Lecture 4

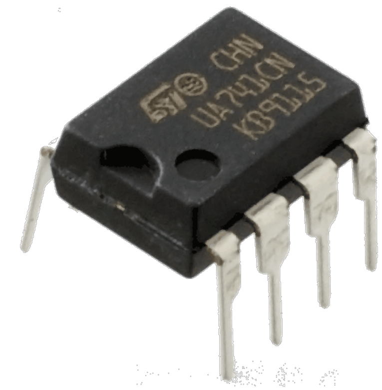
- Operational Amplifiers

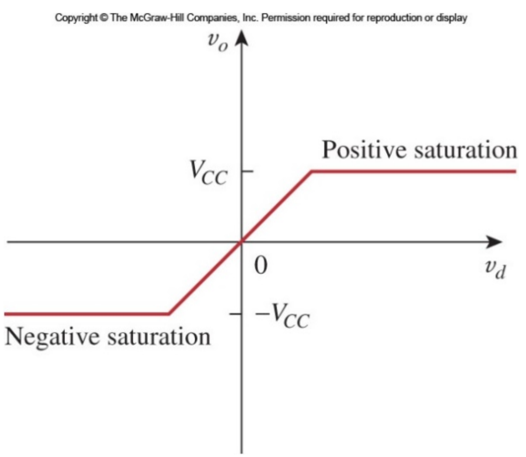
Outline

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

The Op Amp

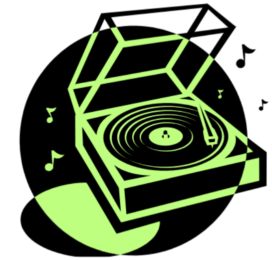
- When combined with resistors, capacitors, and inductors, can perform various functions:
  - amplification/scaling
  - sign changing
  - addition/subtraction/multiplication/division
  - integration
  - differentiation
  - analog filtering
  - nonlinear functions (exponential, log, sqrt)



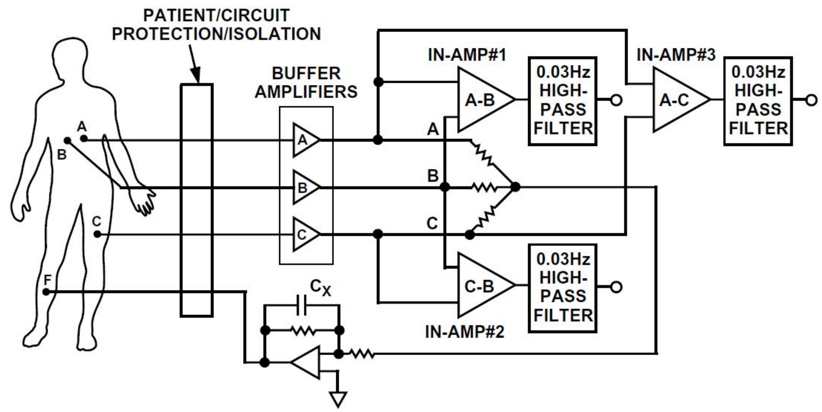


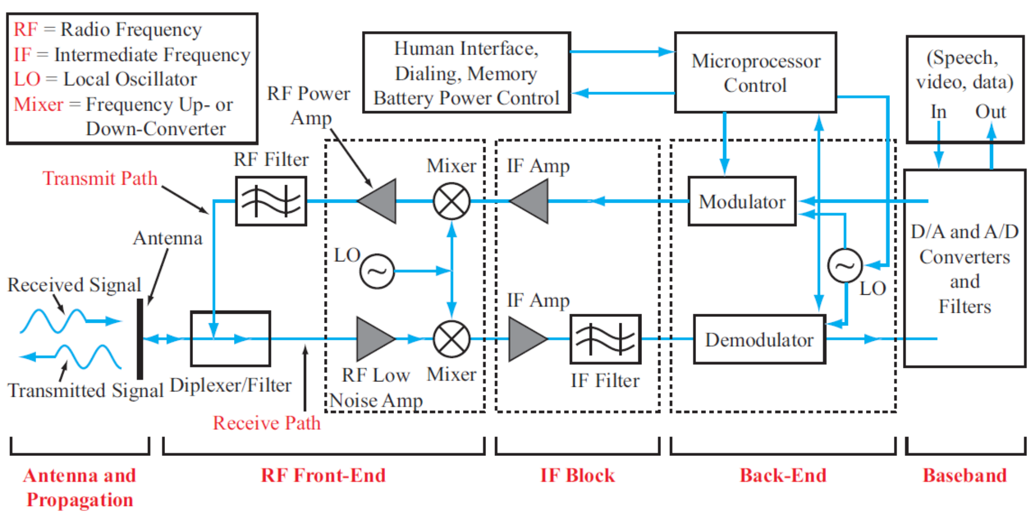
- Isolate input from output.

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

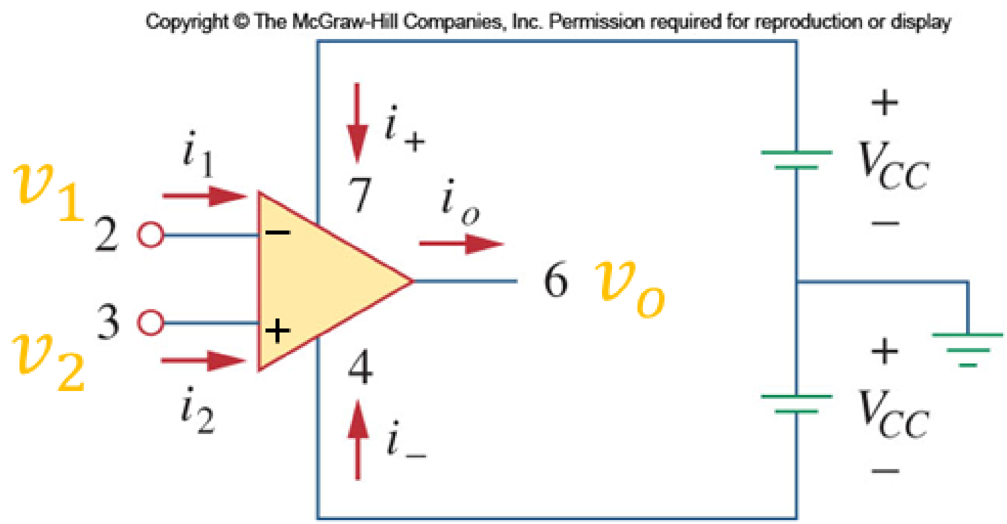
- The Operational Amplifier (op amp) was invented in the 40's.
  - Bell Labs filed a patent in 1941.
- Many consider the first practical op amp to be the vacuum tube K2-W invented in 1952 by George Philbrick.
- Bob Widlar at Fairchild invented the uA702 op amp in 1963.
- Until uA741, released in 1968,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

