
Operational Amplifiers

ECE 211 Circuits I

Lecture #13

Please visit [Bison Academy](#) for corresponding
lecture notes, homework sets, and solutions

What is an Op-Amp?

- Op-Amp: Operational Amplifier
- High-gain differential amplifier

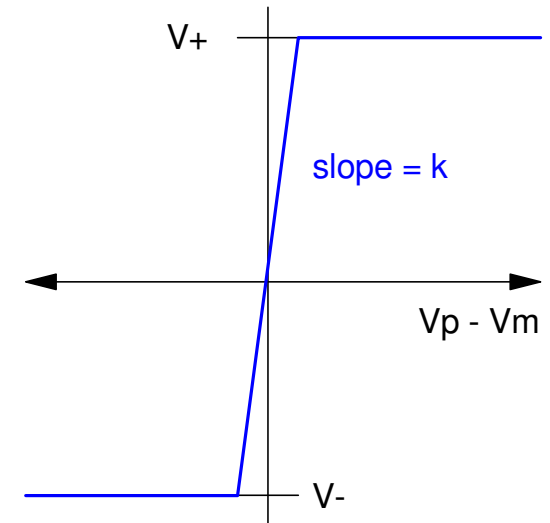
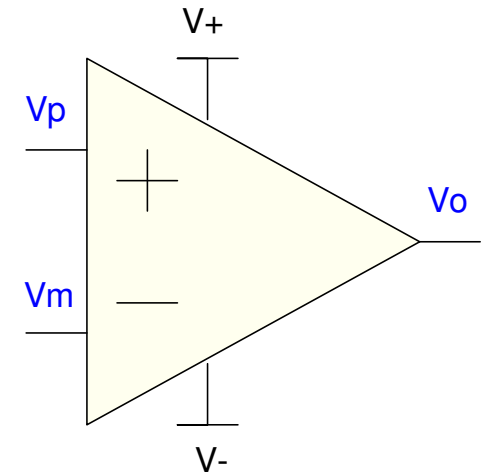
An op-amp is a 2-input device with

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

where k is a large number.

Sometimes, the power supplies are specified

- Sometimes, they're not



Importance of Op-Amps

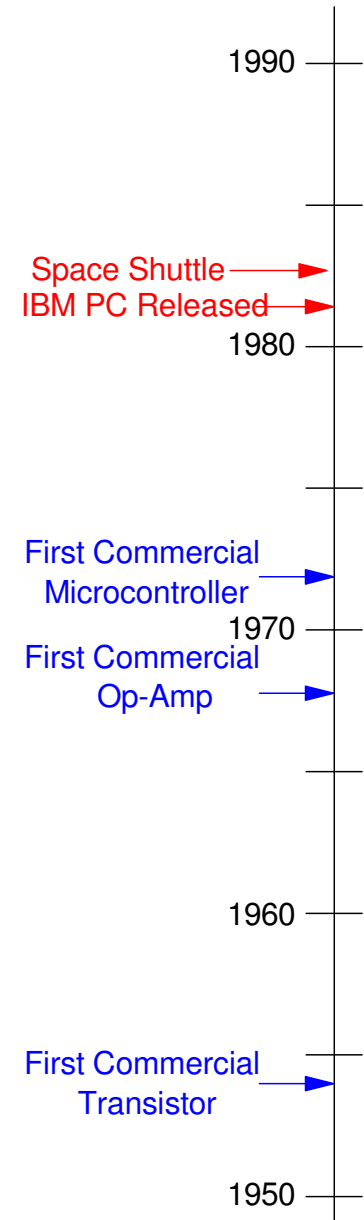
Operational Amplifiers (op-amps) revolutionized electronics

They are the core of many circuits

- Amplifiers
- Comparitors (digital logic)
- Schmitt Triggers (digital logic)
- Mixers
- Analog Computers
- Instrumentation Amplifiers

You *can* design circuits without using op-amps

- They greatly simplify many designs
- They greatly improve



Types of Op-Amps

Digikey sells 17,978 different op-amps

- (October 12, 2025)
- Wide variety of options

Current - Output / Channel

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

Voltage - Supply Span

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

Gain Bandwidth Product

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

The screenshot shows the DigiKey website interface. At the top, the DigiKey logo is in red. A search bar contains the text 'op amp'. Below the search bar, a breadcrumb trail reads: 'Product Index > Integrated Circuits (ICs) > Linear > Amplifiers > Instrumentation, Op Amps, E'. The main heading is 'Instrumentation, Op Amps, Buffer Amps'. A search bar with 'Search Within' and a magnifying glass icon shows 'Results: 17,978'. Below this are three filter panels: 'Amplifier Type' with a search filter and a list of types (Audio, Buffer, Buffer, Voltage Feedback, Chopper (Zero-Drift), CMOS, CMOS, Power, CMOS, Voltage Feedback, CMOS, Zero-Drift, Current Feedback); 'Number of Circuits' with a list of counts (1, 2, 3, 4, 6, 8, 32); and 'Output Type' with a list of types (Differential, Differential, Rail-to-Rail, Open Drain, Push-Pull, Push-Pull, Rail-to-Rail, Rail-to-Rail, Single Ended, Rail-to-Rail, Single-Ended). Below these are three sections: 'Stocking Options' (In Stock, Normally Stocking, New Product), 'Environmental Options' (RoHS Compliant, Non-RoHS Compliant), and 'Media' (Datasheet, Photo, EDA/CAD Models). At the bottom, there is a 'SEARCH ENTRY' section with 'op amp' and a red 'x' icon, and an 'APPLIED FILTERS' section with 'Product Status' and a red 'x' icon. The bottom right shows 'Showing 1 - 25 of 17,978' and a 'Sort By: Featured' dropdown menu.

