Operational Amplifiers

ECE 211 Circuits I

Lecture #13

Please visit Bison Academy for corresponding
lecture notes, homework sets, and solutions

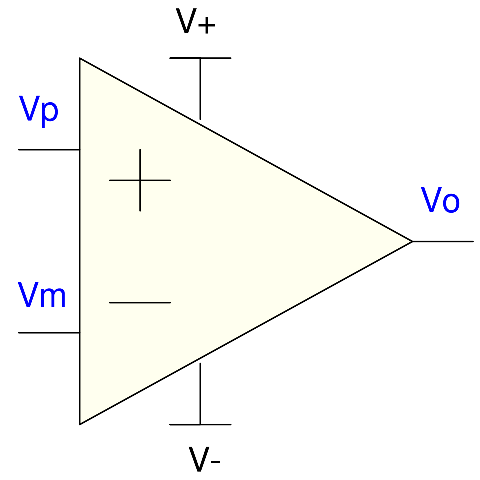
What is an Op-Amp?

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

An op-amp is a 2-input device with

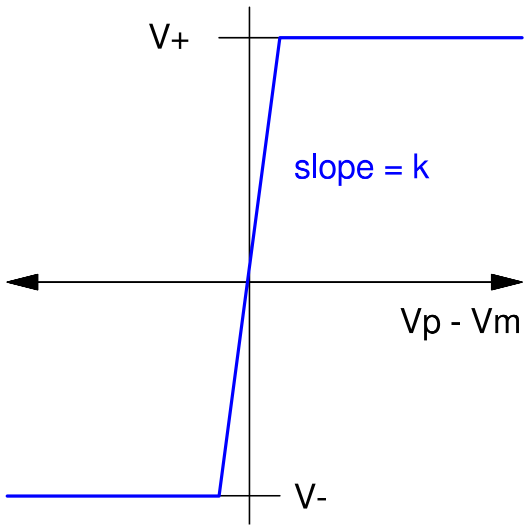
$$V_o = k(V_p - V_m)$$

where k is a large number.



Sometimes, the power supplies are specified

- Sometimes, they're not



Importance of Op-Amps

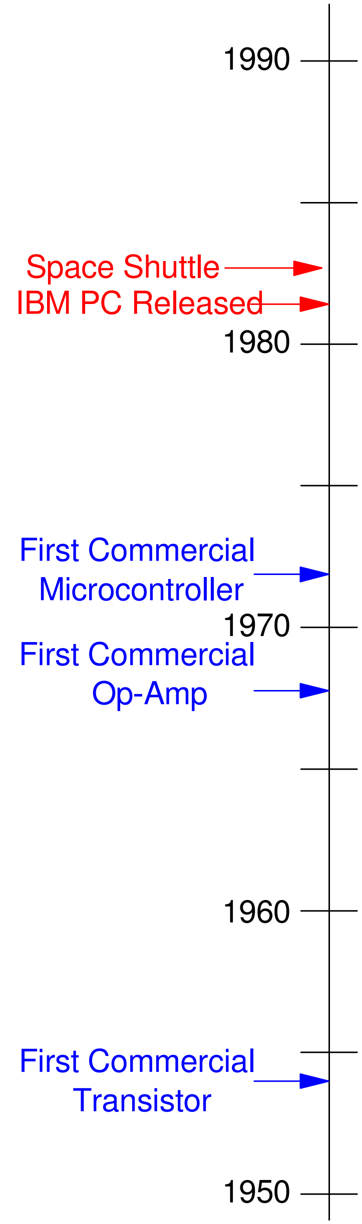
Operational Amplifiers (op-amps) revolutionized electronics

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

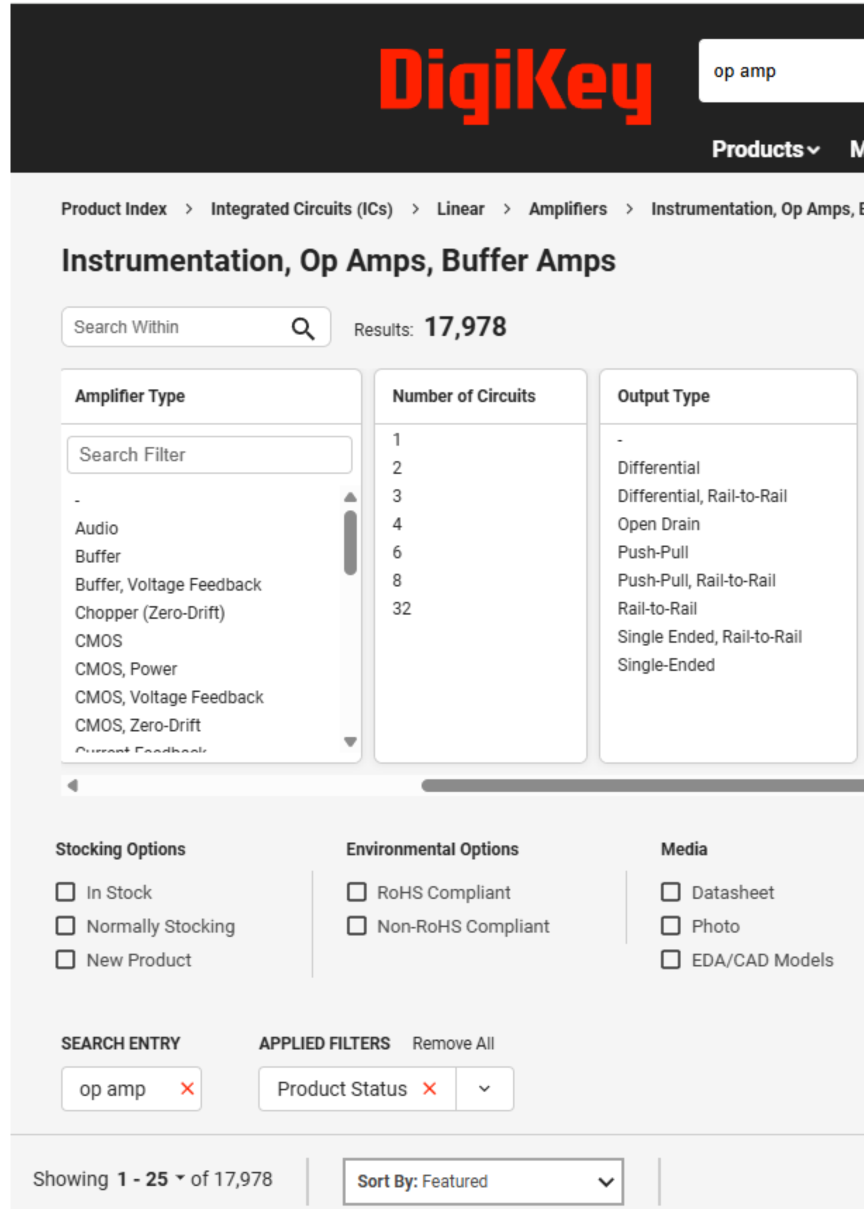
- 50uA (LT1787: $12.56, cell phones)
- 10A (OPA541: $29.28, motor controls)

