table 2.

Term	Datasheet	CircuitLab
Input Bias Current	20nA	45nA
(Input Impedance @ 5V)	250M	111M
Open-Loop Gain	140V/mV	100,000
Gain Bandwidth Product	1.2MHz	1MHz
Slew Rate	0.5 V/us	250,000 V/s
Voltage swing from rail	1.5V	0V
Output Current	20mA	infinity
Output Resistance	300 Ohms	100 Ohms

Table 2: Parameters for an LM358 op-amp

These terms are also what CircuitLab uses to model the op-amp. If you drag and drop an op-amp in CircuitLab and right-click on it, you can select the type of op-amp. It will also show your CircuitLab's parameters. The default values for an LM358 is shown in Figure 3.

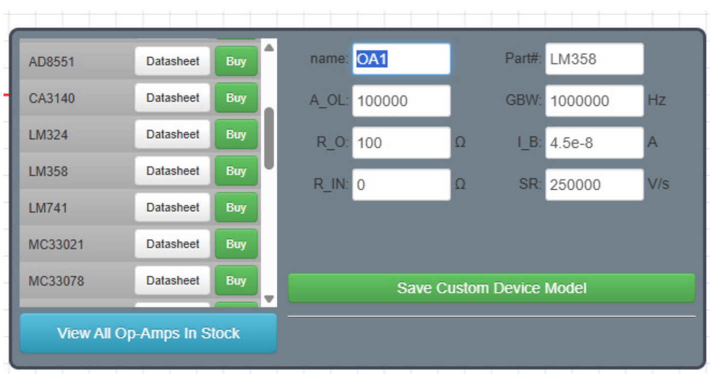

Figure 3: Default parameters for an LM358 op-amp in CircuitLab (equivalent to an LM2904)

What these parameters mean are as follows:

- Open-Loop Gain: The differential gain of the op-amp
- Input Bias Current: The current draw at the input. Assuming the input is 5V, the input impedance of the op-amp.
- Output Resistance: The Thevenin resistance at the output.

Taken together, the model for a LM358 op-amp is shown in Figure 4

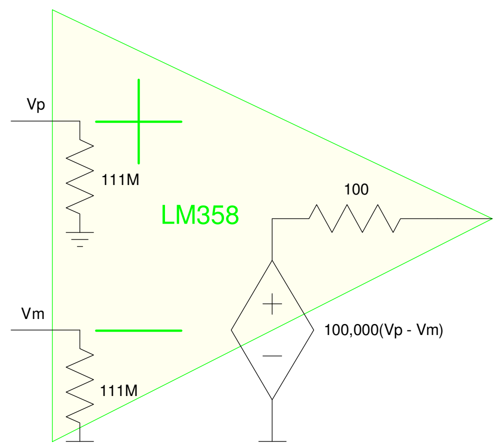

Figure 4: Circuit model for a LM358 op-amp

A couple other parameters in the datasheet give limitations of the op-amp.

Gain-Bandwidth Product: The frequency range an op-amp can pass is limited. This range also depends upon the gain you're implementing with the op-amp. A gain-bandwidth product of 1.2MHz means you can have

- A gain of 1 out to 1.2MHz
- A gain of 10 out to 120kHz
- A gain of 100 out to 12kHz
- A gain of 1000 out to 1.2kHz

What this tells you is that if you're sticking to the audio range (0-20kHz), keep the gain of each op-amp less than 50. If you need a gain more than 50, cascade several op-amps.

Slew-Rate Limit: The output of an op-amp is limited by the slew-rate limit (250,000 V/s for an LM358). For example, if you try to output a 5Vp sine wave at 10kHz, the output will look like a clean sine wave as in Figure 5. If you try to output a 5Vp sine wave at 20kHz, the output looks more like a triangle wave. The slew-rate limit is what causes the distortion at 20kHz.