My Personal Favorites

- Digikey Pricing: October 12, 2025
- * Op-Amps ECE stocks (please use these if possible)

	General Purpose			Digital	Power
	LM741 not a favorite	LM2904N*	LM358G*	MCP602*	OPA2544
Voltage (min)	+/- 5V	+/- 2.5V	+/- 2.5V	2.7V	+/- 10V
Voltage (max)	+/- 18V	+/- 20V	+/- 20V	6.0V	+/- 35V
Current Out	25mA	50mA	50mA	22mA	4A
Gain-Bandwidth	1.5MHz	700kHz	700kHz	2.8MHz	1.4MHz
Package	DIP8	DIP8	DIP8	DIP8	TO220-11
Price (ea)	\$0.58	\$0.16	\$0.11	\$0.61	\$21.70
CircuitLab?	yes	LM358	yes	yes	OP07

Op-Amps in CircuitLab

CircuitLab has two op-amp models

- 5 Lead (includes power inputs)
- 3 Lead (excludes power inputs)

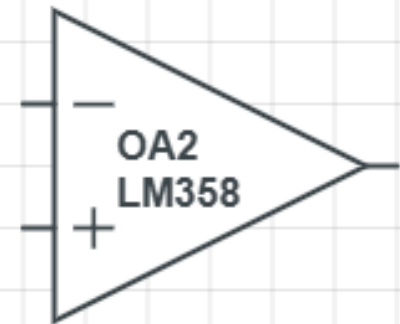
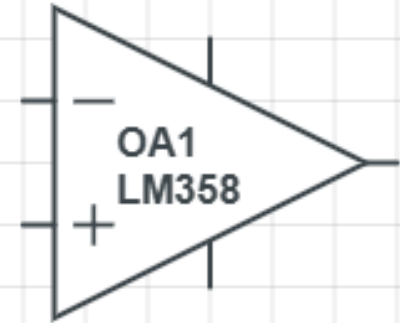
The type you used depends upon the circuit

Digital Amplifier

- 5-Lead
- Logic levels needs to be specified
- Logic 1 (output rails at + power supply)
- Logic 0 (output rails at - power supply)

Analog Amplifiers

- 3-Lead
- Assumes power supply doesn't matter

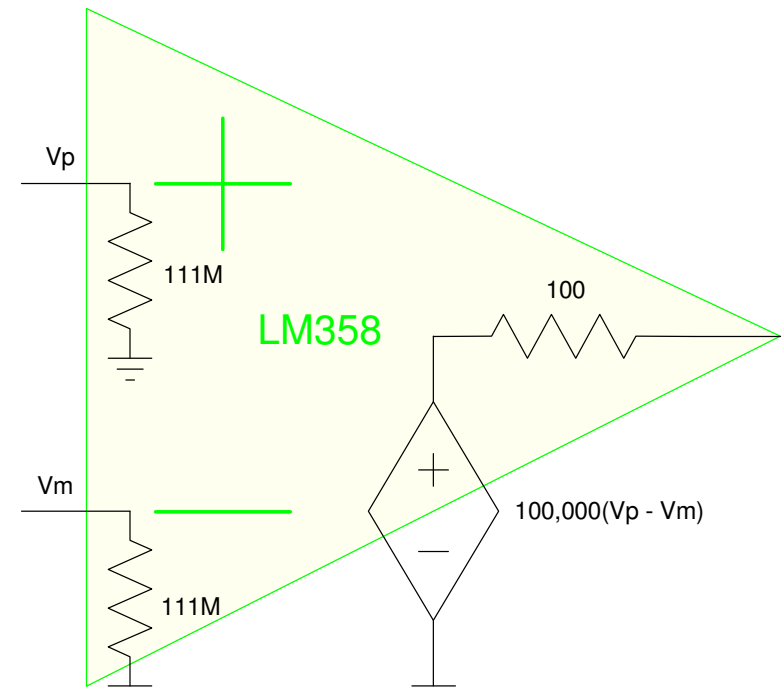


Op-Amp Models

- Found in Data-Sheets (Digikey)
- Found in CircuitLab (Double-click)

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

The screenshot shows the 'Configure' dialog for an Op-Amp model in CircuitLab. On the left, a list of op-amp models is shown with 'Datasheet' and 'Buy' buttons for each: AD8551, CA3140, LM324, LM358, LM741, MC33021, and MC33078. The 'LM358' model is selected. On the right, the configuration parameters are displayed: name: OA1, Part#: LM358, A_OL: 100000, GBW: 1000000 Hz, R_O: 100 Ω , I_B: 4.5e-8 A, R_IN: 0 Ω , SR: 250000 V/s. A green 'Save Custom Device Model' button is at the bottom right, and a blue 'View All Op-Amps In Stock' button is at the bottom left.



Gain-Bandwidth Product

- Gain-Bandwidth Product
- LM358 or LM2904

Gain * Bandwidth = 1.2MHz

- Gain = 1, BW = 1.2MHz
- Gain = 10, BW = 120kHz
- Gain = 100, BW = 12kHz
- Gain = 1000, BW = 1.2kHz