Voltage - Supply Span

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

Gain Bandwidth Product

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



My Personal Favorites

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

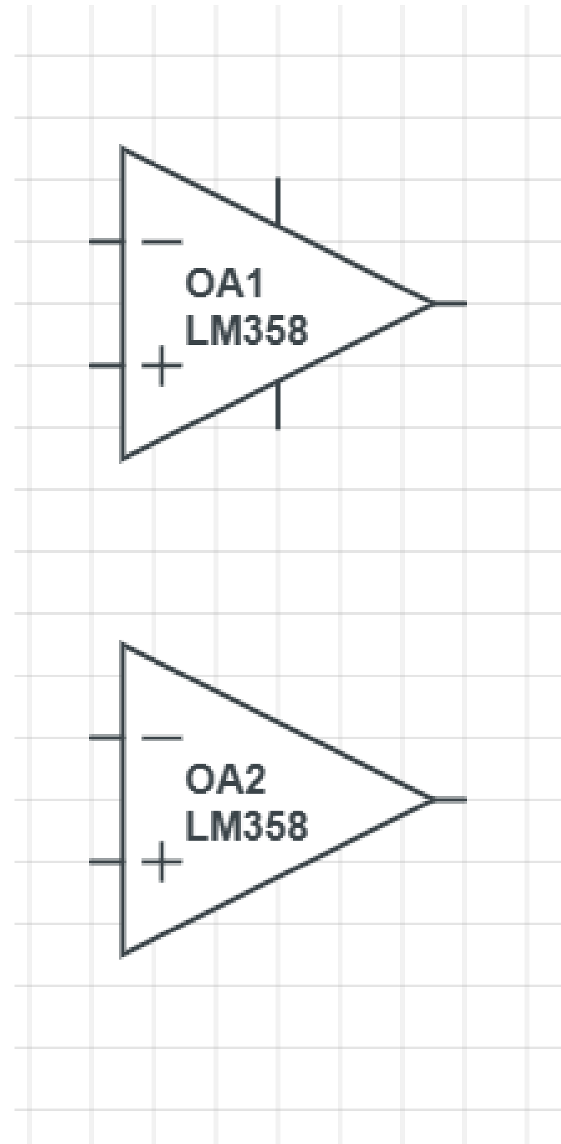
	General Purpose			Digital	Power
	LM741 not a favorite	LM2904N*	LM358G*	MCP602*	OPA2544
Voltage (min)	+/- 5V	+/- 2.5V	+/- 2.5V	2.7V	+/- 10V
Voltage (max)	+/- 18V	+/- 20V	+/- 20V	6.0V	+/- 35V
Current Out	25mA	50mA	50mA	22mA	4A
Gain-Bandwith	1.5MHz	700kHz	700kHz	2.8MHz	1.4MHz
Package	DIP8	DIP8	DIP8	DIP8	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)