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

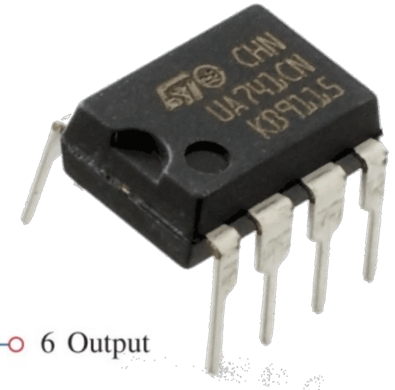
Output Voltage

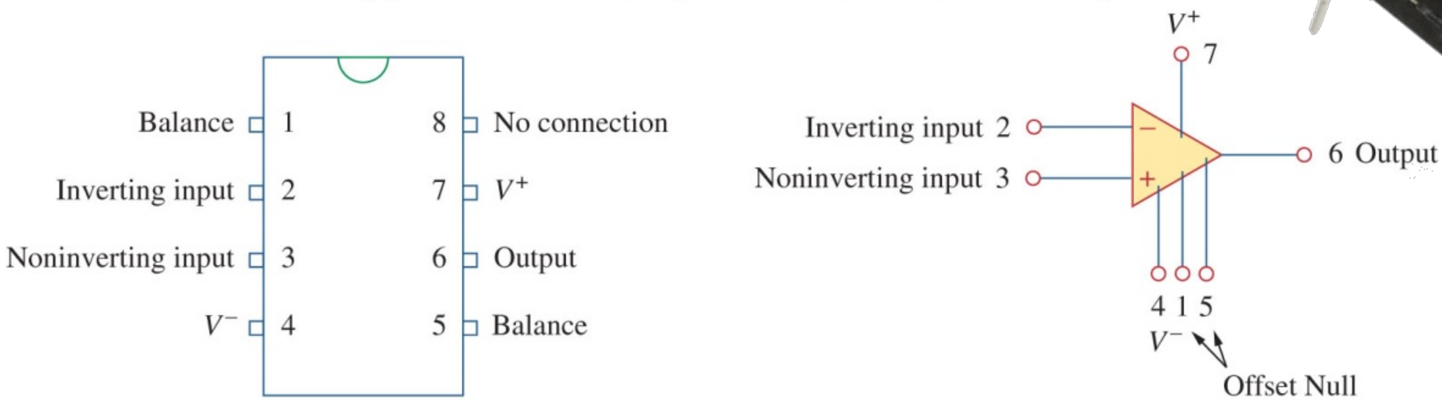
- The voltage output of an op-amp is proportional to the difference between the noninverting and inverting inputs

$$\boxed{v_o = Av_d = A(v_2 - v_1)}$$



Op Amp Terminals

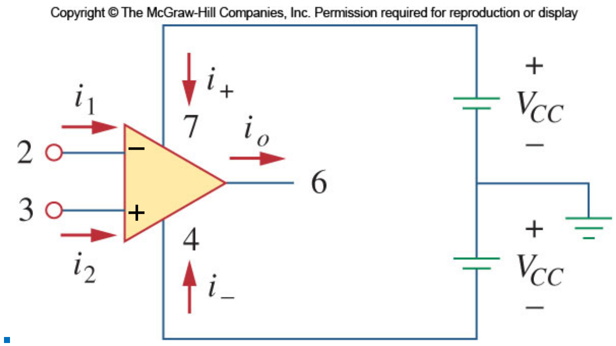




(a) (b)

- 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



$$i_0 = i_1 + i_2 + i_+ + i_-$$

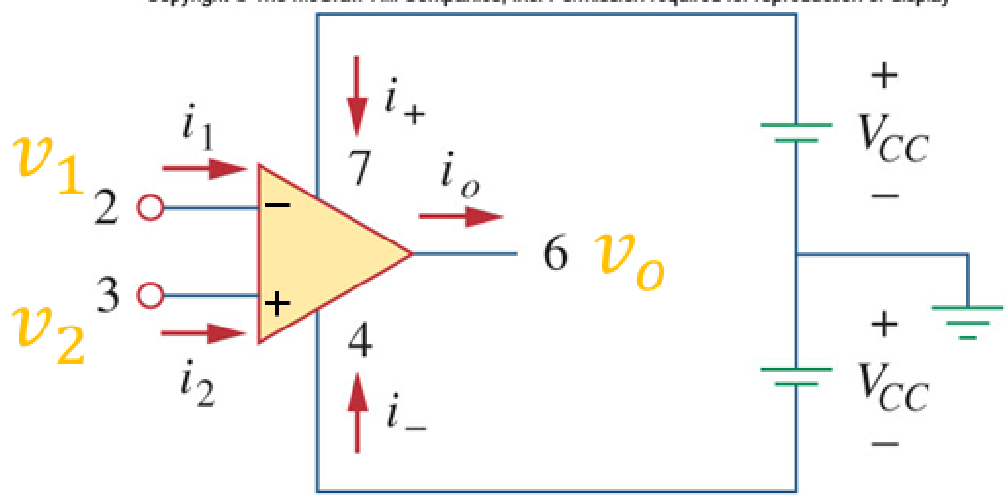
- As an *active* element, the op-amp requires a power source.
  - Often in circuit diagrams the power supply terminals are obscured (ignored).
  - The supply current <u>cannot</u> be overlooked.