Keep the gain less than 50 for audio applications

Slew Rate Limit

- 500,000 V/s
- LM354 or LM2904

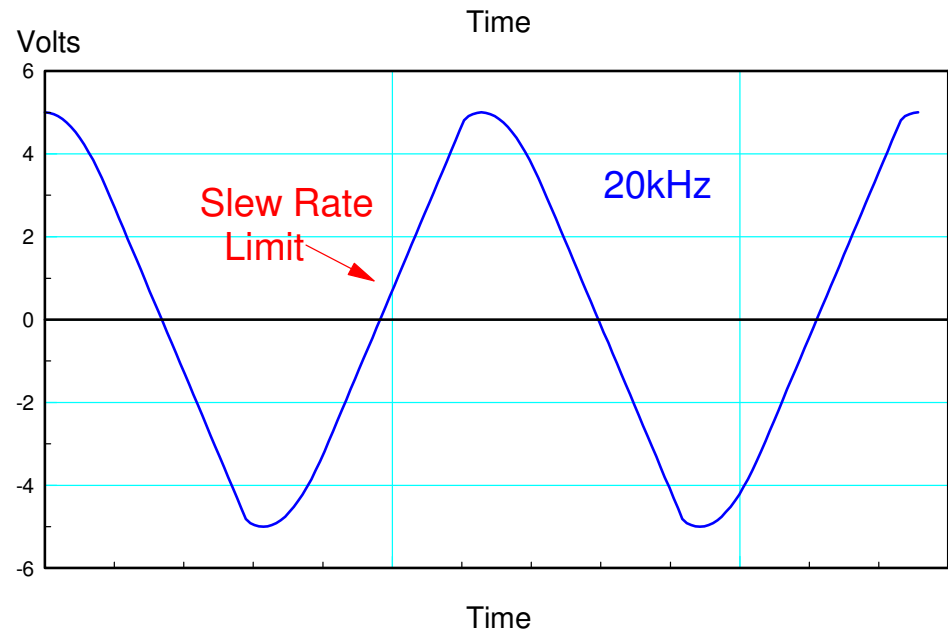
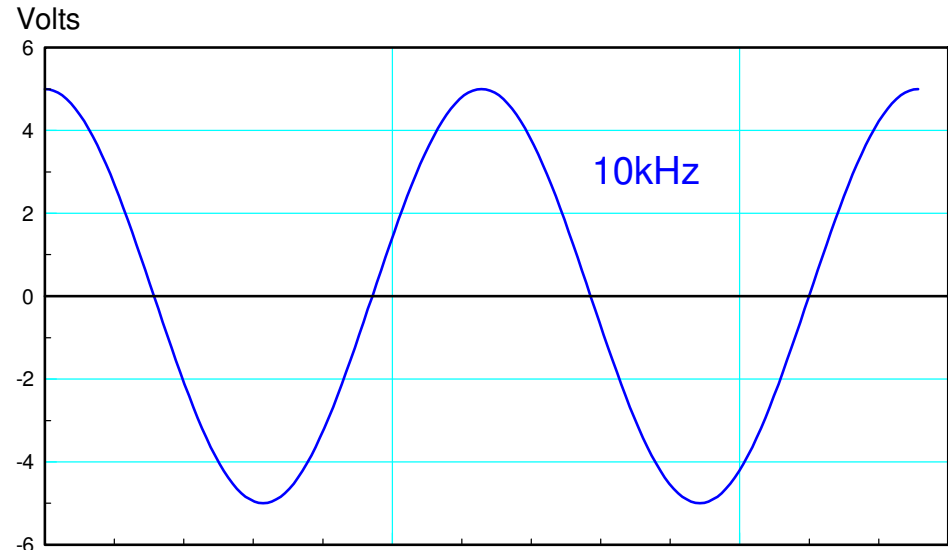
The fastest the output can change

Top:

- 5Vp
- 10kHz sine wave
- No Distortion

Bottom:

- 5Vp
- 20kHz sine wave
- Hit the slew-rate limit



Op-Amp Circuit Model

- LM2904
- LM358

A_OL

- Open-Loop Gain
- 100,000

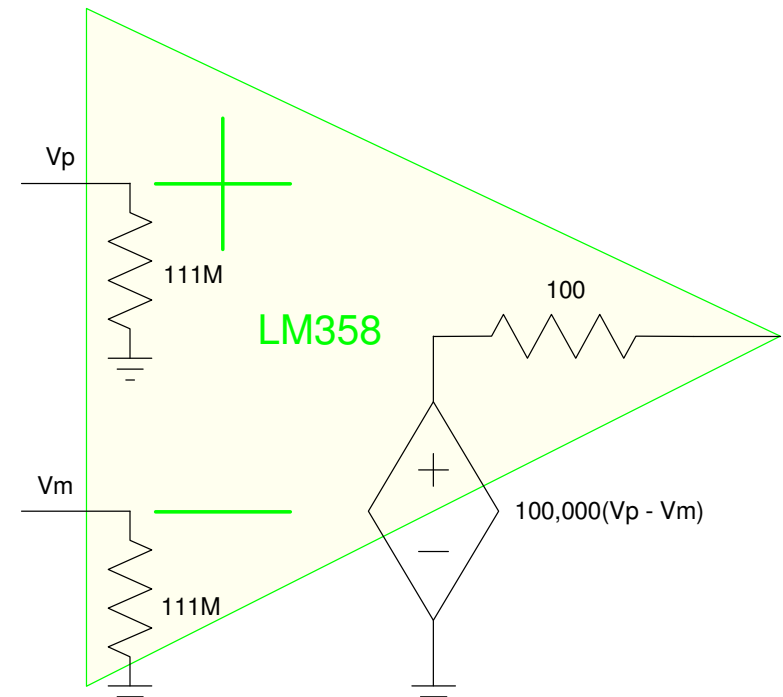
R_O

- Output Resistance
- 100 Ohms

I_B

- Input Bias Current
- 45nA
- 111M Ohms @ 5V

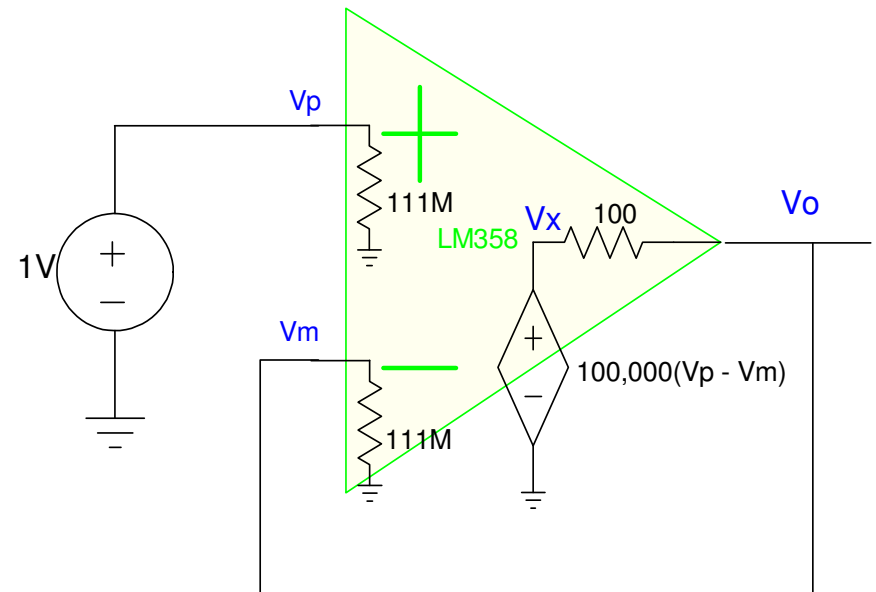
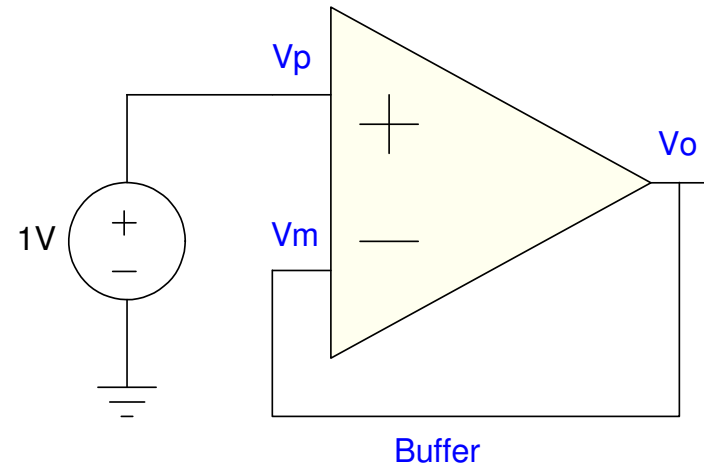
A screenshot of a software interface for configuring an op-amp model. On the left, a list of op-amp models is shown with 'Datasheet' and 'Buy' buttons for each: AD8551, CA3140, LM324, LM358, LM741, MC33021, and MC33078. On the right, a configuration panel for a device named 'OA1' (Part#: LM358) is displayed. It includes input fields for A_OL (100000), GBW (1000000 Hz), R_O (100 Ω), I_B (4.5e-8 A), R_IN (0 Ω), and SR (250000 V/s). A green 'Save Custom Device Model' button is at the bottom right, and a blue 'View All Op-Amps In Stock' button is at the bottom left.



Buffer

Replace the op-amp with its circuit model

Write the voltage node equations



Buffer

Node Equations

$$V_p = 1$$

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

$$V_o = V_m$$

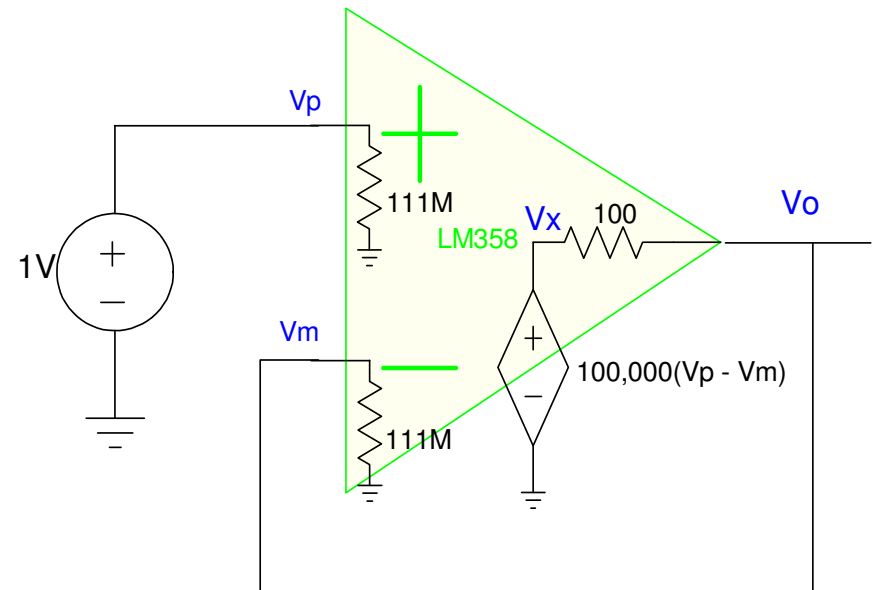
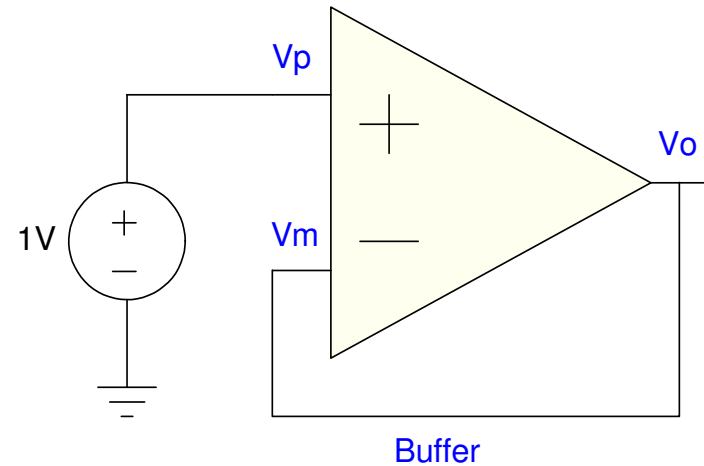
$$\left(\frac{V_o - V_x}{100}\right) + \left(\frac{V_o}{111M}\right) = 0$$

