



Lecture 4

- Operational Amplifiers

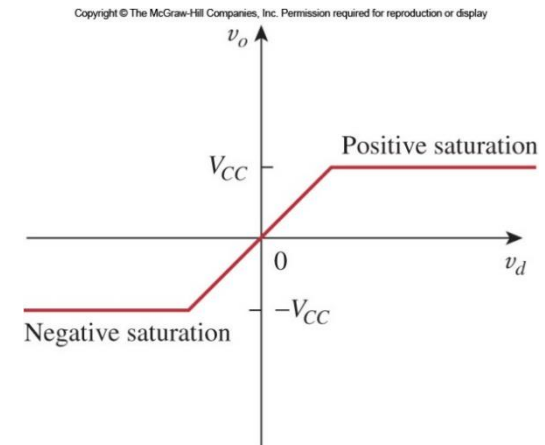
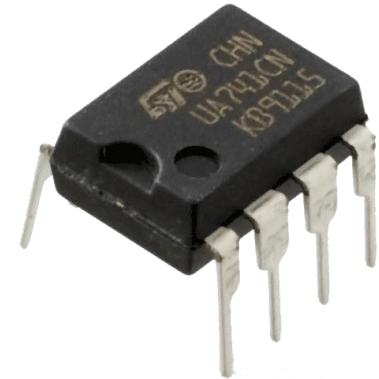


Outline

- Operational amplifier (op amp)
- Ideal op amp
 - Inverting op amp
 - Noninverting op amp
 - Voltage follower
 - Difference amplifier
- Application: DAC

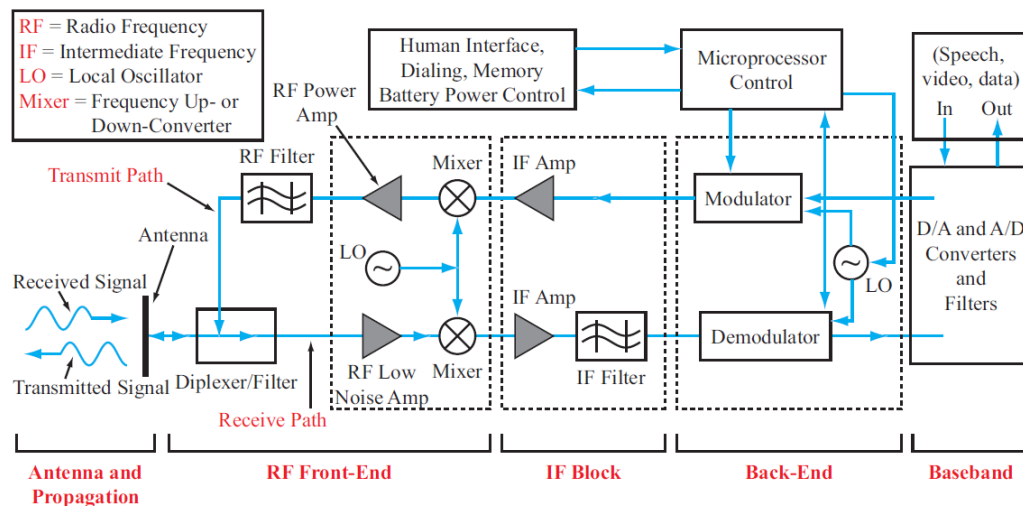
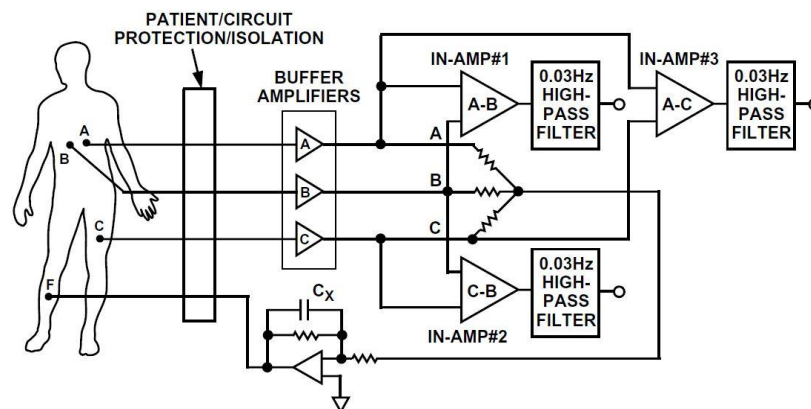
The Op Amp

- When combined with resistors, capacitors, and inductors, can perform various functions:
 - amplification/scaling
 - sign changing
 - addition/subtraction/multiplication/division
 - integration
 - differentiation
 - analog filtering
 - nonlinear functions (exponential, log, sqrt)
- Isolate input from output.



Where do You Use Op AMP?

- Signal generators
- Audio amplifiers
- Hearing aids
- Medical sensor interface
- Baseband receivers
- A/D converters
- Oscillators
- Voltage regulators
- Active filters





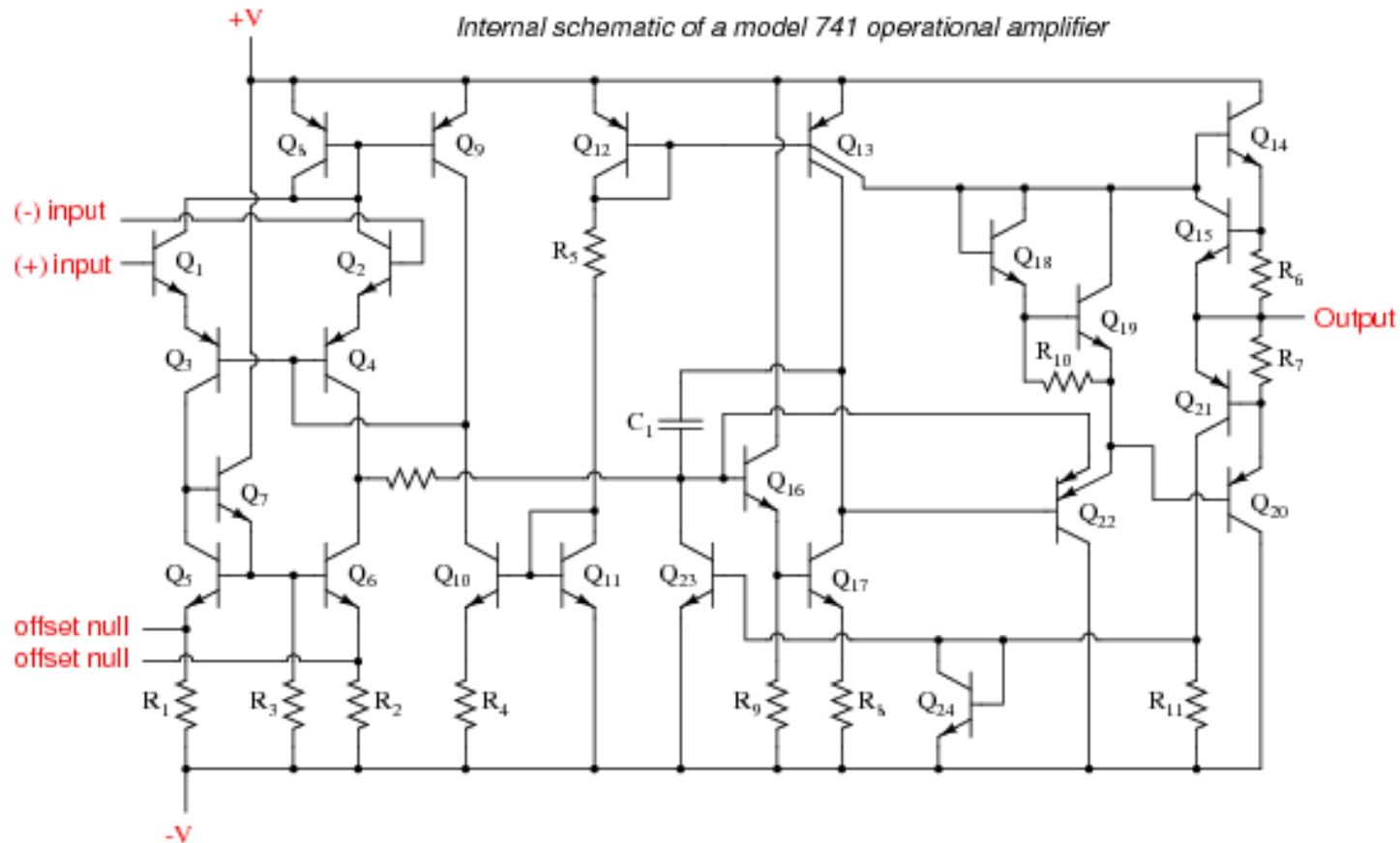
Brief History

- The Operational Amplifier (op amp) was invented in the 40's.
 - Bell Labs filed a patent in 1941.
- Many consider the first practical op amp to be the vacuum tube K2-W invented in 1952 by George Philbrick.
- Bob Widlar at Fairchild invented the uA702 op amp in 1963.
- Until **uA741**, released in 1968, op amps became relatively inexpensive and started on the road to ubiquity.

https://en.wikipedia.org/wiki/Operational_amplifier

What are Inside an Op Amp?