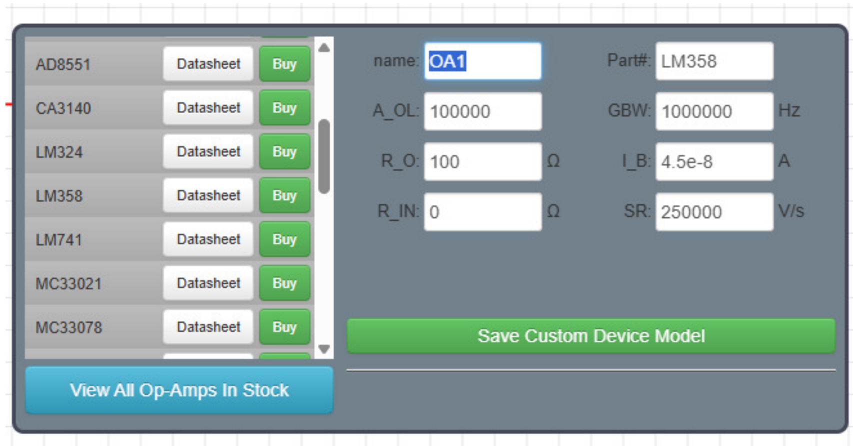
Analog Amplifiers

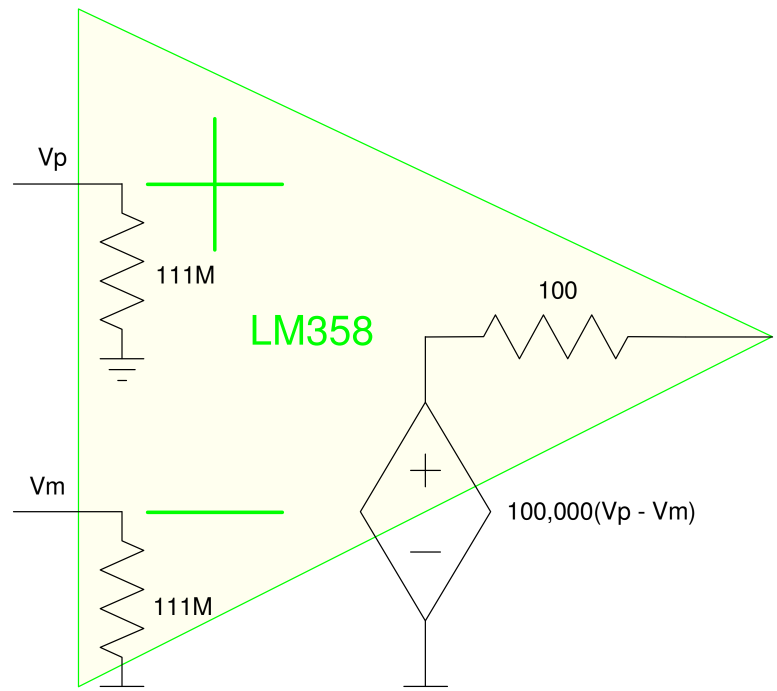
- 3-Lead
- Assumes power supply doesn't matter

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





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

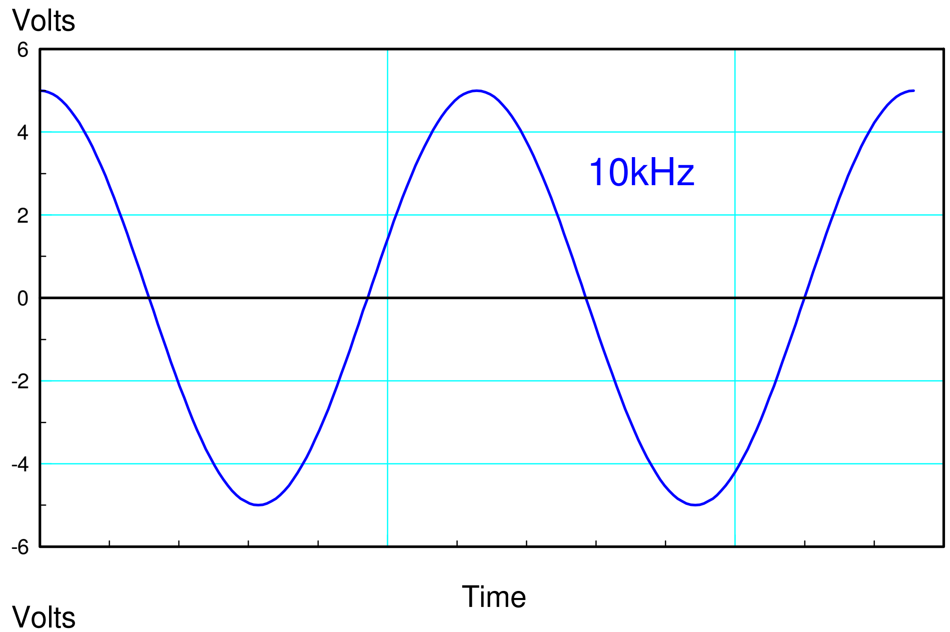
The fastest the output can change

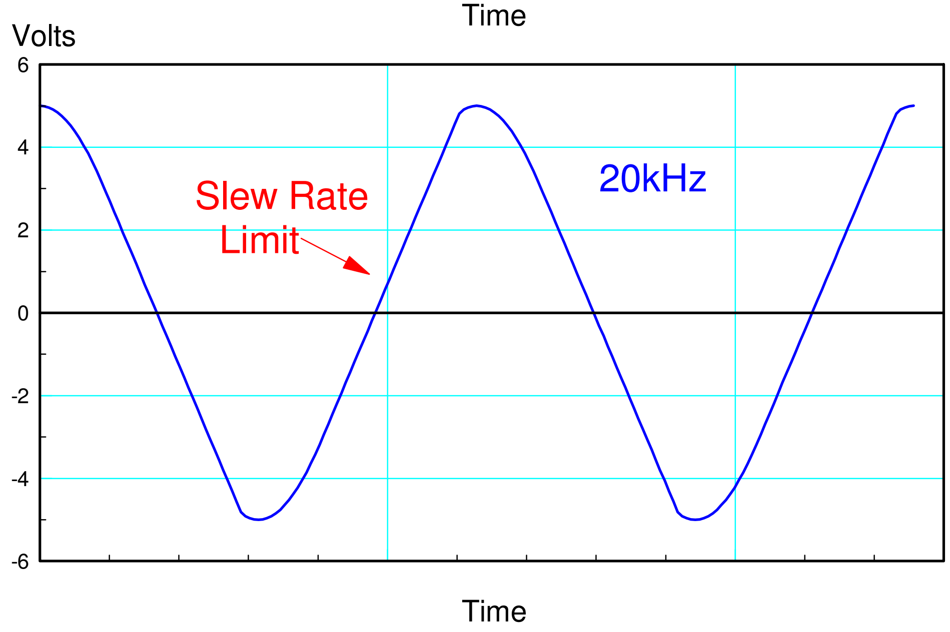
Top:

- 5Vp
- 10kHz sine wave
- No Distortion

Bottom:

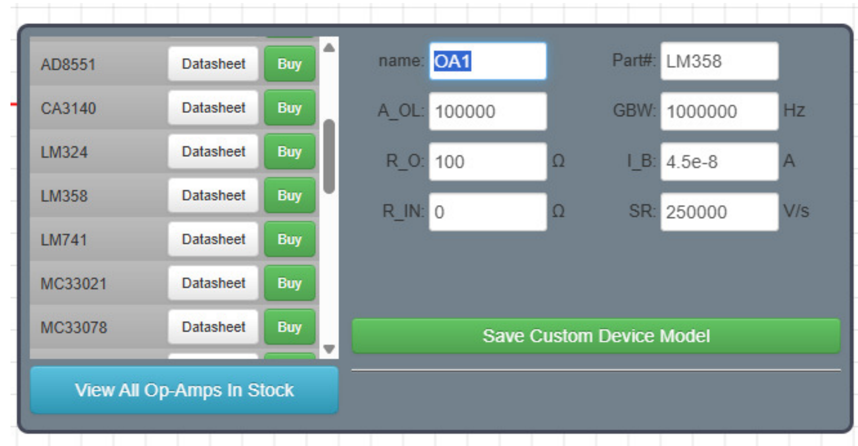
- 5Vp
- 20kHz sine wave
- Hit the slew-rate limit





Op-Amp Circuit Model

- LM2904
- LM358



A_OL

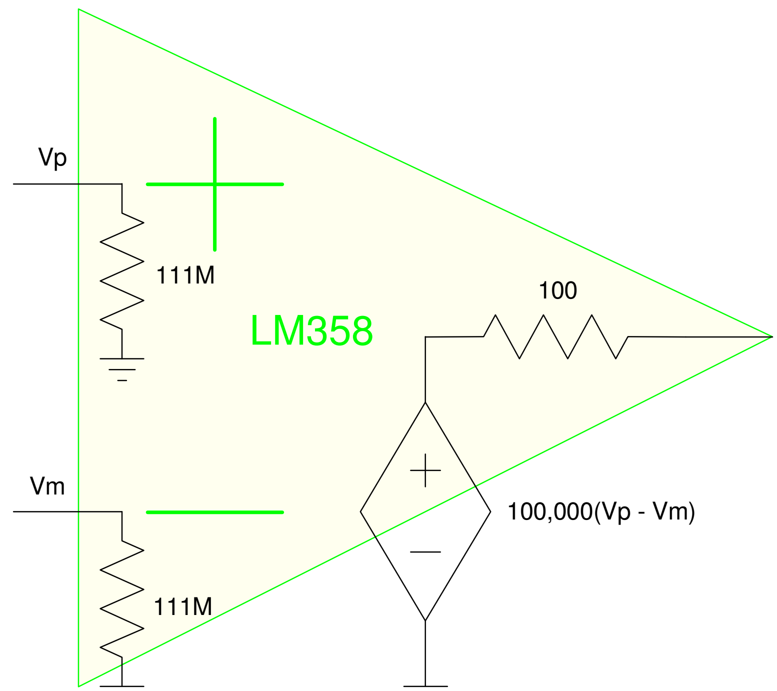
- Open-Loop Gain
- 100,000

R_O

- Output Resistance
- 100 Ohms

I_B

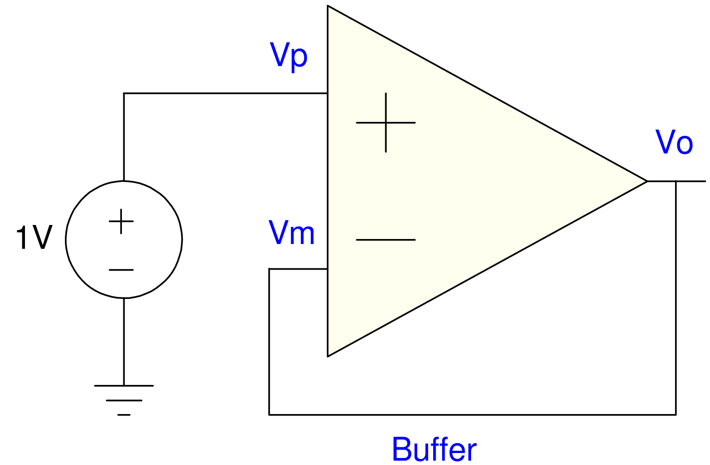
- Input Bias Current
- 45nA
- 111M Ohms @ 5V