- Most op-amps use <u>two</u> voltage sources, with a ground reference between them.
  - This gives a positive and negative supply voltage.

Output Voltage

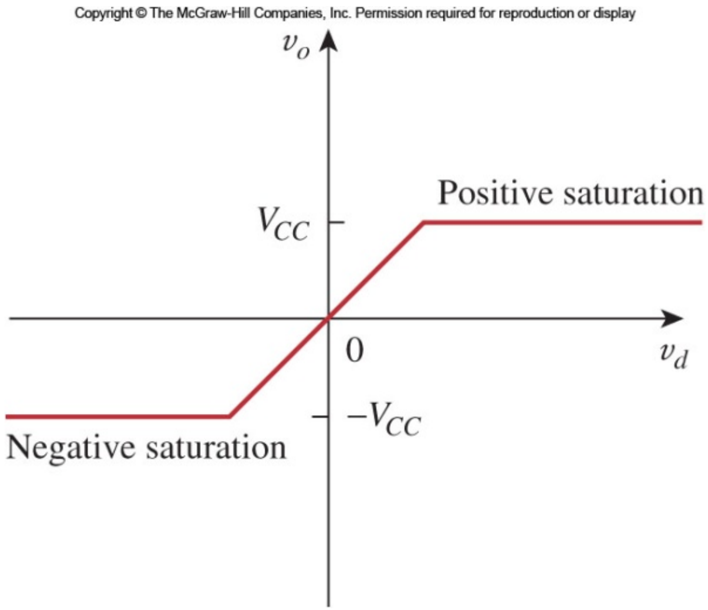
- The voltage output of an op-amp is proportional to the difference between the noninverting and inverting inputs

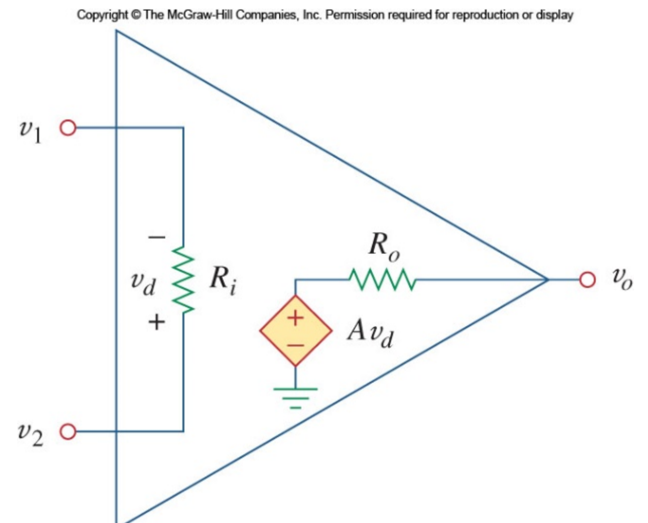
$$\boxed{v_o = Av_d = A(v_2 - v_1)}$$



Voltage Saturation

- Is the output voltage unlimited?

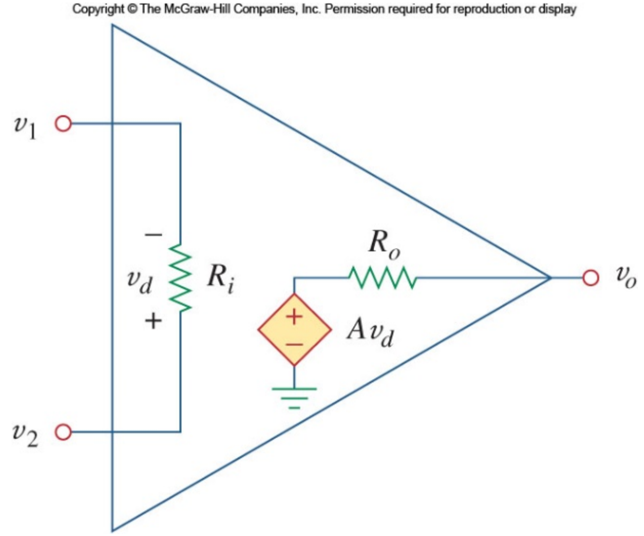




$$\boxed{v_o = Av_d = A(v_2 - v_1)}$$

$$v_0 = \begin{cases} -V_{cc} & Av_d < -V_{cc} \\ Av_d & -V_{cc} \le Av_d \le +V_{cc} \\ +V_{cc} & Av_d > +V_{cc} \end{cases}$$