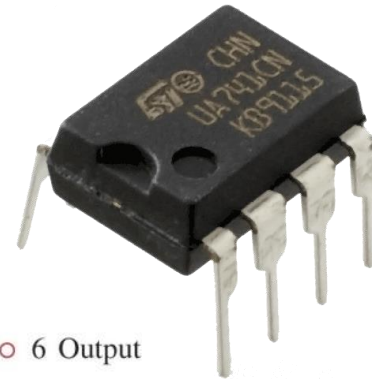
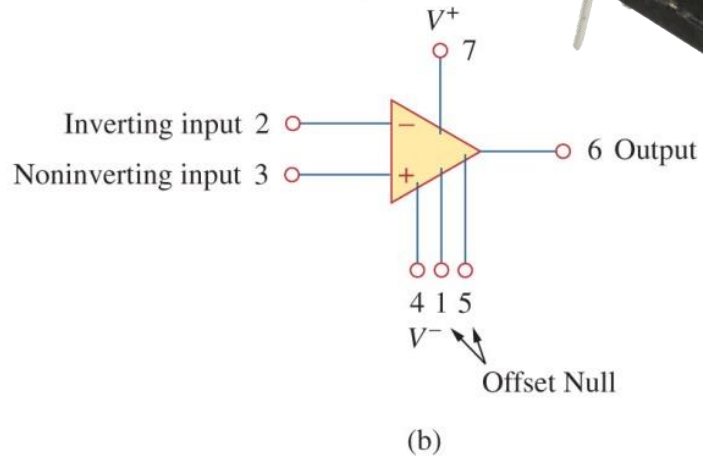
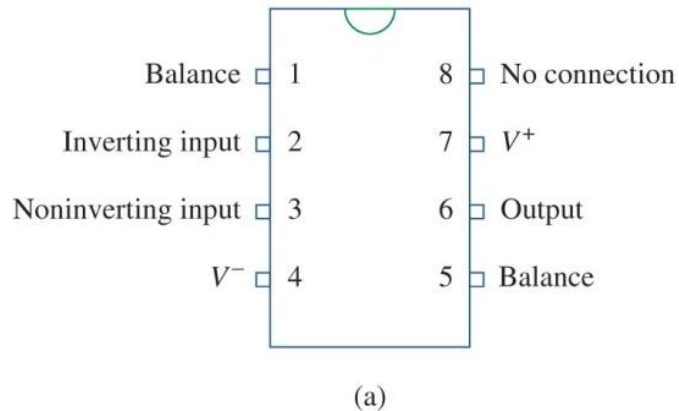
- Origins at Fairchild Semiconductor in 1968.



Source: http://www.ibiblio.org/kuphaldt/electricCircuits/Semi/SEMI_8.html#xtocid109742.

Op Amp Terminals

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• Five important terminals

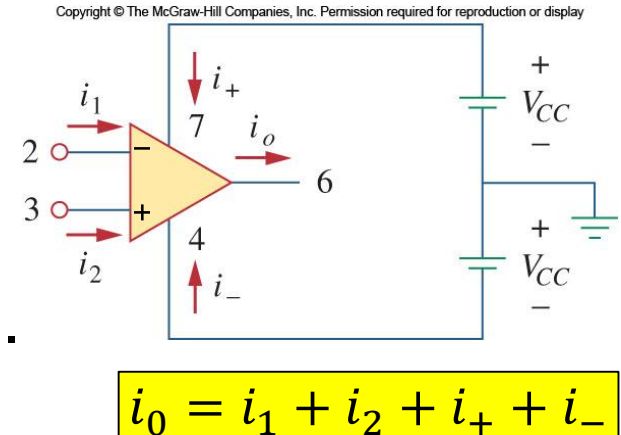
- The inverting input
- The noninverting input
- The output
- The positive (+) power supply
- The negative (-) power supply

• The rest three terminals

- 2 Offset Null (Balance)
 - May used in auxiliary circuit to compensate for performance degradation due to aging etc.
- 1 No Connection (NC)
 - Unused, not connected to the amplifier circuit.

Powering an Op Amp

- As an *active* element, the op-amp requires a power source.
 - Often in circuit diagrams the power supply terminals are obscured (ignored).
 - The supply current cannot be overlooked.
- Most op-amps use two voltage sources, with a ground reference between them.
 - This gives a positive and negative supply voltage.



Output Voltage

- The voltage output of an op-amp is proportional to the difference between the noninverting and inverting inputs

$$v_o = Av_d = A(v_2 - v_1)$$

- Here, A is called the open loop gain.
- Ideally A is infinite. In real devices, it is still high: 10^5 to 10^8 .

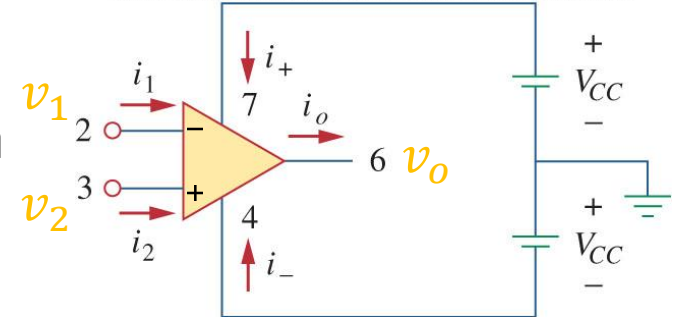
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TABLE 5.1

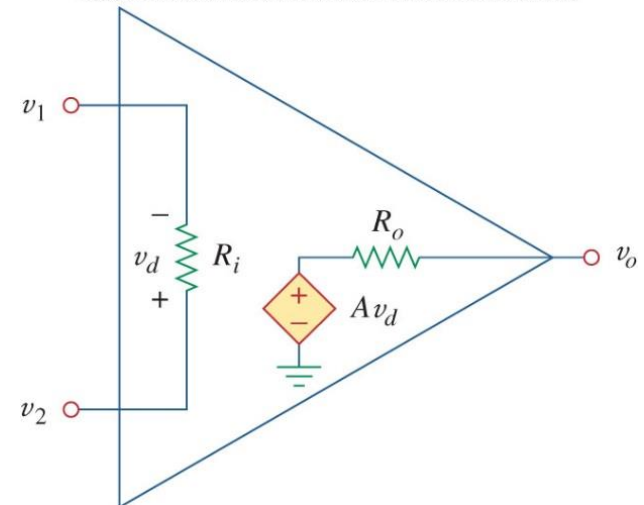
Typical ranges for op amp parameters.

Parameter	Typical range	Ideal values
Open-loop gain, A	10^5 to 10^8	∞
Input resistance, R_i	10^5 to $10^{13} \Omega$	$\infty \Omega$
Output resistance, R_o	10 to 100Ω	0Ω
Supply voltage, V_{CC}	5 to 24 V	

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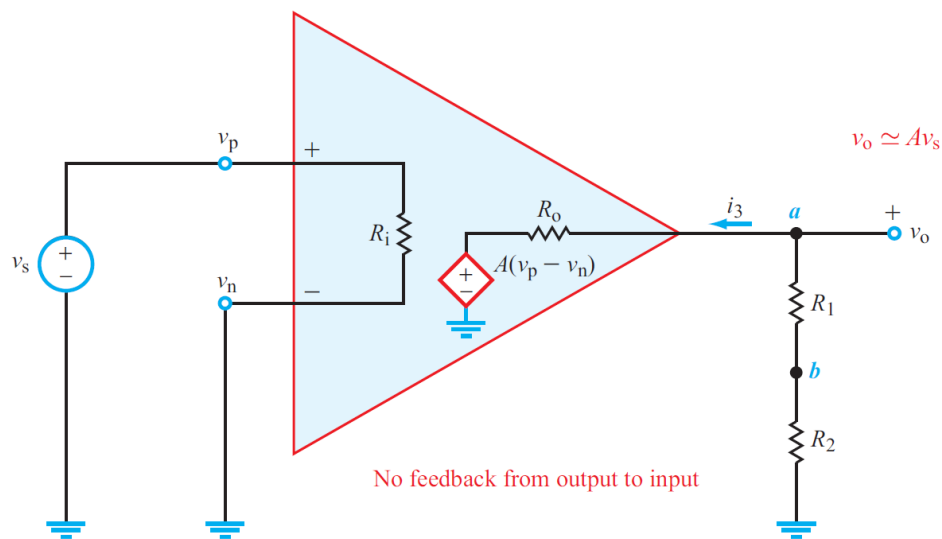
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Example 1