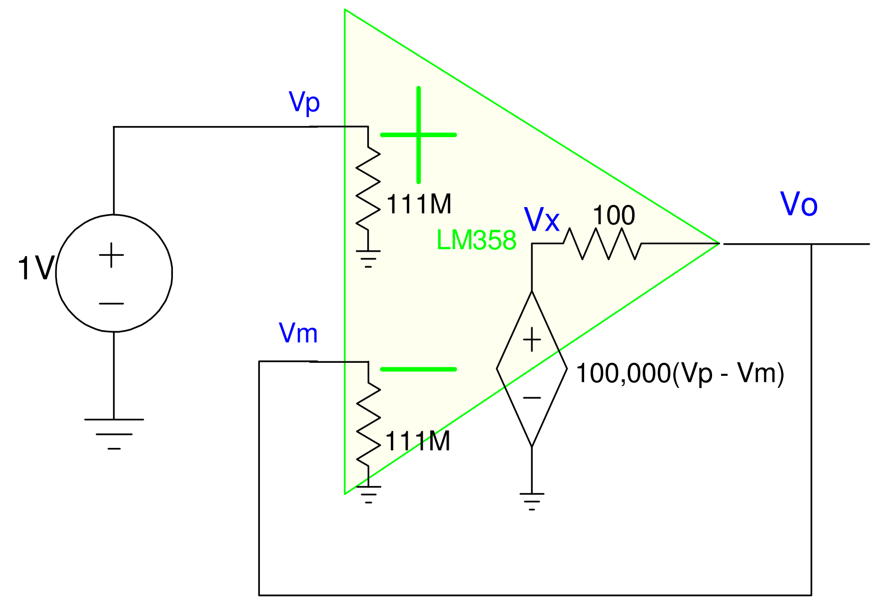


Buffer

Replace the op-amp with its circuit model

Write the voltage node equations





Buffer

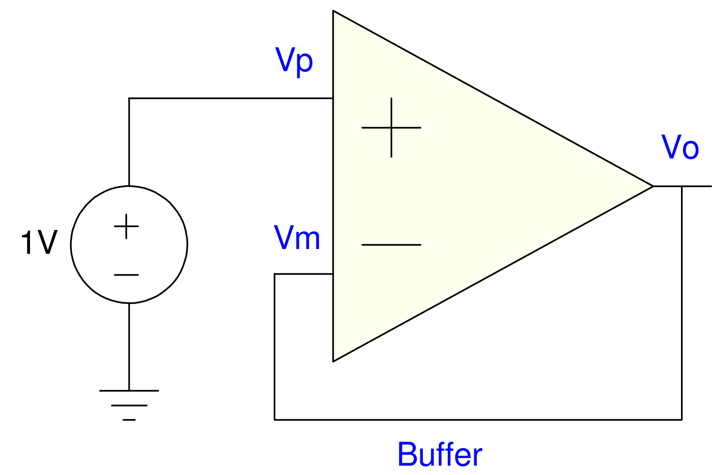
Node Equations

$$V_p = 1$$

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

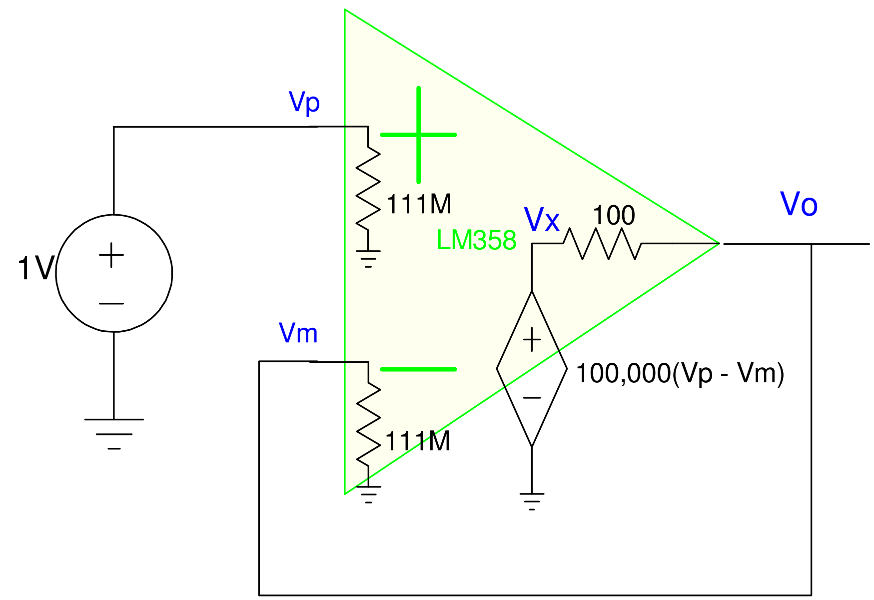
$$V_o = V_m$$

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



Solve (Matlab)

```
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

Buffer

CircuitLab Simulation

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

V1 = V2

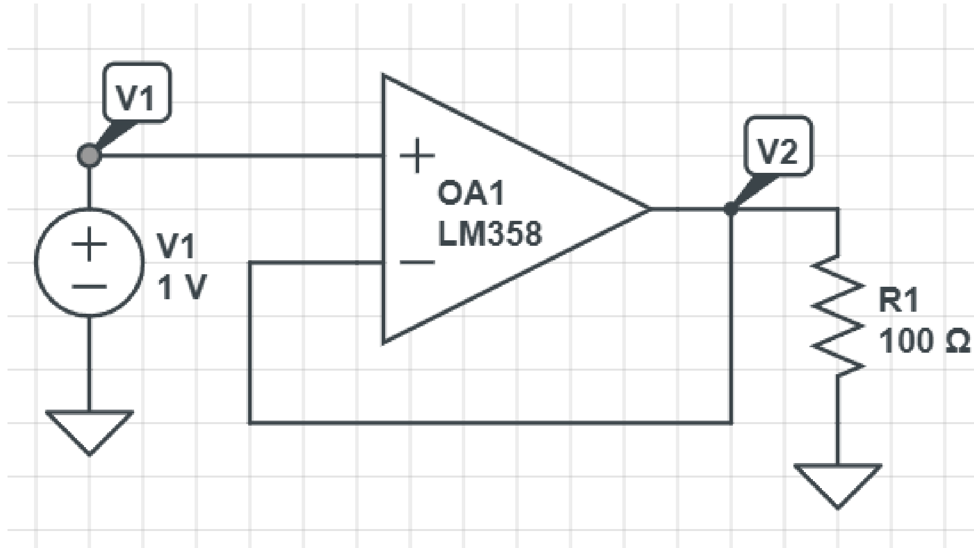