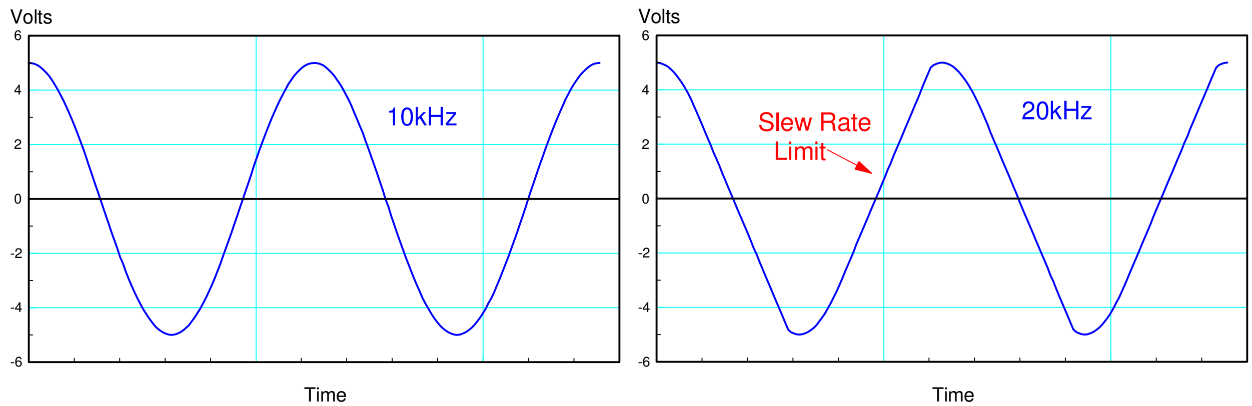

Figure 5: The slew rate limit causes sine waves to look like triangle waves

Common Op-Amp Circuits

With this op-amp model, you can build many circuits. Three common ones will be presented here.

Buffer

A buffer circuit is used when you want to avoid loading a signal. The circuit model for a buffer is shown on the left in Figure 6. If you replace the circuit model for a LM358 op-amp, you get the circuit to the right.

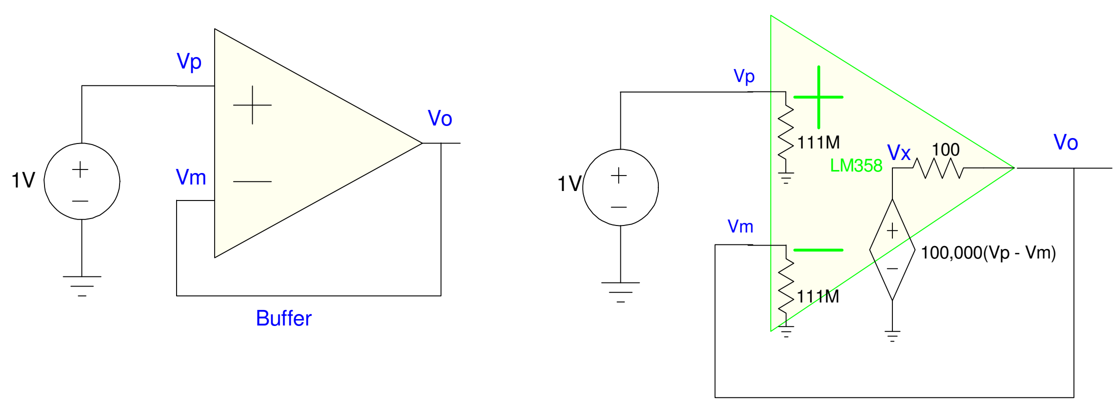

Figure 6: Buffer circuit and it's circuit equivalent.

To find the output, Vo. write the voltage node equations:

$$V_p = 1$$

$$V_x = 100,000(V_p - V_m)$$

$$V_o = V_m$$

$$\left(\frac{V_o - V_x}{100}\right) + \left(\frac{V_o}{111M}\right) = 0$$

Solving in Matlab results in

```
Vo    0.999990000090990
Vx    0.999990900976501
Vp    1.000000000000000
Vm    0.999990000090990
```

Note:

- V(open) = Vo = 0.99999V
- I(short) = 1000A (CircuitLab)
- Rth = 0.001 Ohm

In CircuitLab, you can simulate a butter. Just to show what's happening, a 100 Ohm resistor is added to the output of the buffer - showing that it is capable of driving a load.