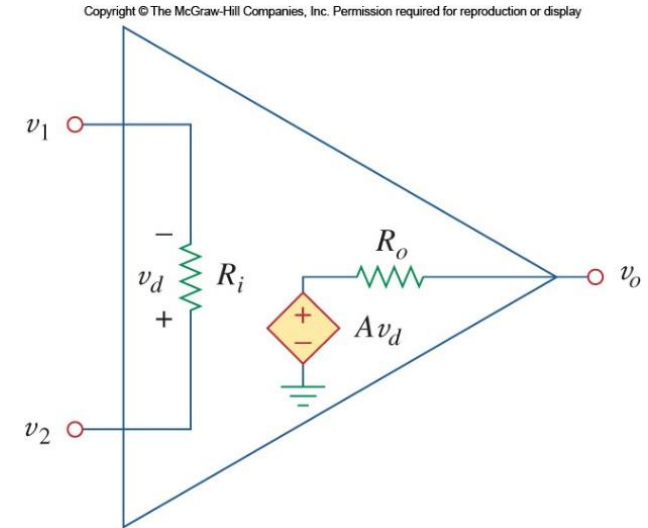
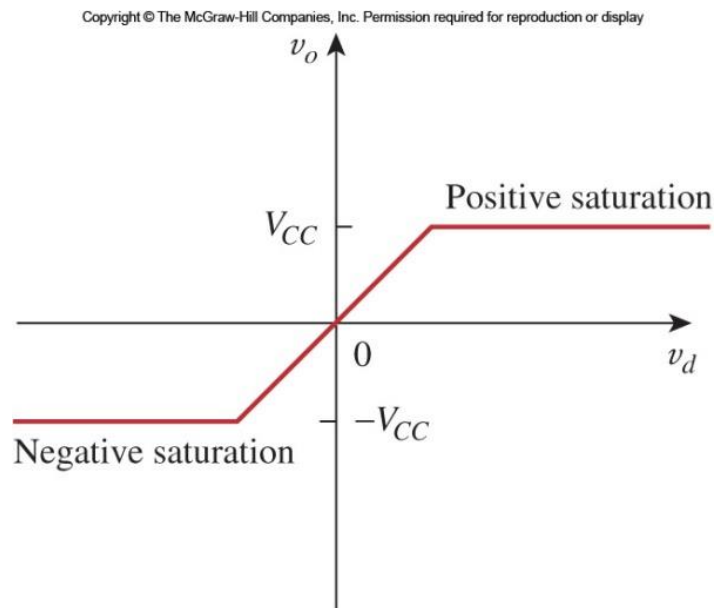
For $V_{cc} = 10 \text{ V}$, $A = 10^6$, $R_i = 10^7 \text{ } \Omega$, $R_o = 10 \text{ } \Omega$,
 $R_1 = 80 \text{ k}\Omega$, and $R_2 = 20 \text{ k}\Omega$,





Voltage Saturation

- Is the output voltage unlimited?

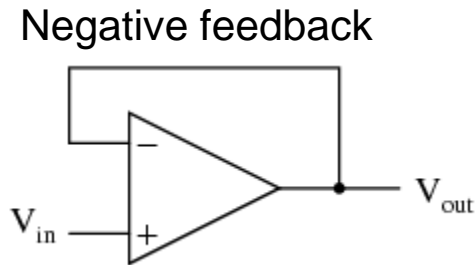


How do we know the op-amp is operating in linear region?

$$v_o = \begin{cases} -V_{cc} & A v_d < -V_{cc} \\ A v_d & -V_{cc} \leq A v_d \leq +V_{cc} \\ +V_{cc} & A v_d > +V_{cc} \end{cases}$$



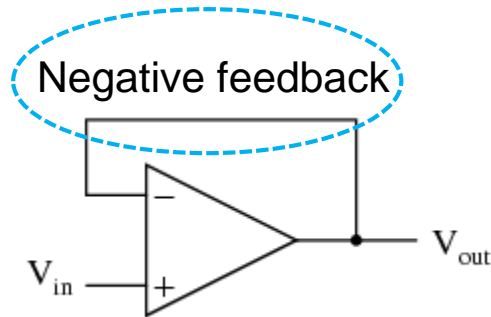
Negative Feedback



- A self-stabilizing system (also true for any dynamic system in general), giving the op-amp the capacity to work in its linear (active) mode.



How Negative Feedback Works?

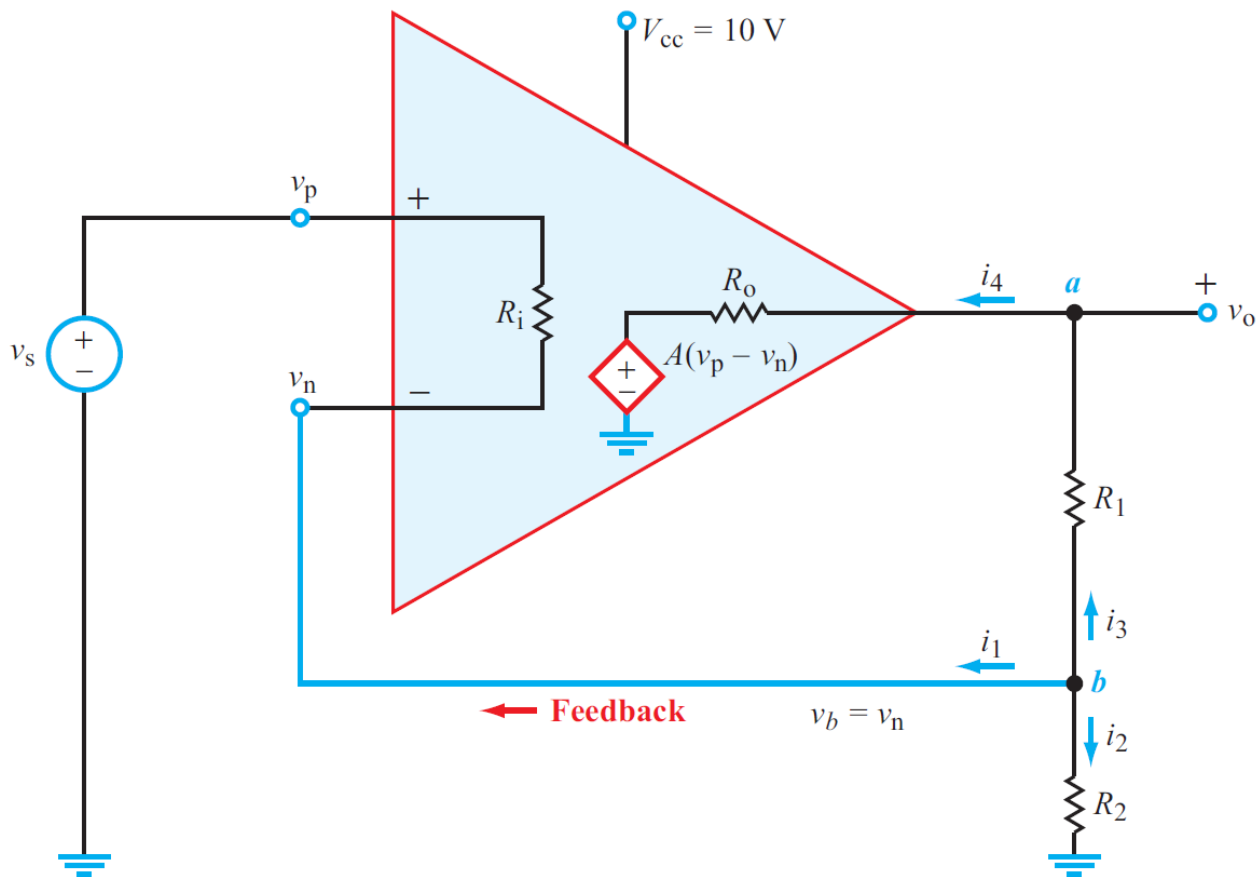


$V_{in} \uparrow \Rightarrow \text{voltage differential} \uparrow \Rightarrow V_{out} \uparrow$
 $\Rightarrow \text{voltage differential} \downarrow \Rightarrow V_{out} \downarrow$
 $\Rightarrow \dots$
 $\Rightarrow V_{out} \rightarrow V_{in}$ but small difference exists