Solve (Matlab)

V _o	0.999990000090990
V _x	0.999990900976501
V _p	1.000000000000000
V _m	0.999990000090990

Note:

- V(open) = V_o = 0.99999V
- I(short) = 1000A (CircuitLab)
- R_{th} = 0.001 Ohm



Buffer

CircuitLab Simulation

- 100 Ohm resistor added to the output
- (10mA load)

$$V1 = V2$$

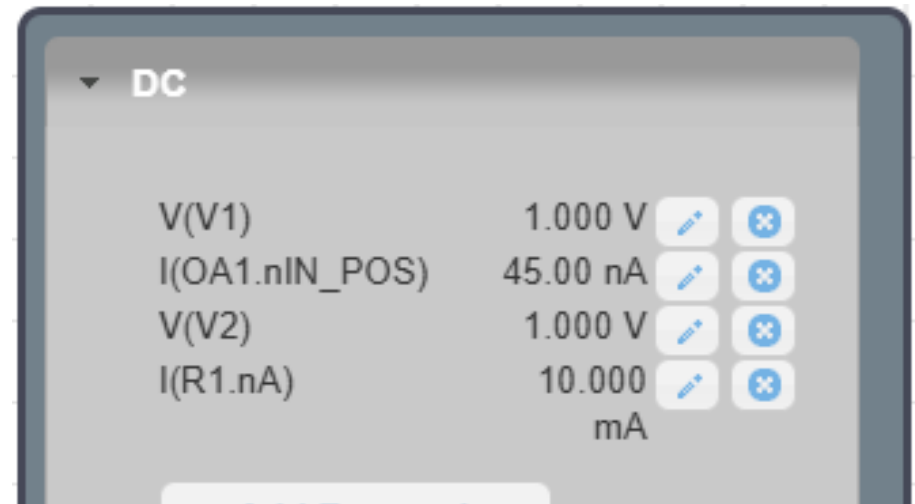
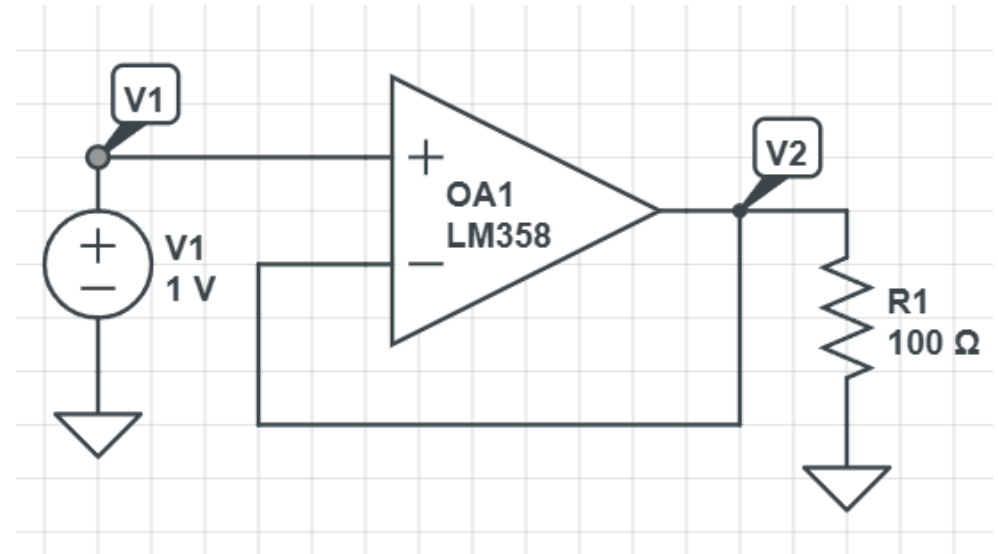
- Rounding to 3 decimal place