Output Voltage



$$\boxed{v_o = Av_d = A(v_2 - v_1)}$$

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

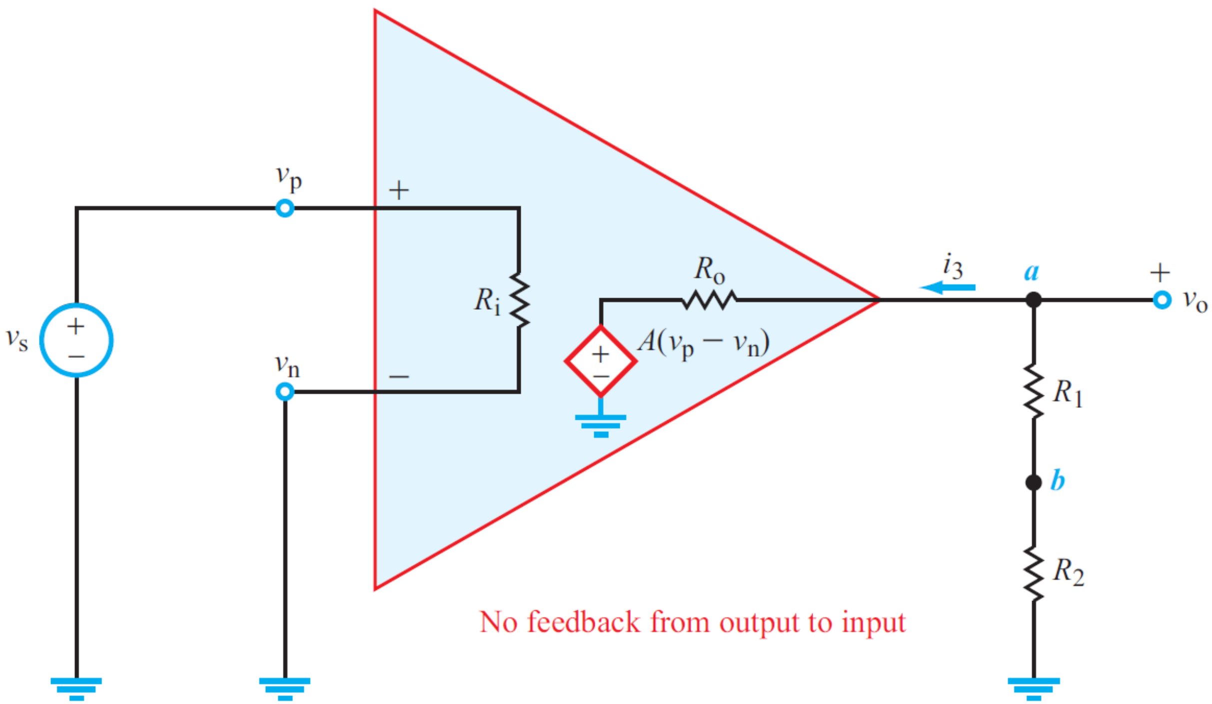
TABLE 5.1

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} Ω	∞ Ω
Output resistance, R_o	10 to 100 Ω	0 Ω
Supply voltage, V_{CC}	5 to 24 V	

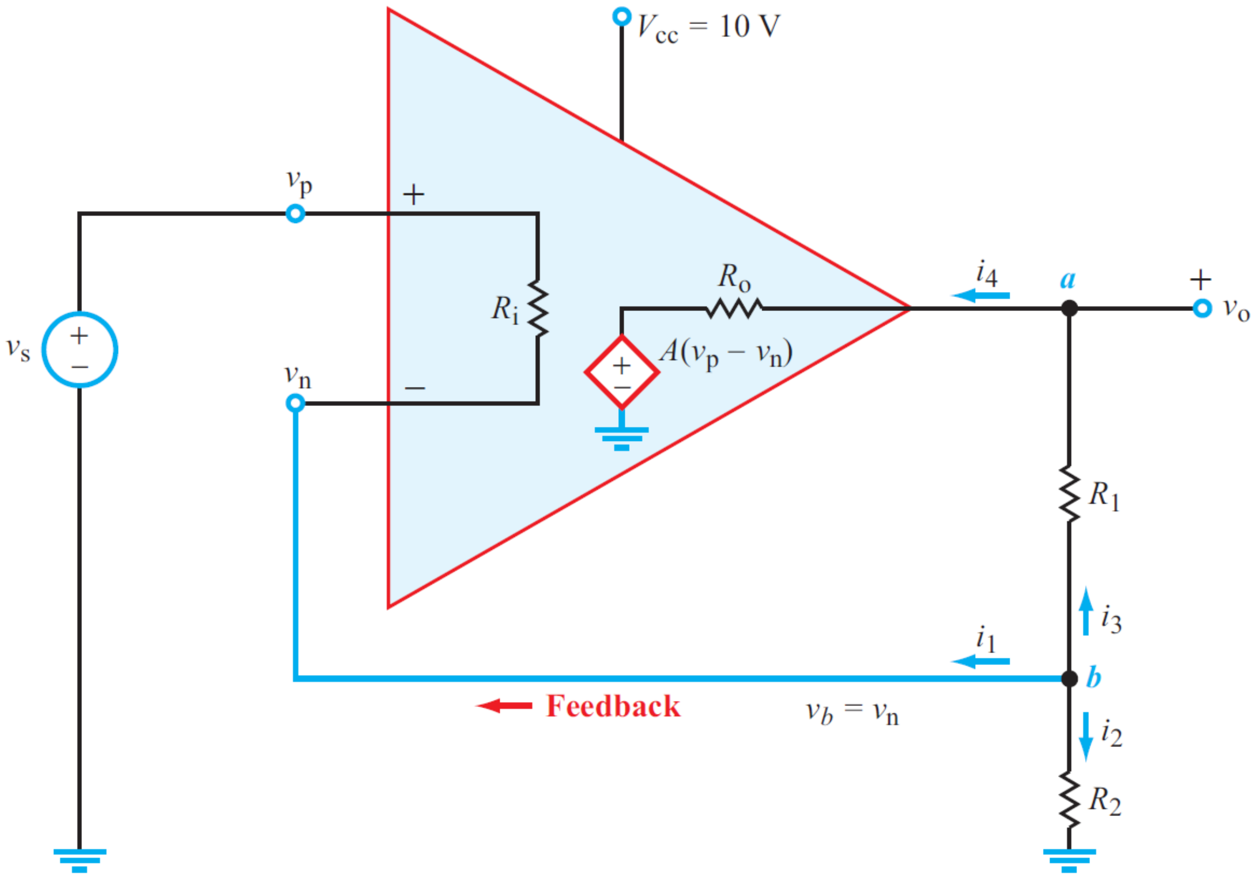
Example 1

For $V_{cc} = 10$ V, $A = 10^6$, $R_i = 10^7$ Ω, $R_o = 10$ Ω, $R_1 = 80$ kΩ, and $R_2 = 20$ kΩ, Find v_o



Example

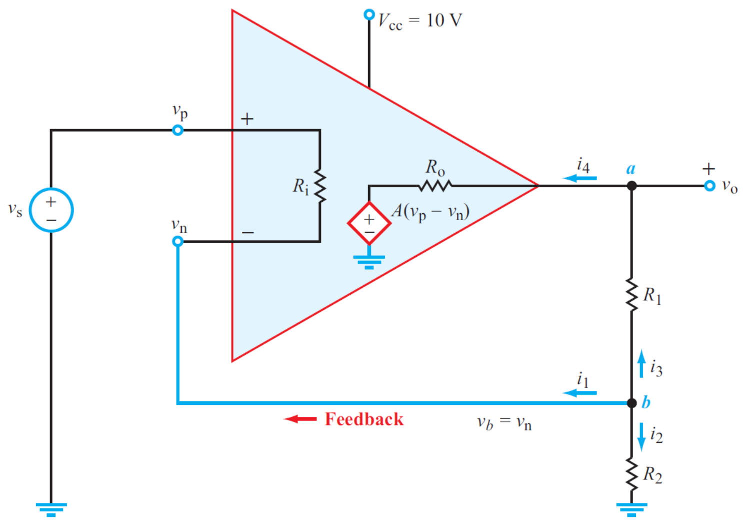
For $V_{cc} = 10$ V, $A = 10^6$, $R_i = 10^7$ Ω, $R_o = 10$ Ω, $R_1 = 80$ kΩ, and $R_2 = 20$ kΩ, Find v_o / v_s