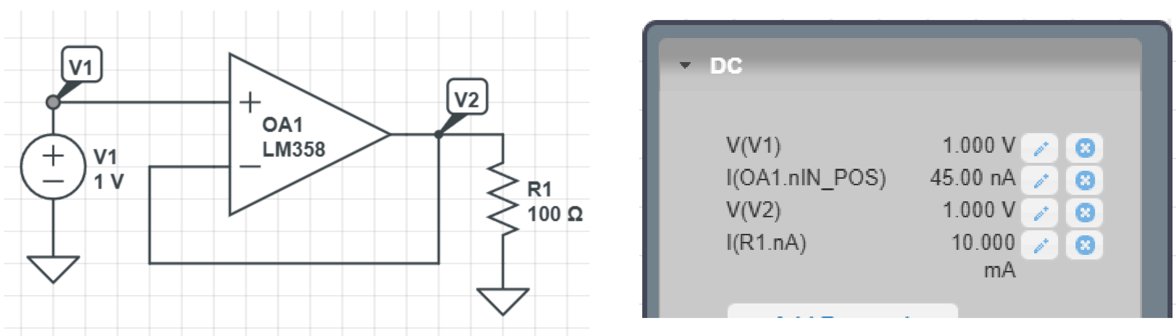

Figure 7: Buffer circuit in CircuitLab

Note that this circuit

- Amplifies the input by 1x
- Has a high input impedance (111M Ohms), and
- Has a low output impedance (0.001 Ohm)

Noninverting Amplifier

Another common circuit is a noninverting amplifier as shown in Figure 8.

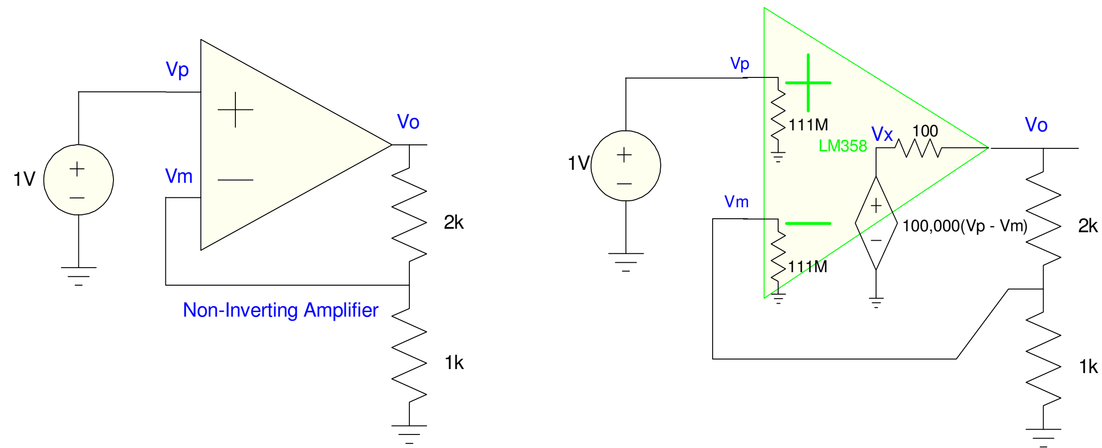

Figure 8: Non-inverting amplifier and its circuit equivalent

The voltage node equations for the circuit to the right are

$$V_p = 1$$

$$V_x = 100,000(V_p - V_m)$$

$$\left(\frac{V_o - V_x}{100}\right) + \left(\frac{V_o - V_m}{2k}\right) = 0$$

$$\left(\frac{V_m}{111M}\right) + \left(\frac{V_m - V_o}{2k}\right) + \left(\frac{V_m}{1k}\right) = 0$$

Solving using Matlab results in

```
Vo   2.999928019625697
Vx   3.099925920556440
Vp   1.000000000000000
Vm   0.999970000719804
```