Example

For $V_{cc} = 10 \text{ V}$, $A = 10^6$, $R_i = 10^7 \Omega$, $R_o = 10 \Omega$,
 $R_1 = 80 \text{ k}\Omega$, and $R_2 = 20 \text{ k}\Omega$,

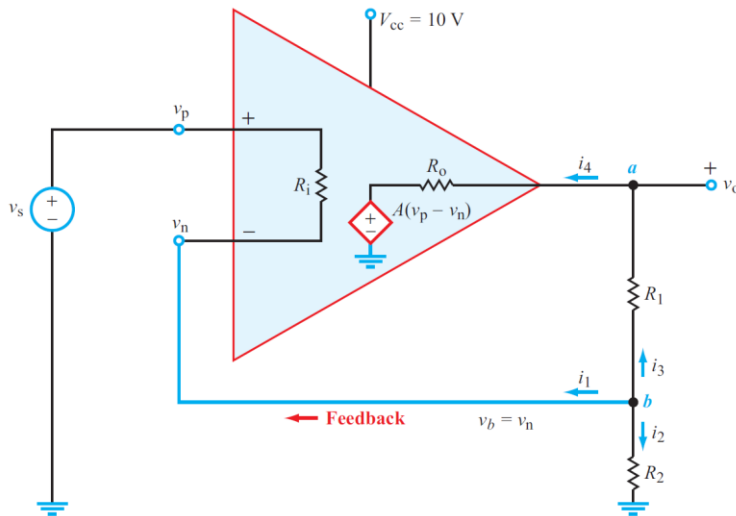




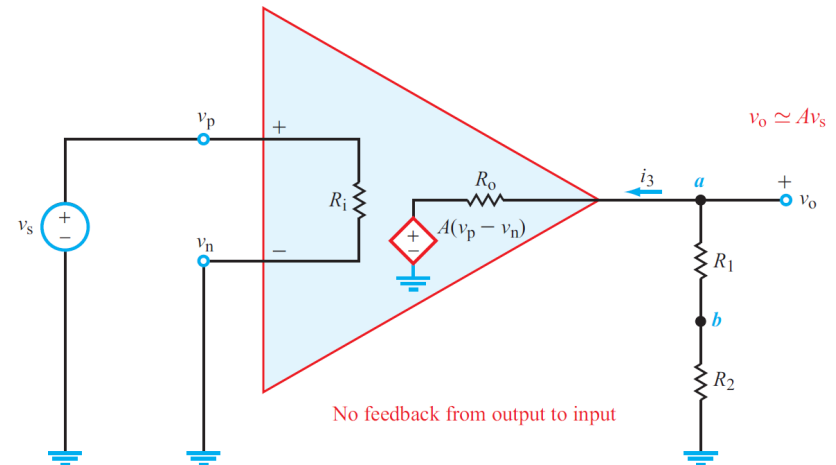
Tradeoff

For $V_{cc} = 10 \text{ V}$, $A = 10^6$, $R_i = 10^7 \Omega$, $R_o = 10 \Omega$,
 $R_1 = 80 \text{ k}\Omega$, and $R_2 = 20 \text{ k}\Omega$,

Negative Feedback



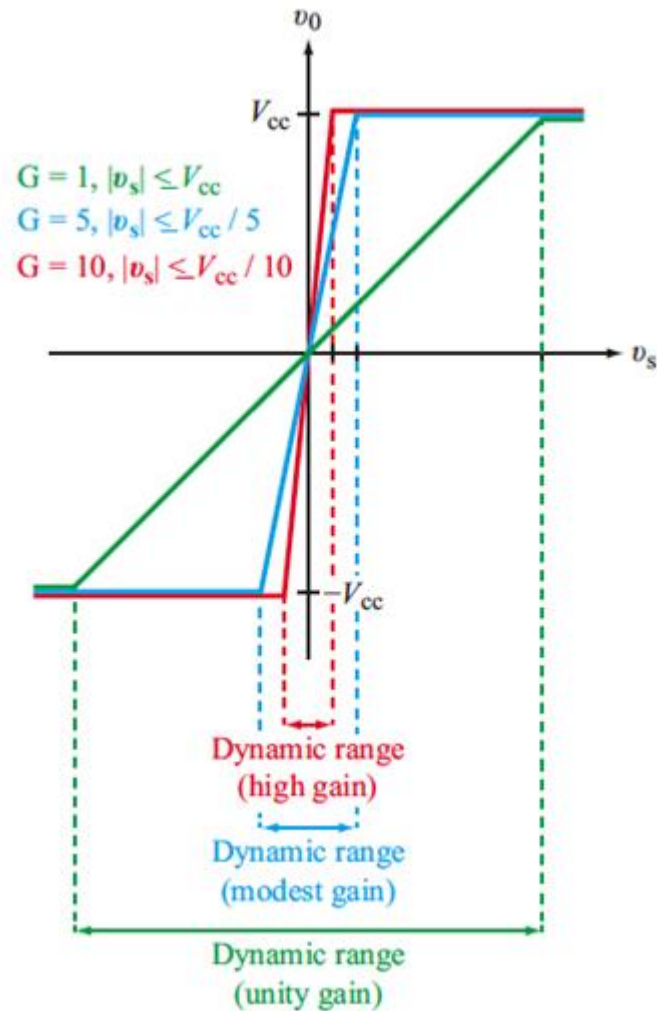
No Feedback



- Circuit gain G
- Linear dynamic range of v_s



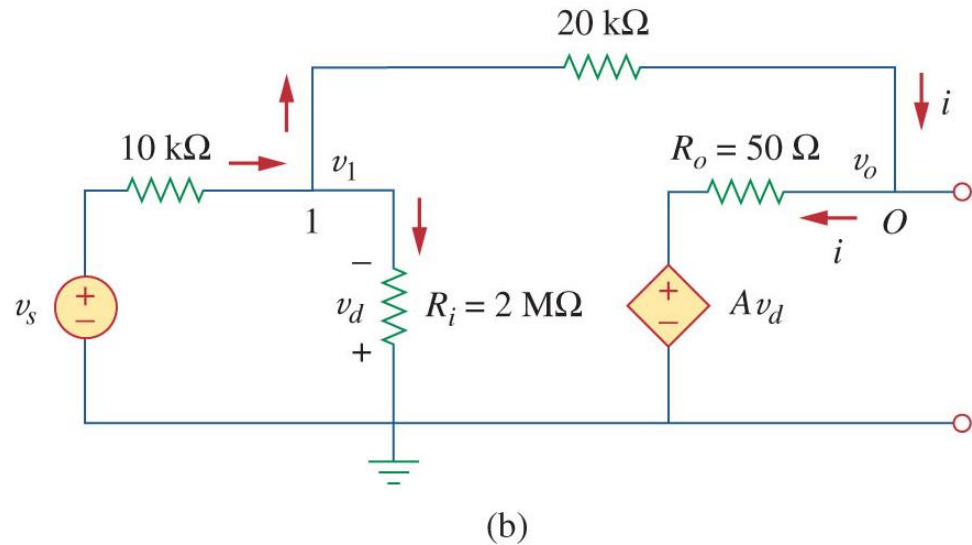
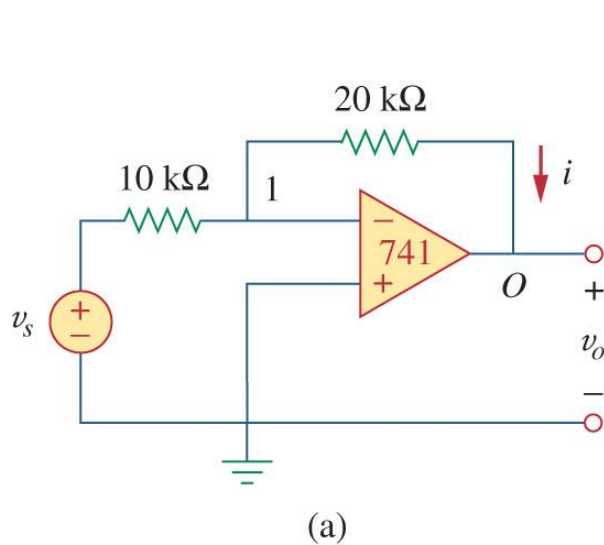
Input-Output Transfer Plot