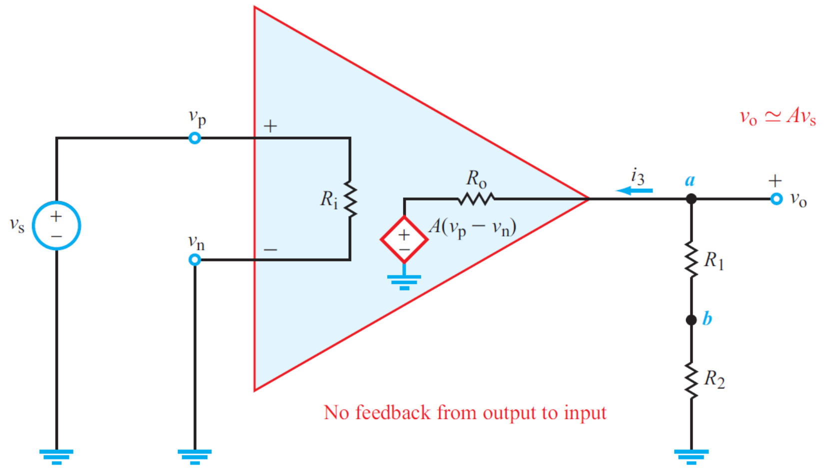
Tradeoff

For $V_{cc} = 10$ V, $A = 10^6$, $R_i = 10^7$ Ω, $R_o = 10$ Ω, $R_1 = 80$ kΩ, and $R_2 = 20$ kΩ,

Negative Feedback

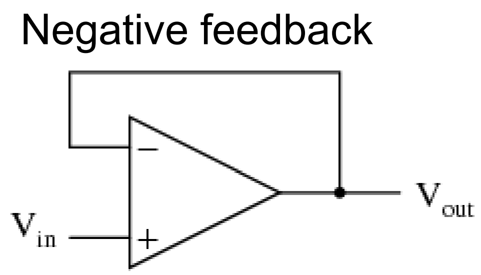


No Feedback



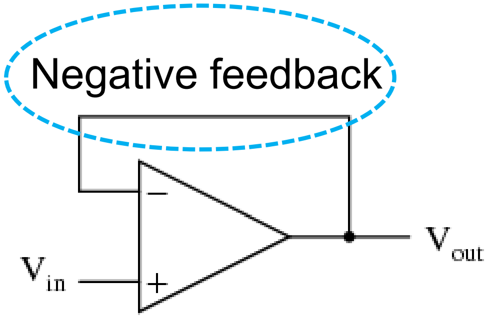
- Circuit gain G
- Linear dynamic range of v_s

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?



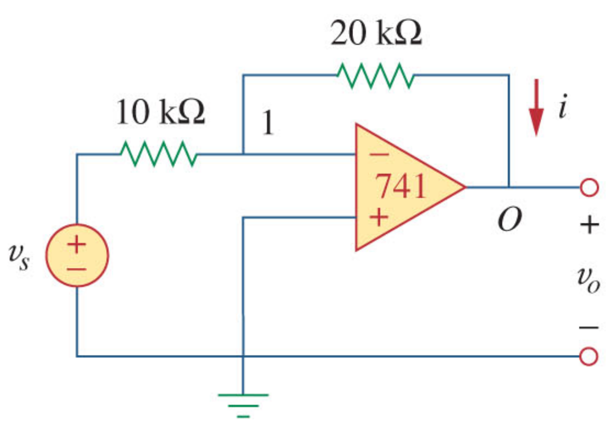
$$V_{in} \uparrow \Longrightarrow \text{voltage differential} \uparrow \Longrightarrow V_{out} \uparrow$$
$$\Longrightarrow \text{voltage differential} \downarrow \Longrightarrow V_{out} \downarrow$$
$$\Longrightarrow \cdots$$
$$\Longrightarrow V_{out} \to V_{in} \text{ but small difference exists}$$

Practice

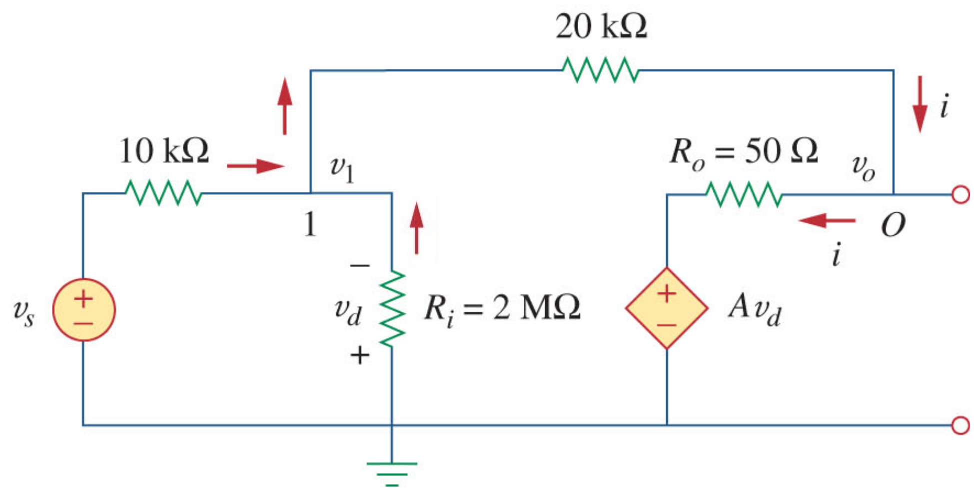
A 741 op amp has an open-loop voltage gain of 2×10^5, input resistance of $2M\Omega$, and output resistance of 50Ω.