- Rounding to 3 decimal place

I(in) = 45nA

- R(in) = 1V @ 45nA = 22M

I(out) = 10mA

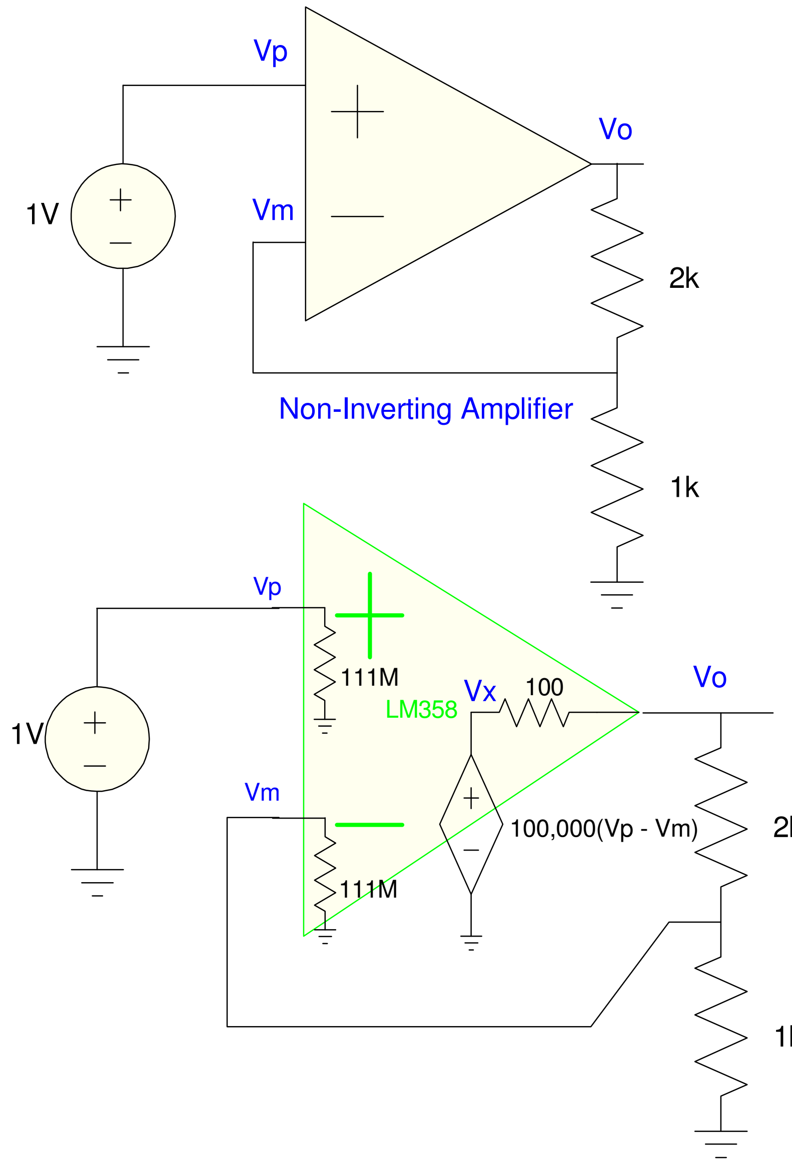
- This circuit has a gain of 1.000
- The input impedance is 111M Ohm
- The output impedance is 0.001 Ohm
- V2 = V1
- R1 doesn't load V1 ("buffer")



Noninverting Amplifier

Replace the op-amp with its circuit model

Write the voltage node equations



Non-Inverting Amplifier

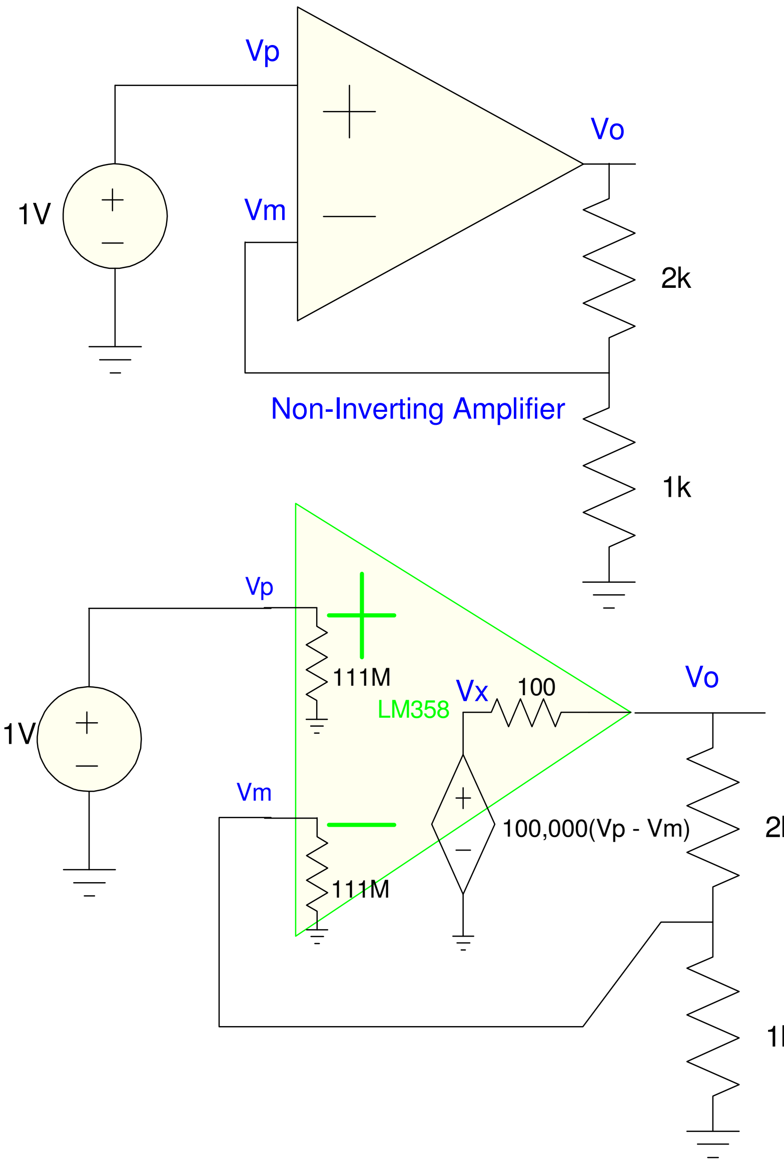
Node Equations

$$V_p = 1$$

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

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