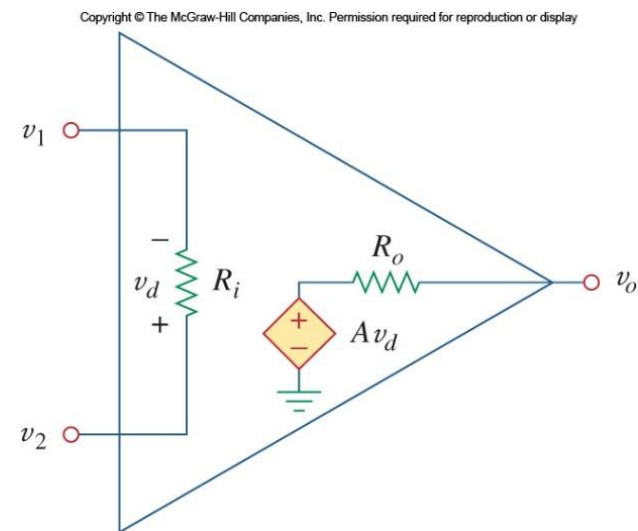
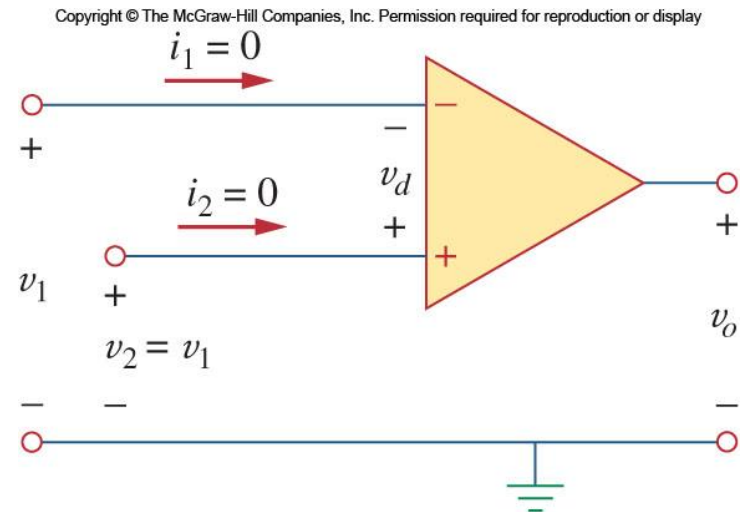
Practice

A 741 op amp has an open-loop voltage gain of 2×10^5 , input resistance of $2M\Omega$, and output resistance of 50Ω . Find the closed-loop gain v_o/v_s . Determine current i when $v_s = 2V$.



Ideal Op Amp

- Attributes of ideal op-amp:
 - infinite open-loop gain, $A \simeq \infty$
 - Implies that $v_2 = v_1$.
 - infinite resistance of the two inputs, $R_i \simeq \infty$
 - This means it will not affect any node it is attached to
 - Implies that $i_1 = i_2 = 0$.
 - zero output impedance, $R_o \simeq 0$
 - From Thevenin's theorem one can see that this means it is load independent.

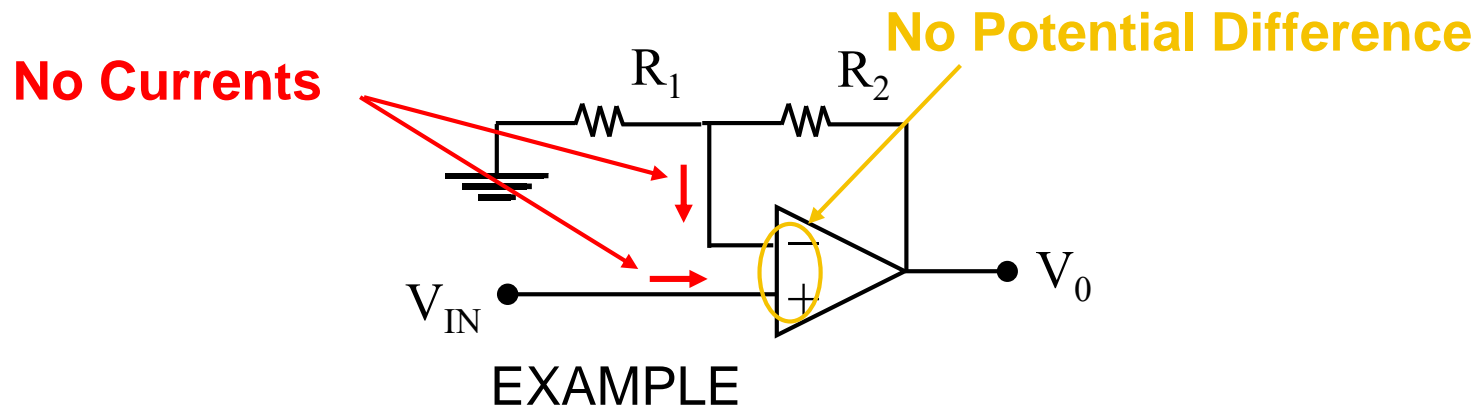




Ideal Op-Amp Analysis – Golden Rules

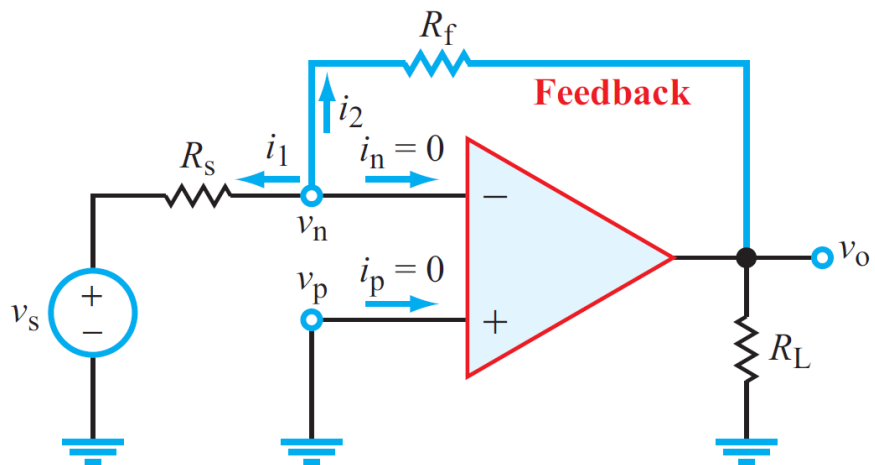
Assumption 1: The **potential** between the op-amp input terminals, $v_{(+)} - v_{(-)}$, equals **zero**.

Assumption 2: The **currents** flowing into the op-amp's two input terminals both equal **zero**.