(1) Find the closed-loop gain v_o/v_s.

(2) Determine current i when $v_s = 2V$.



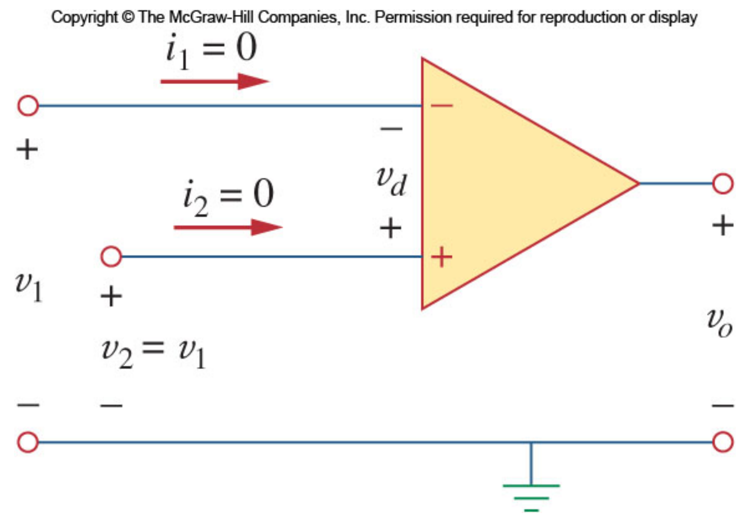
(a)

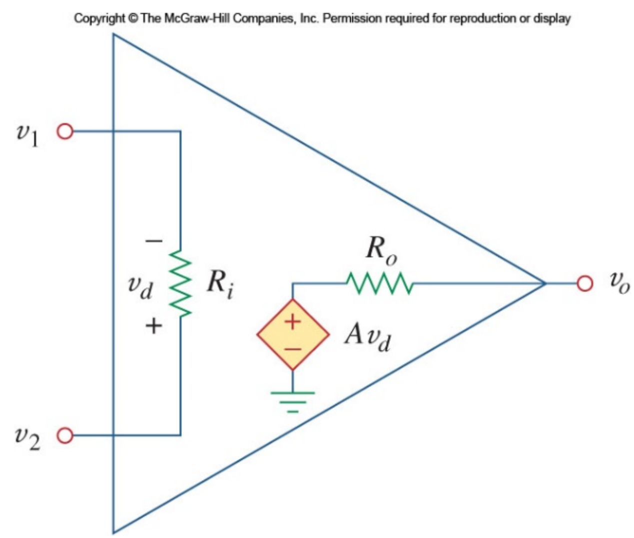


(b)

Ideal Op Amp

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

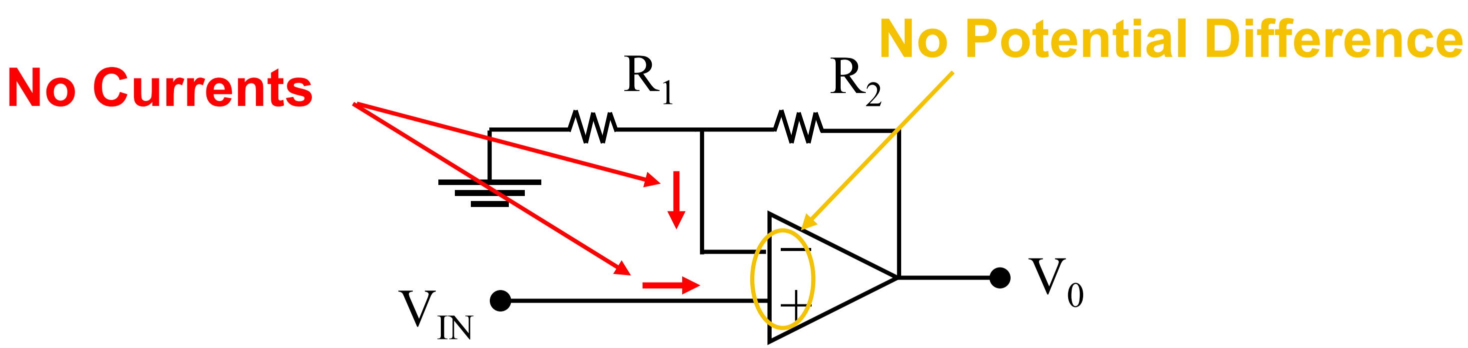




Ideal Op-Amp Analysis – Golden Rules

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.



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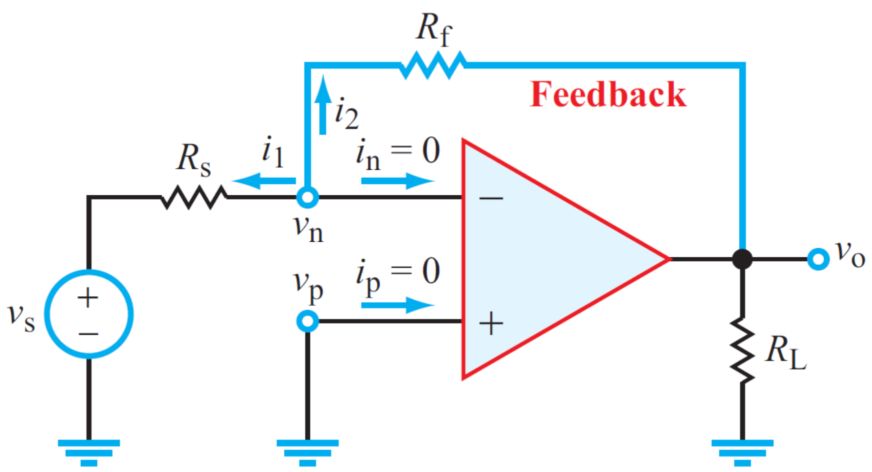
Inverting Amplifier