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



Solve (Matlab)

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

Note:

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

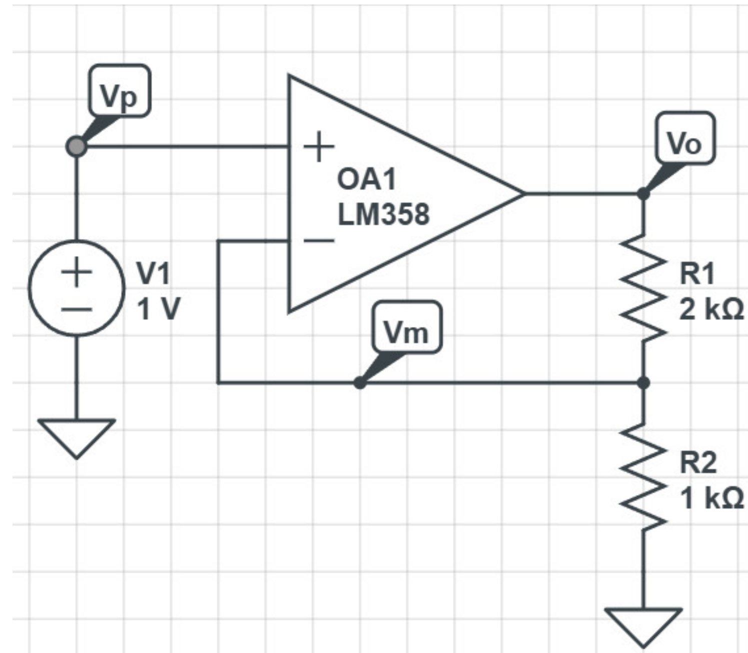
Non-Inverting Amplfiier

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)

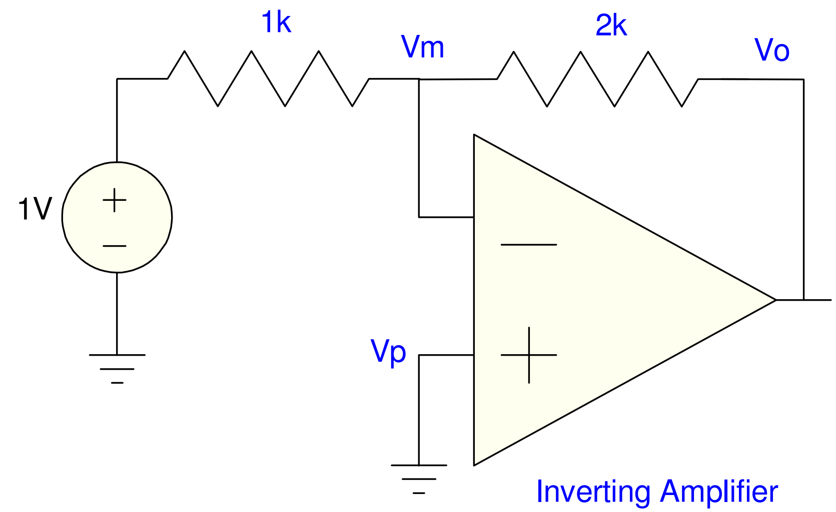


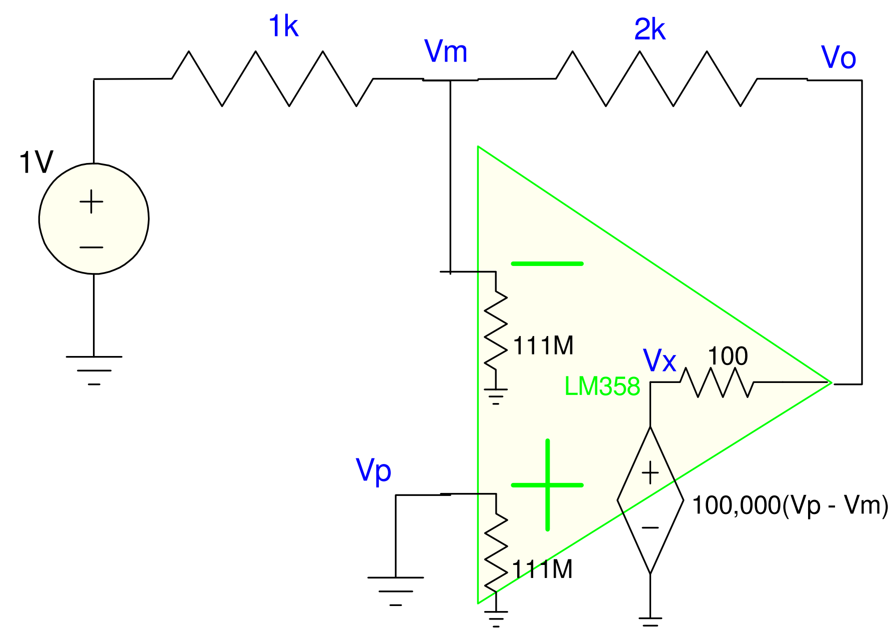
V(Vo)	3.000 V
V(Vp)	1.000 V
V(Vm)	1.000 V
I(OA1.nIN_POS)	45.00 nA
I(OA1.nIN_NEG)	45.00 nA
I(OA1.nOUT)	-1.000 mA

Inverting Amplifier

Replace the op-amp with its circuit model

Write the voltage node equations





Inverting Amplifier