In CircuitLab, you get the same results

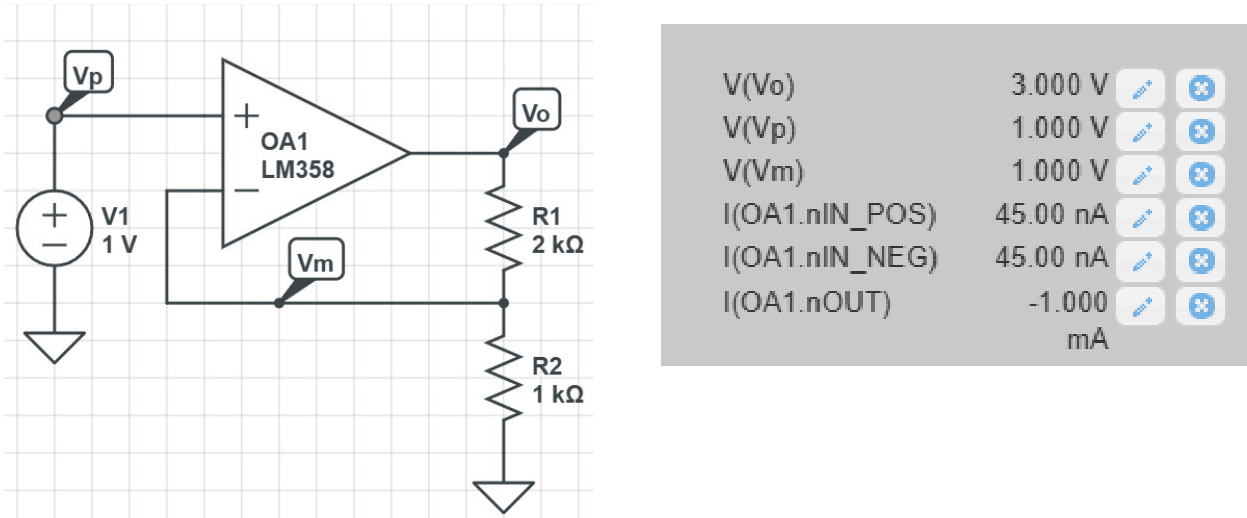

Figure 9: CircuitLab simulation of a noninverting amplifier

Note that this circuit

- Amplifies the input by 3x
- Has a high input impedance (111M Ohms), and
- Has a low output impedance (0.003 Ohms)

Inverting Amplifier

Finally, consider an inverting amplifier as shown in Figure 10

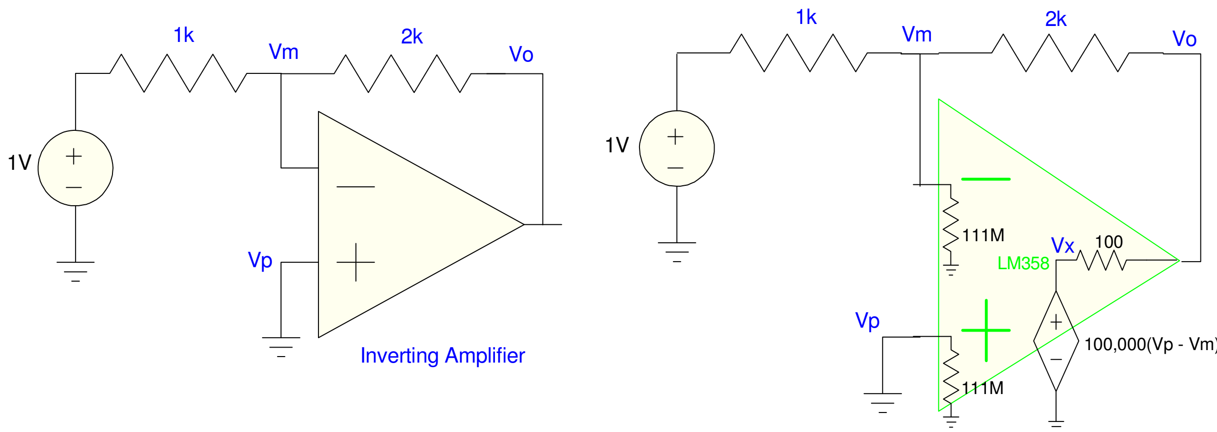

Figure 10: Inverting Amplifier and it's circuit equivalent.