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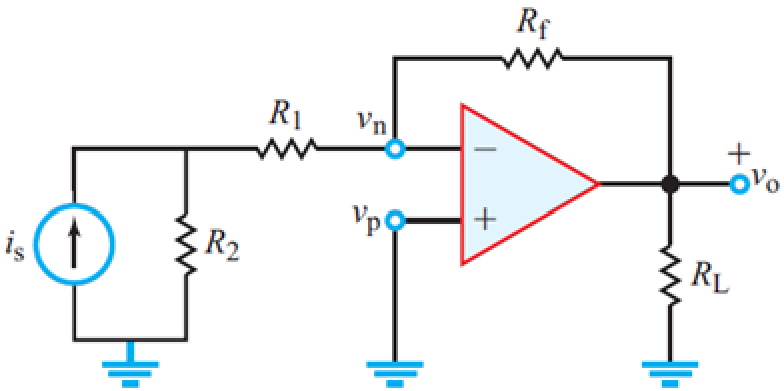
Example



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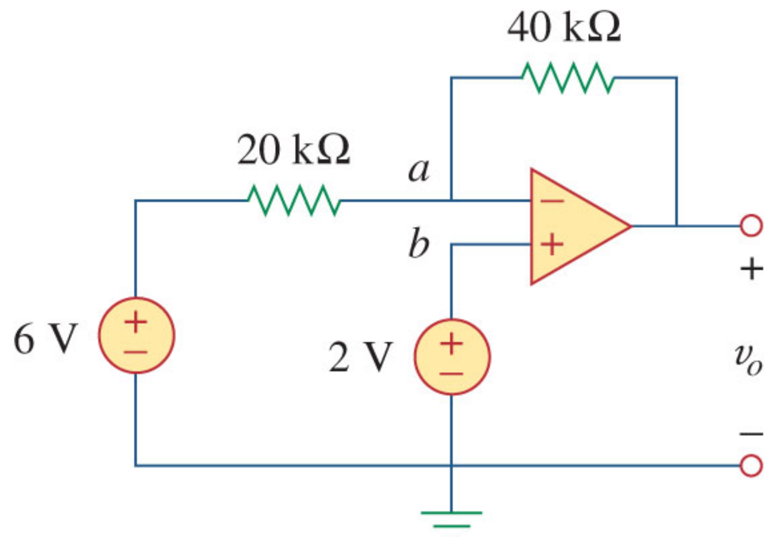
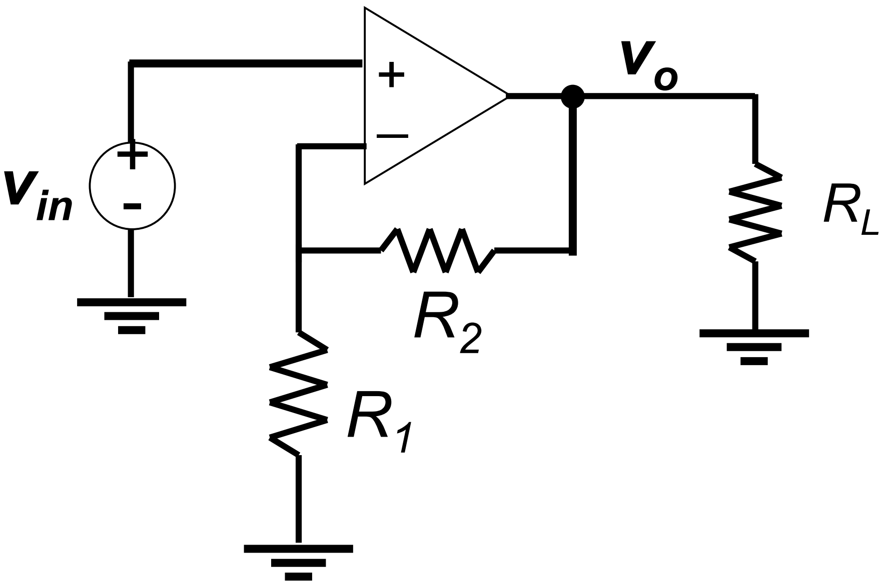
Practice

- Determine v_o in the circuit shown below



Non-Inverting Amplifier



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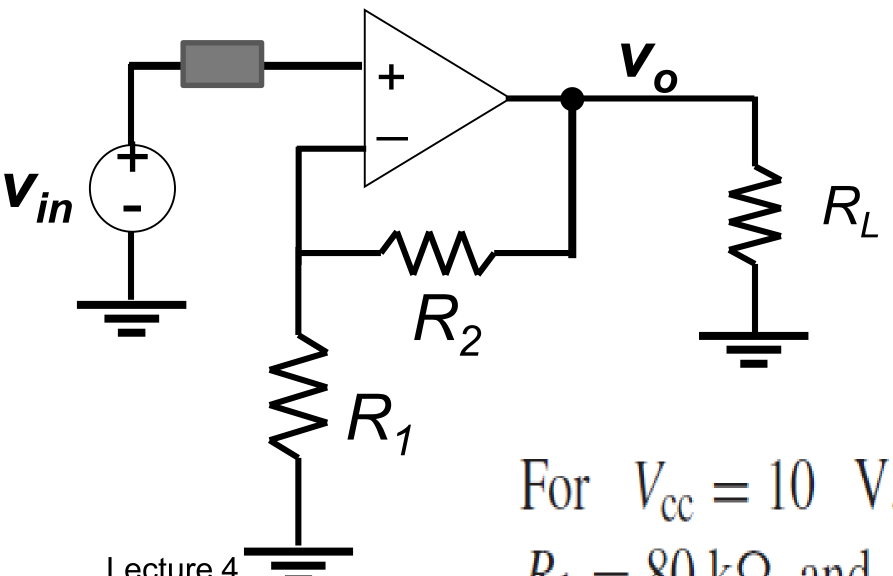
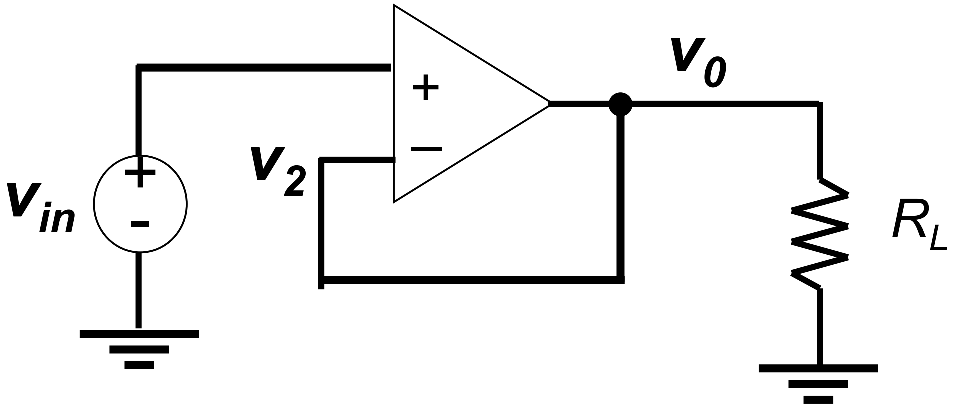
ECG Measurement