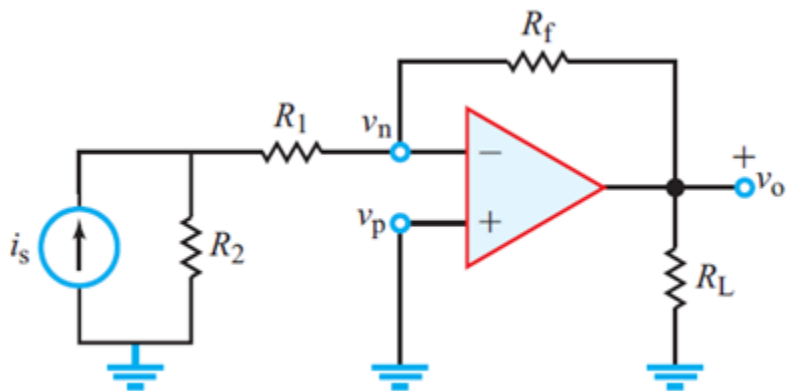


Inverting Amplifier





Example

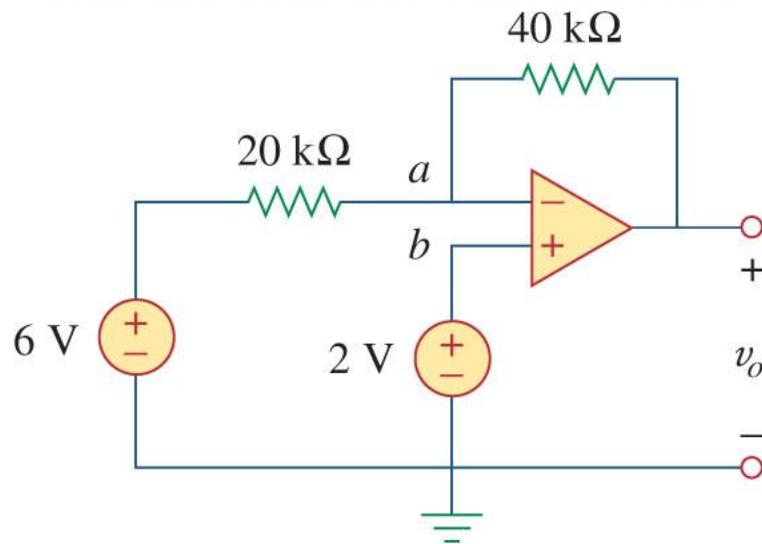




Practice

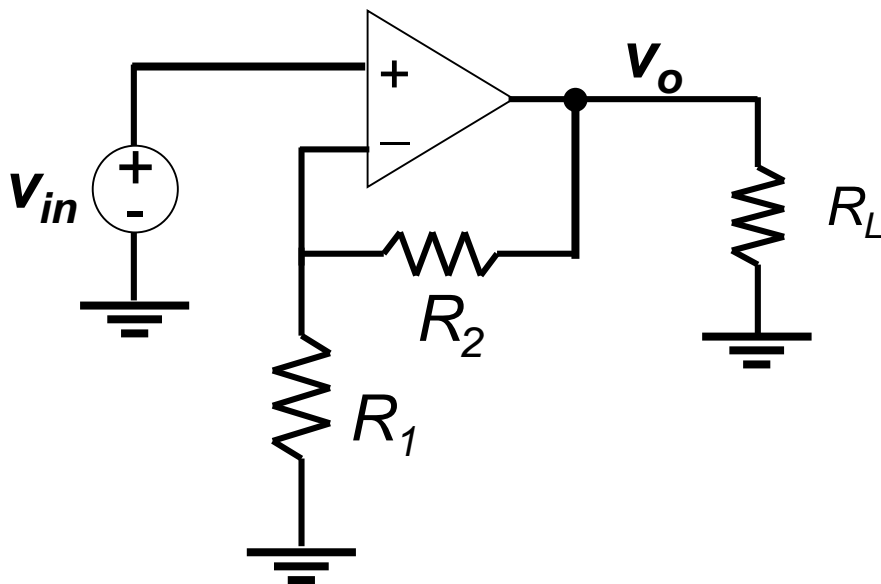
- Determine v_o in the circuit shown below

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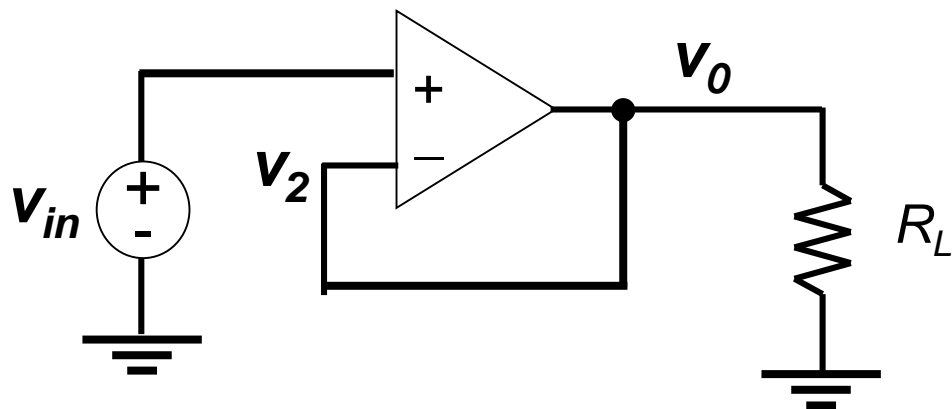


Non-Inverting Amplifier



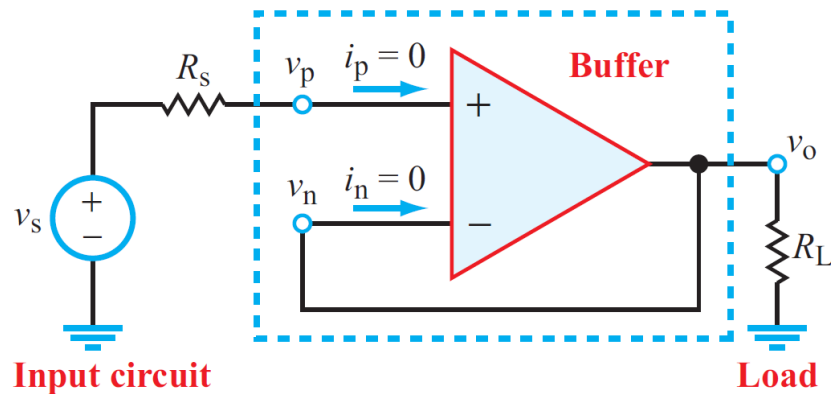


Application: Voltage Follower





Application of Voltage Follower

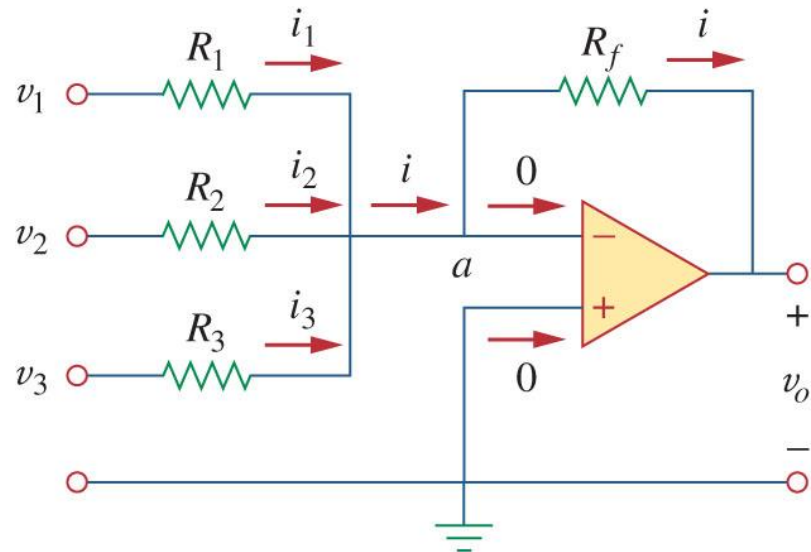
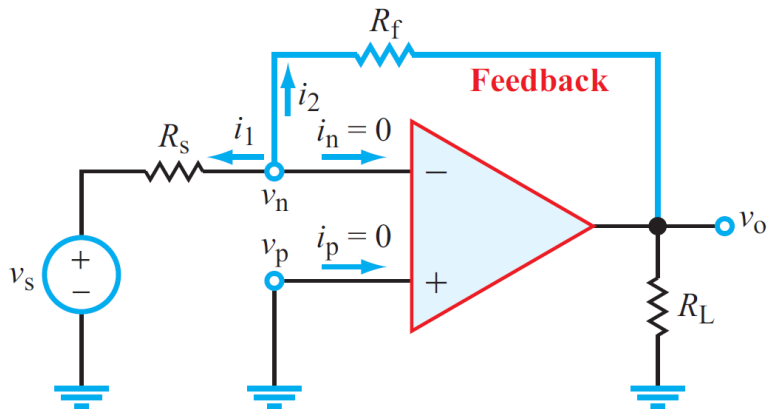


“Buffer” sections of Circuit

Summing Amplifier

- Aside from amplification, the op-amp can be made to do addition very readily.

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Example

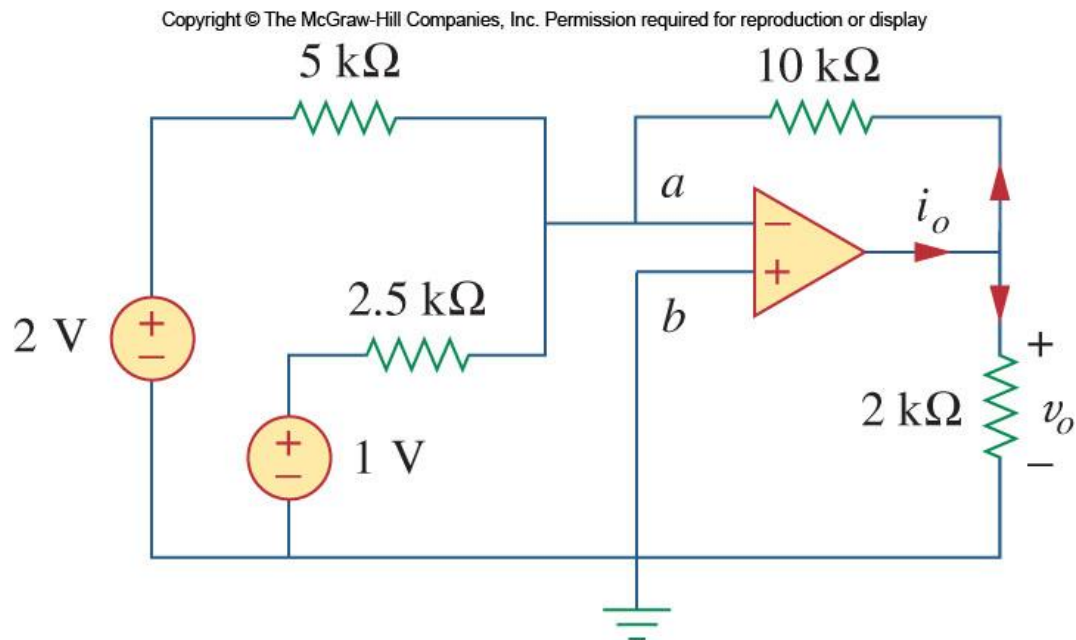
Design a circuit that performs the operation