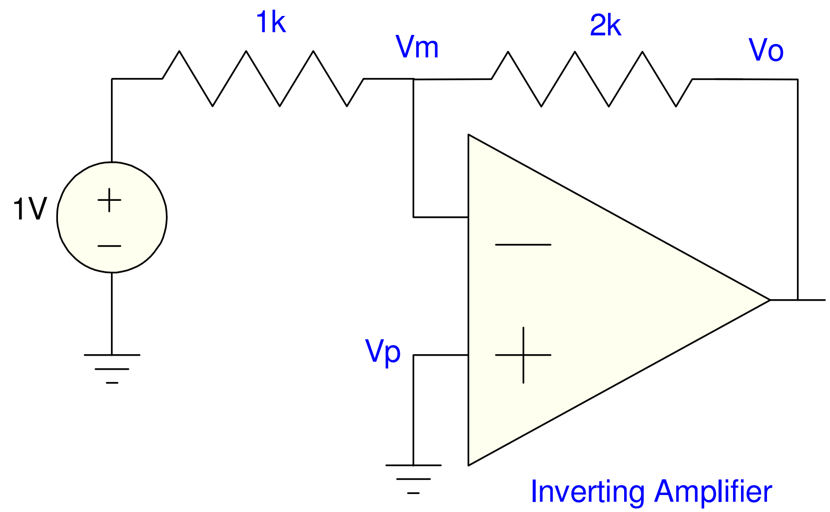
Voltage Node Equations

$$V_p = 0$$

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

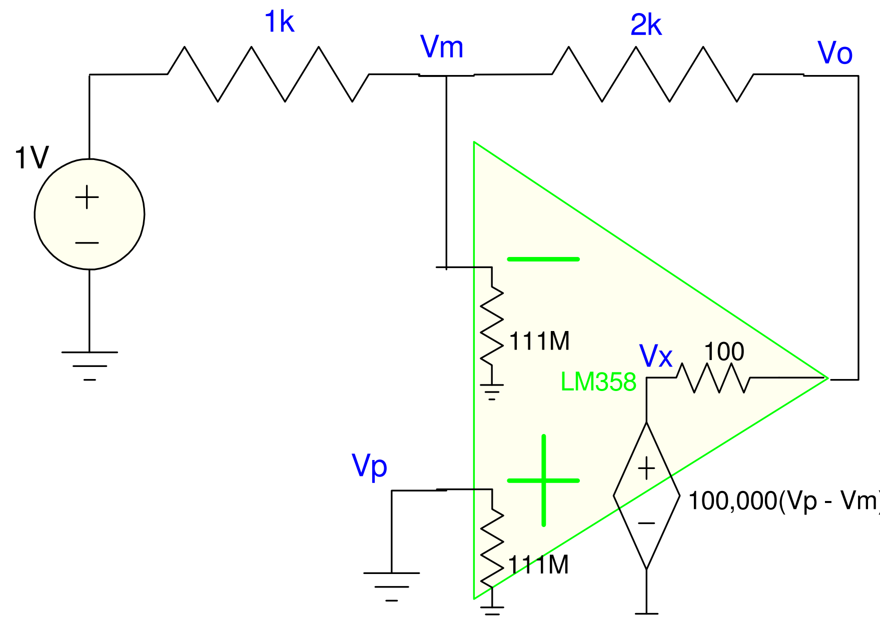
$$\left(\frac{V_m - 1}{1k}\right) + \left(\frac{V_m}{111M}\right) + \left(\frac{V_m - V_o}{2k}\right) = 0$$

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



Solving in Matlab

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



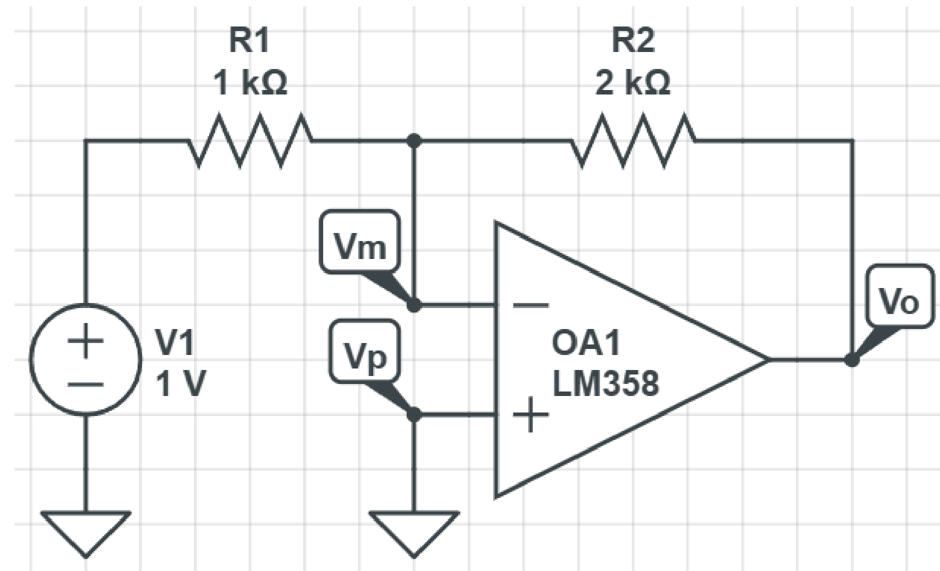
Note:

- I(short) = -666.6A (CircuitLab)
- Rth = 0.003 Ohms

Inverting Amplfiier

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