$$I(\text{in}) = 45\text{nA}$$

- $R(\text{in}) = 1\text{V} @ 45\text{nA} = 22\text{M}$

$$I(\text{out}) = 10\text{mA}$$

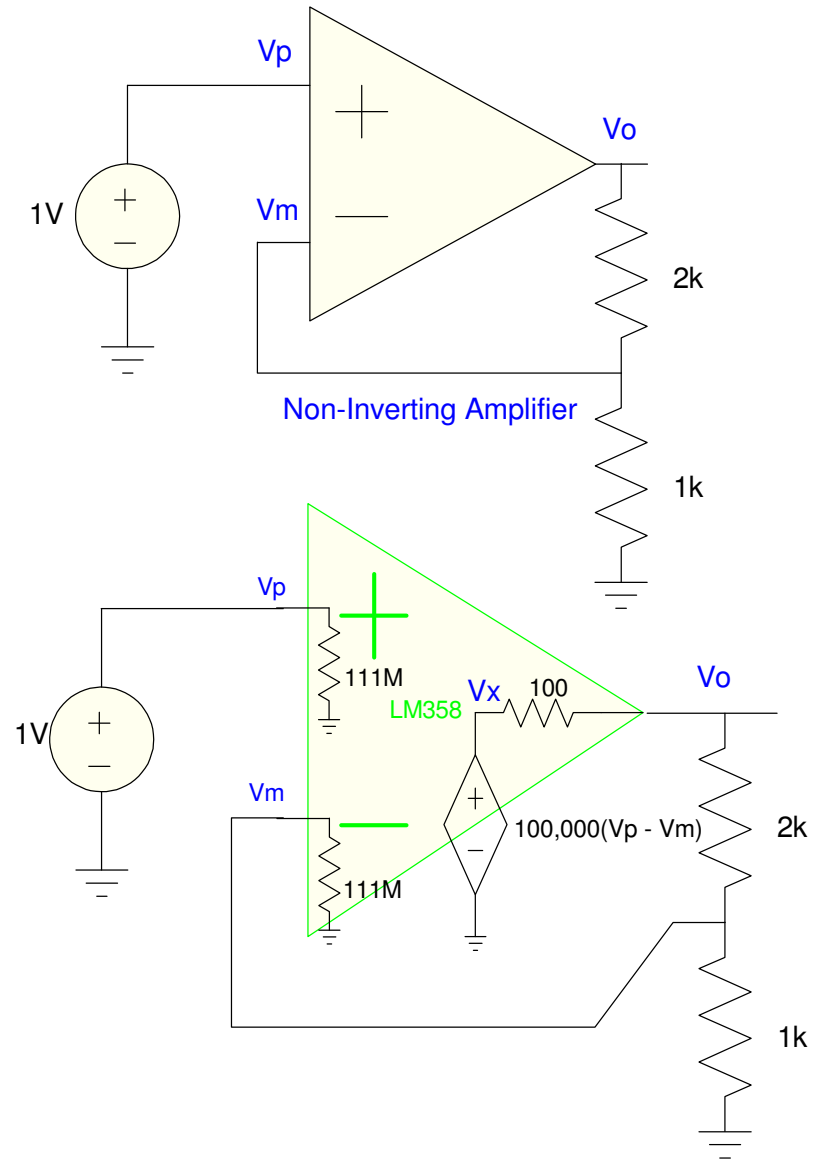
- This circuit has a gain of 1.000
- The input impedance is 111M Ohm
- The output impedance is 0.001 Ohm
- $V2 = V1$
- R1 doesn't load V1 ("buffer")



Noninverting Amplifier

Replace the op-amp with its circuit model

Write the voltage node equations



Non-Inverting Amplifier

Node Equations

$$V_p = 1$$

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

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

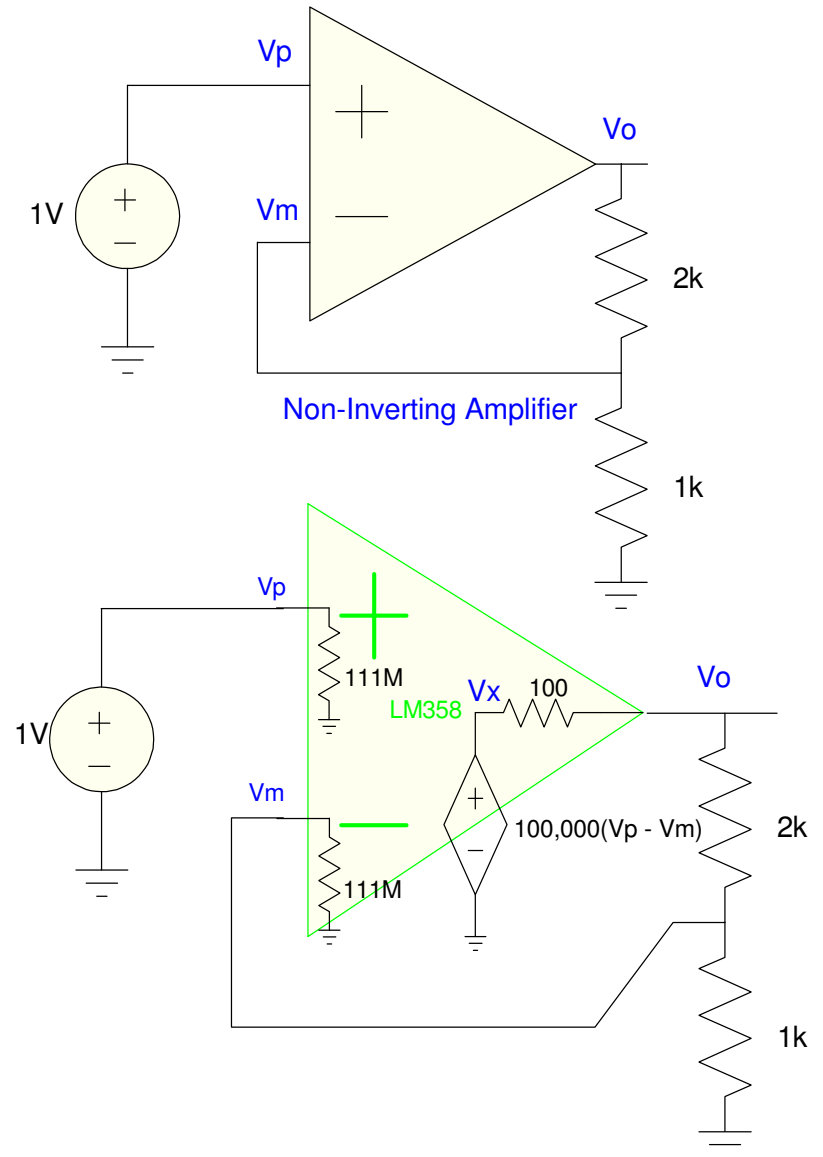
$$\left(\frac{V_m}{111M}\right) + \left(\frac{V_m - V_o}{2k}\right) + \left(\frac{V_m}{1k}\right) = 0$$

Solve (Matlab)

V _o	2.999928019625697
V _x	3.099925920556440
V _p	1.0000000000000000
V _m	0.999970000719804

Note:

- I(short) = 1000A (CircuitLab)
- R(th) = 0.003 Ohms



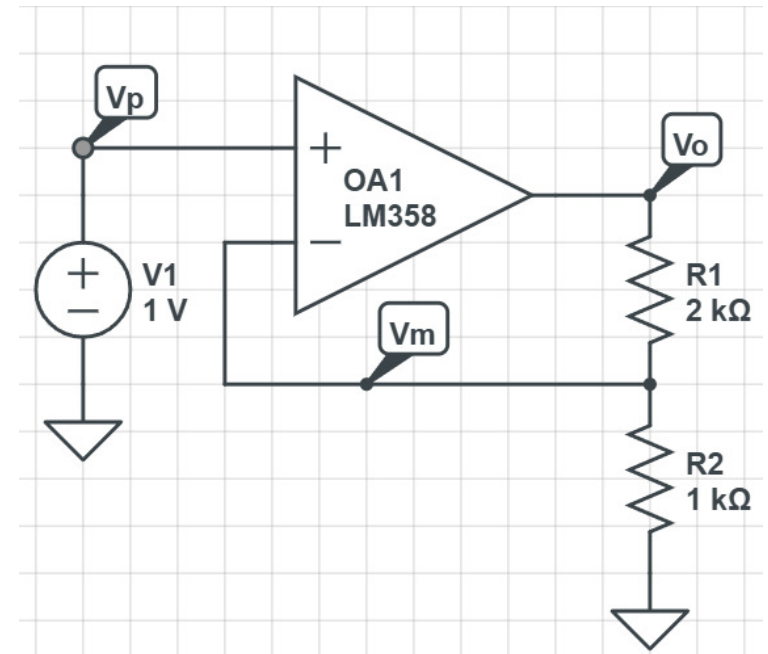
Non-Inverting Amplifier

CircuitLab Simulation

- Same results
- Rounded to 3 decimal places

This circuit amplifies V1 by 3x

- High input impedance (111M Ohm)
- Low output impedance (0.003 Ohm)

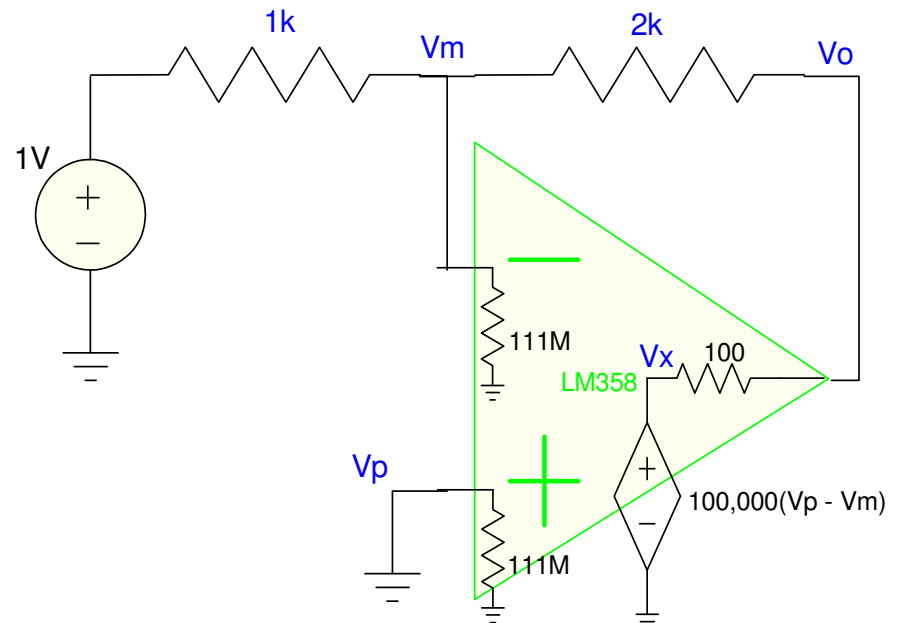
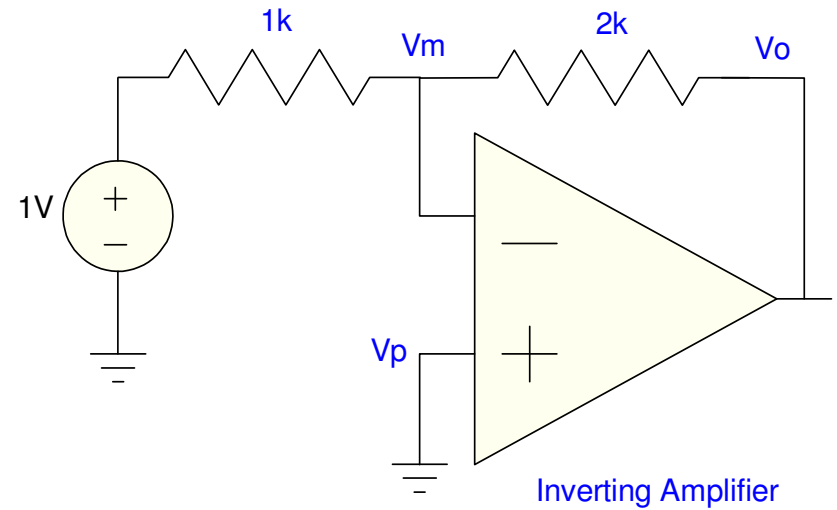


V(Vo)	3.000 V		
V(Vp)	1.000 V		
V(Vm)	1.000 V		
I(OA1.nIN_POS)	45.00 nA		
I(OA1.nIN_NEG)	45.00 nA		
I(OA1.nOUT)	-1.000 mA		