$$v_o = 4v_1 + 7v_2.$$



Practice

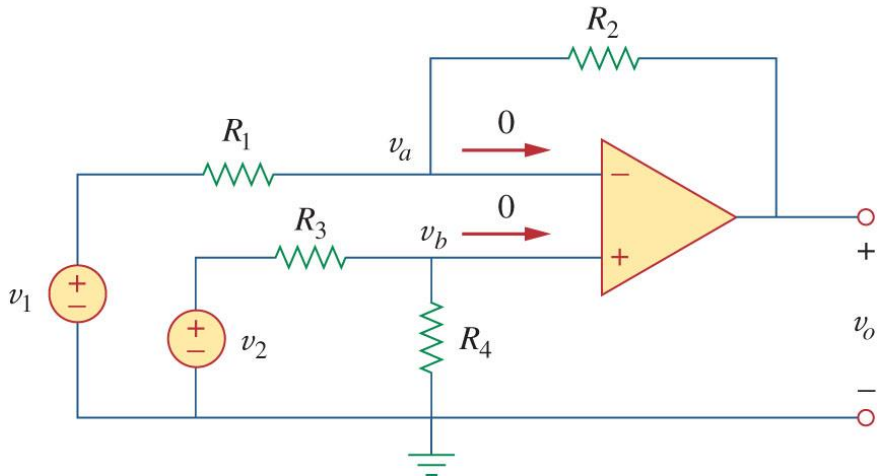
- Find v_o and i_o in the circuit shown below





Difference Amplifier

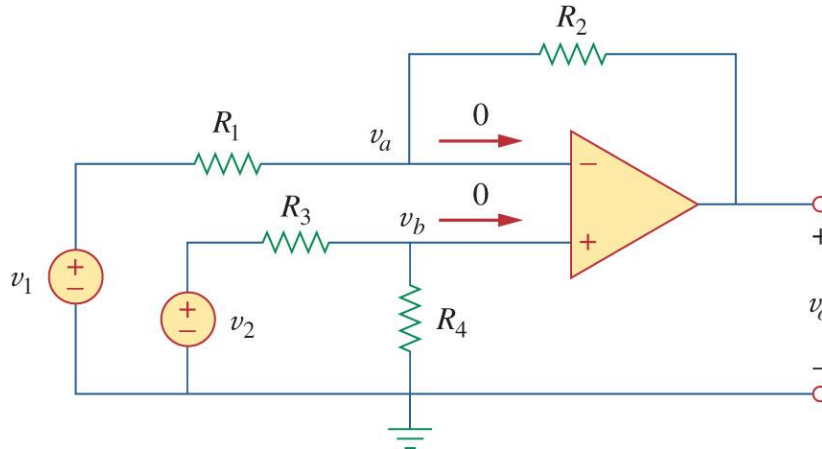
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Common Mode Rejection

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$$v_o = \frac{R_2 (1 + R_1/R_2)}{R_1 (1 + R_3/R_4)} v_2 - \frac{R_2}{R_1} v_1$$

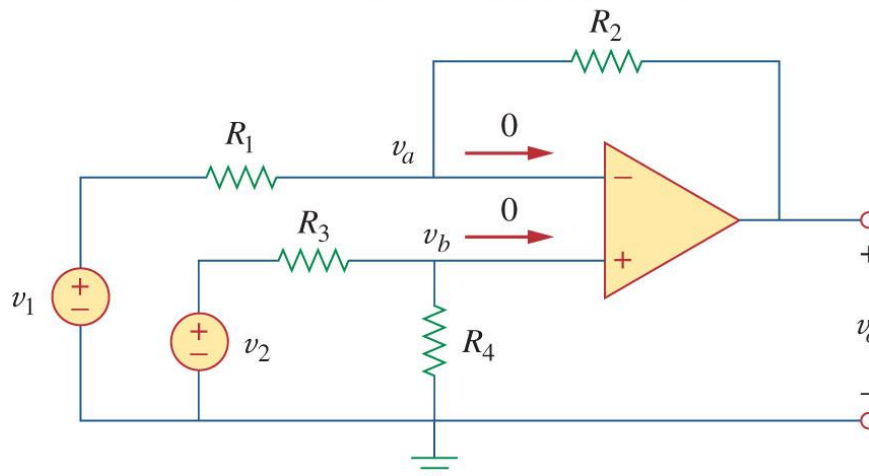
- It is important that a difference amplifier rejects any signal that is common to the two inputs.
 - Which implies that when $v_1 = v_2$, $v_o = 0$.



Example

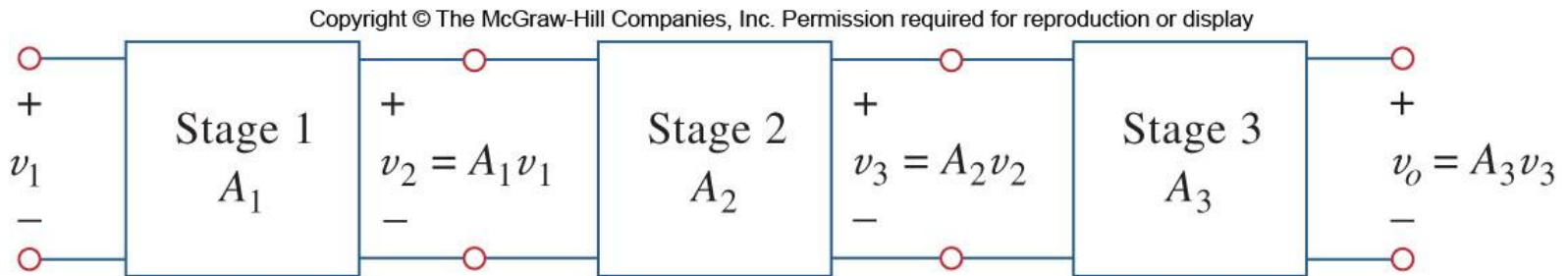
- Design an op amp circuit with inputs v_1 and v_2 such that $v_o = -5v_1 + 3v_2$.

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Cascaded Op Amps

- This head to tail configuration is called “cascading”.
 - Each amplifier is then called a “stage”.



- The gain of a series of amplifiers is the product of the individual gains:

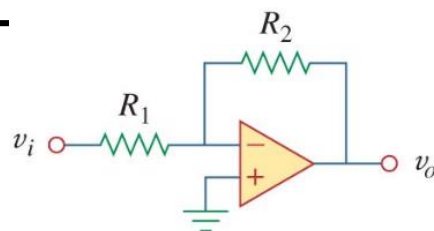
$$A = A_1 \cdot A_2 \cdot A_3$$



Summary

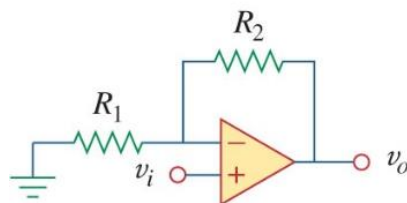
Op amp circuit

Name/output-input relationship



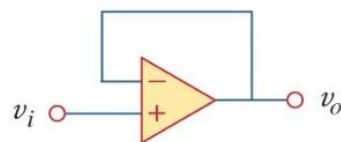
Inverting amplifier

$$v_o = -\frac{R_2}{R_1}v_i$$



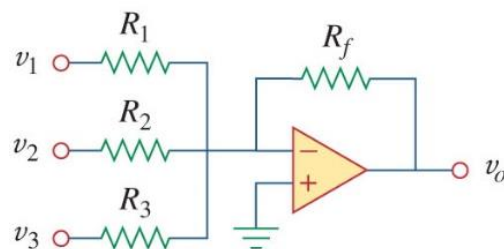
Noninverting amplifier

$$v_o = \left(1 + \frac{R_2}{R_1}\right)v_i$$



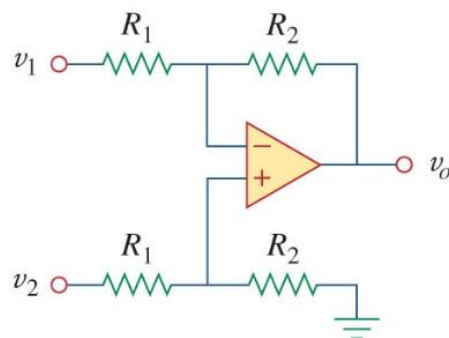
Voltage follower

$$v_o = v_i$$



Summer

$$v_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right)$$



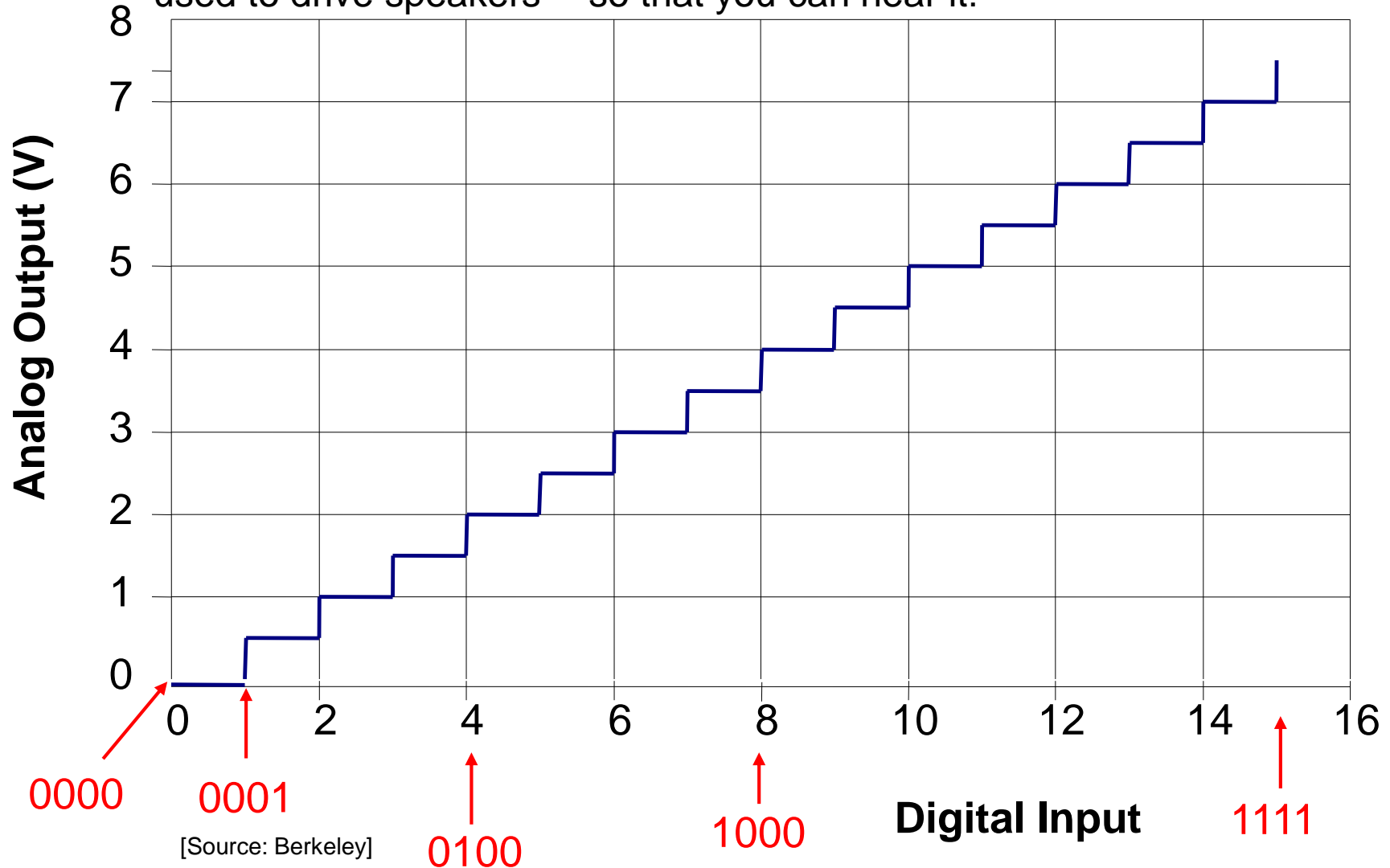
Difference amplifier

$$v_o = \frac{R_2}{R_1}(v_2 - v_1)$$



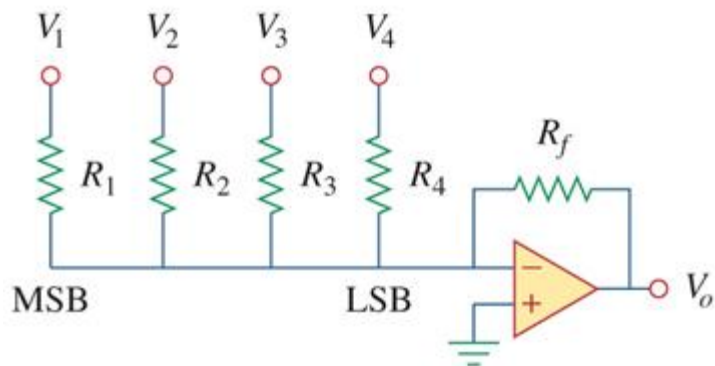
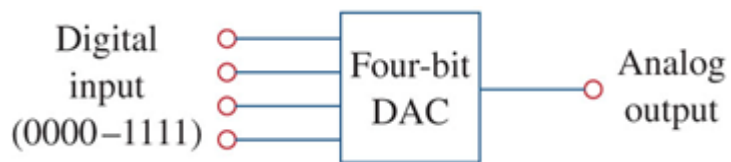
Application - DAC

A DAC can be used to convert the digital representation of an audio signal into an analog voltage that is then used to drive speakers -- so that you can hear it!





DAC



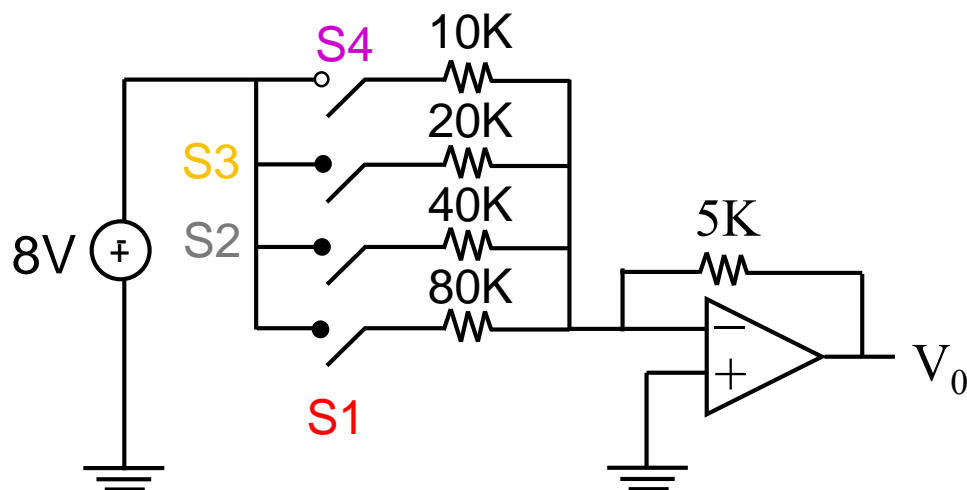
$$-V_o = \frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3 + \frac{R_f}{R_4} V_4$$



DAC

A DAC can be used to convert the digital representation of an audio signal into an analog voltage that is then used to drive speakers -- so that you can hear it!

“Weighted-adder D/A converter”



4-Bit D/A

(Transistors are used as electronic switches)

S1 closed if LSB = 1
S2 " if next bit = 1
S3 " if " " = 1
S4 " if MSB = 1

Binary number	Analog output ($-V_o$)
0 0 0 0	0
0 0 0 1	.5
0 0 1 0	1
0 0 1 1	1.5
0 1 0 0	2
0 1 0 1	2.5
0 1 1 0	3
0 1 1 1	3.5
1 0 0 0	4
1 0 0 1	4.5
1 0 1 0	5
1 0 1 1	5.5
1 1 0 0	6
1 1 0 1	6.5
1 1 1 0	7
1 1 1 1	7.5

↑
↑
 MSB LSB



What are Inside an Op Amp?

Thevenin's Theorem applicable?

- Origins at Fairchild Semiconductor in 1968.