Writing the voltage node equations for this circuit gives

$$V_p = 0$$

$$V_x = 100,000(V_p - V_m)$$

$$\left(\frac{V_m - 1}{1k}\right) + \left(\frac{V_m}{111M}\right) + \left(\frac{V_m - V_o}{2k}\right) = 0$$

$$\left(\frac{V_o - V_m}{2k}\right) + \left(\frac{V_o - V_x}{100}\right) = 0$$

If you solve for the voltages using Matlab, you get

```
Vo  -1.999940001439607
Vx  -2.099938001481589
Vp                   0
Vm   0.000019999400014
```

Note: The short-circuit current will be -666.6A, meaning

- Rth = 0.003 Ohms

In CircuitLab, you get the results of Figure 11

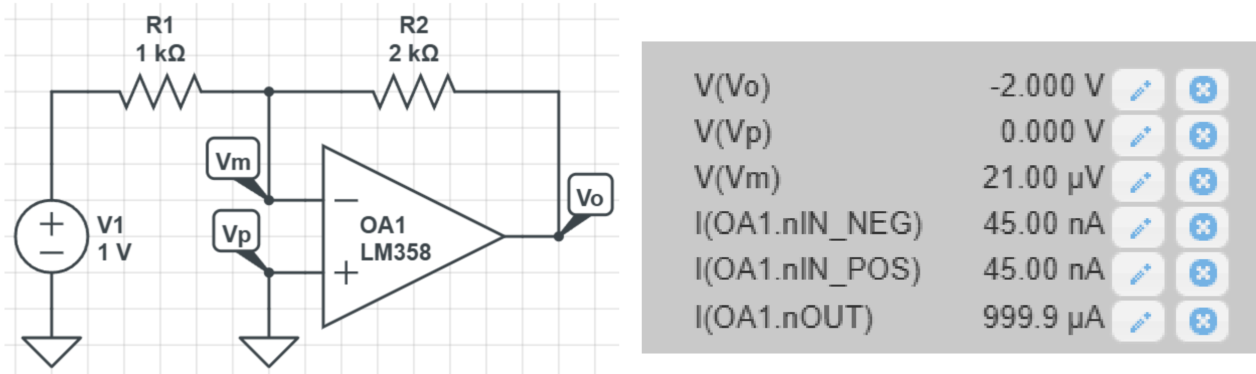

Figure 11: CircuitLab simulation of an LM358 configured as an inverting amplifier.

Note that this circuit

- Has a gain of -2.000
- Has an input impedance of 1k (R1)
- Has an output impedance of 0.003 Ohms

These are just a few of the circuits you can build using op-amps. There are many more.

Summary

Circuit analysis with op-amps is fairly easy: you just replace the op-amp with its model such as the circuit shown in Figure 11. This is what CircuitLab does when it analyzes op-amp circuits.

One problem with these circuits with the circuit analysis presented in this lecture is it's rather complicated. If you have a circuit with multiple op-amps, using voltage nodes and the circuit model for an op-amp gets just too unwieldy. We need a better tool.

That tool is the ideal op-amp model and is the topic of the next lecture.

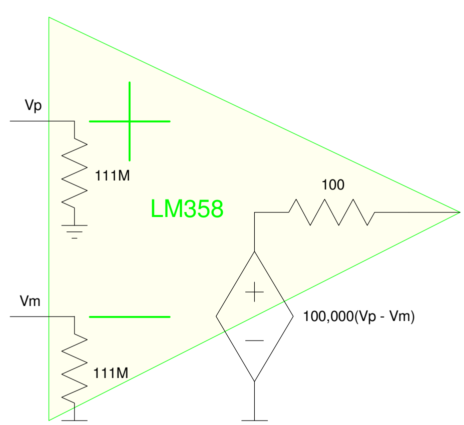

Figure 12: Circuit model for a LM358 op-amp