Inverting Amplifier

Replace the op-amp with its circuit model

Write the voltage node equations



Inverting Amplifier

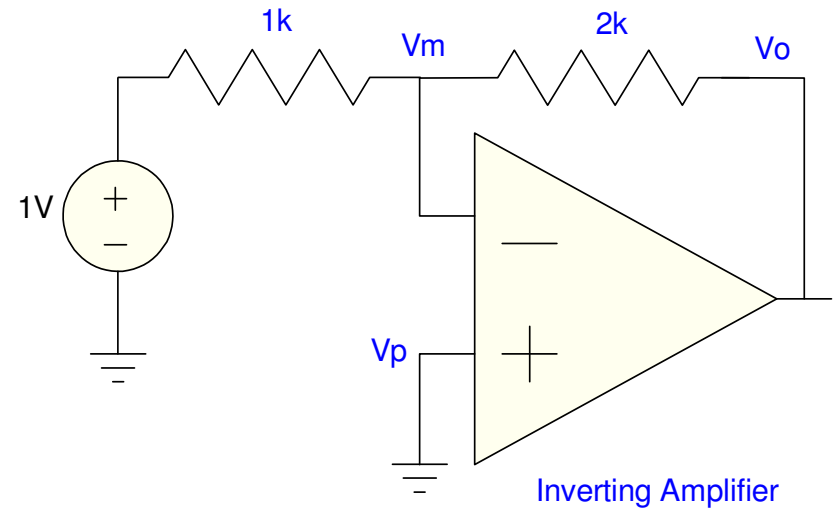
Voltage Node Equations

$$V_p = 0$$

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

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

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

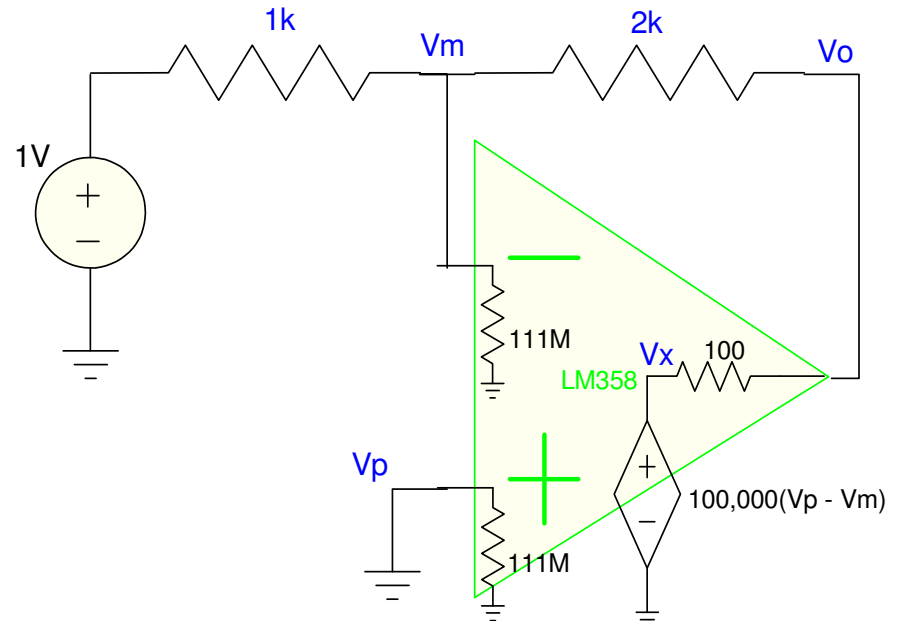


Solving in Matlab

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

Note:

- $I(\text{short}) = -666.6\text{A}$ (CircuitLab)
- $R_{th} = 0.003\text{ Ohms}$



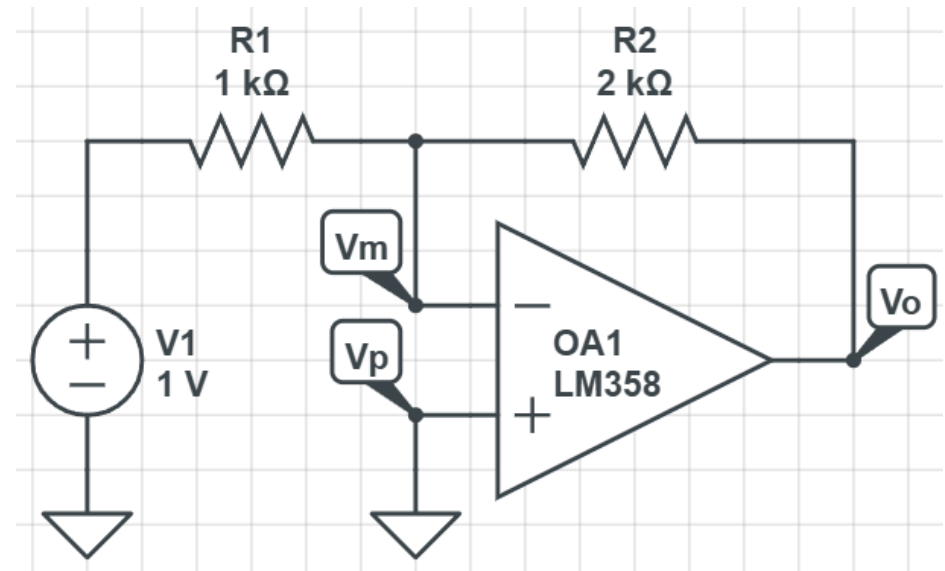
Inverting Amplifier

CircuitLab Simulation

- Same answers as before (rounding)

This circuit

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



V(Vo)	-2.000 V		
V(Vp)	0.000 V		
V(Vm)	21.00 μV		
I(OA1.nIN_NEG)	45.00 nA		
I(OA1.nIN_POS)	45.00 nA		
I(OA1.nOUT)	999.9 μA		

Summary

Circuit analysis with op-amps is fairly easy

- Replace the op-amp with it's circuit model

This is somewhat painful for circuits with one op-amp

- It's going to get much worse with multiple op-amp circuits

We need a better tool

- Ideal Op-Amp Model
- Next lecture