For $V_{cc} = 10$ V, $A = 10^6$, $R_i = 10^7$ Ω, $R_o = 10$ Ω, $R_1 = 80$ kΩ, and $R_2 = 20$ kΩ,

Application: Voltage Follower



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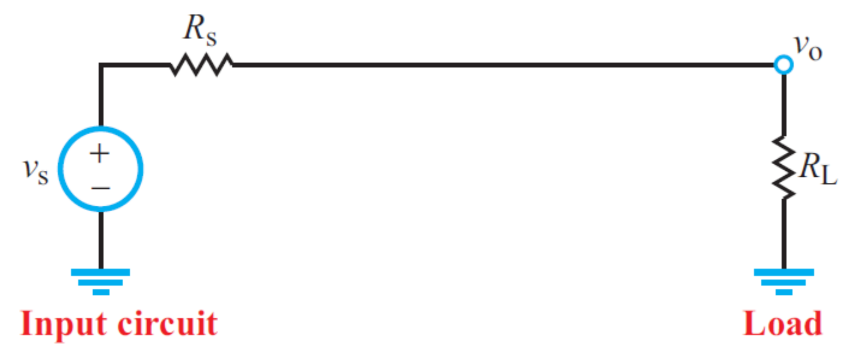
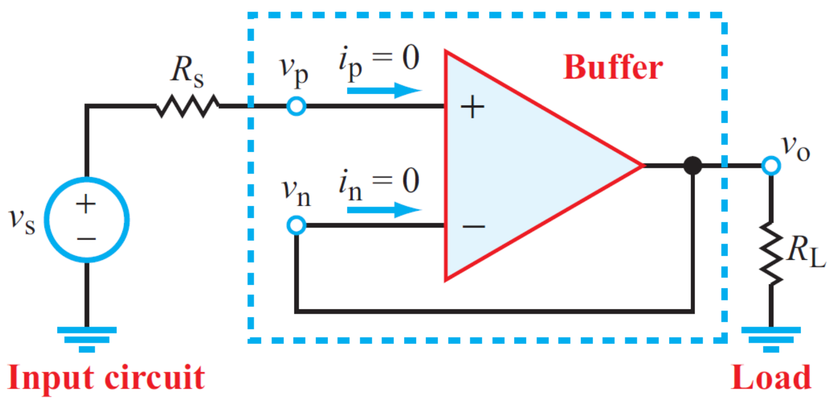
Application of Voltage Follower

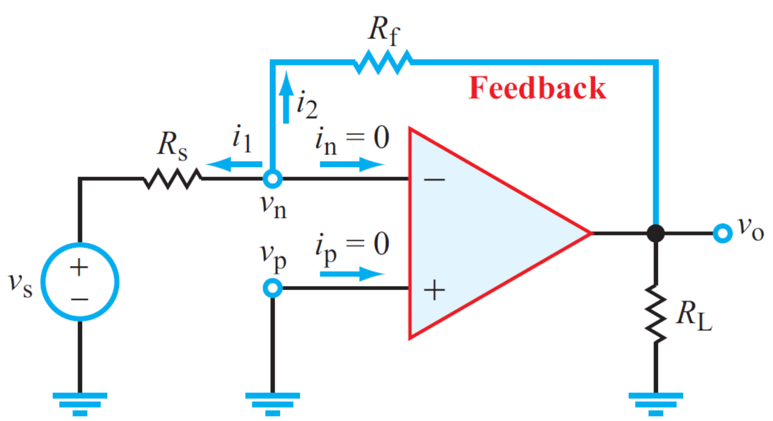


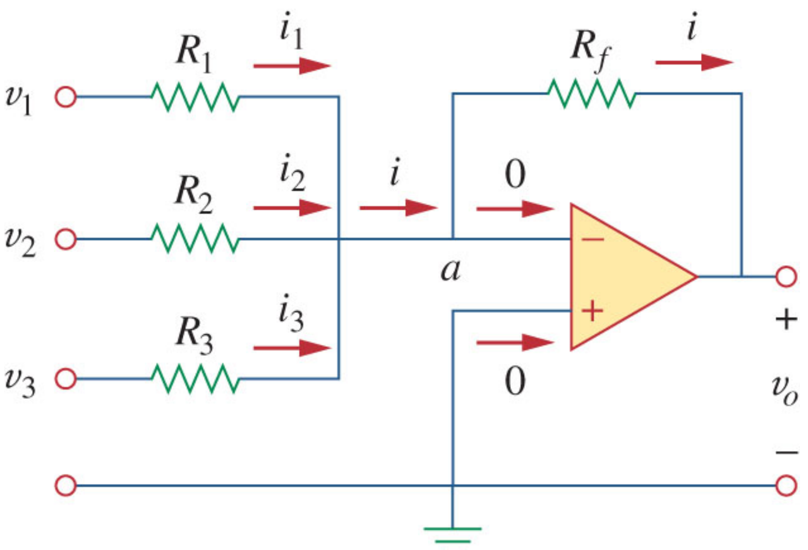


"Buffer" sections of Circuit

Summing Amplifier

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





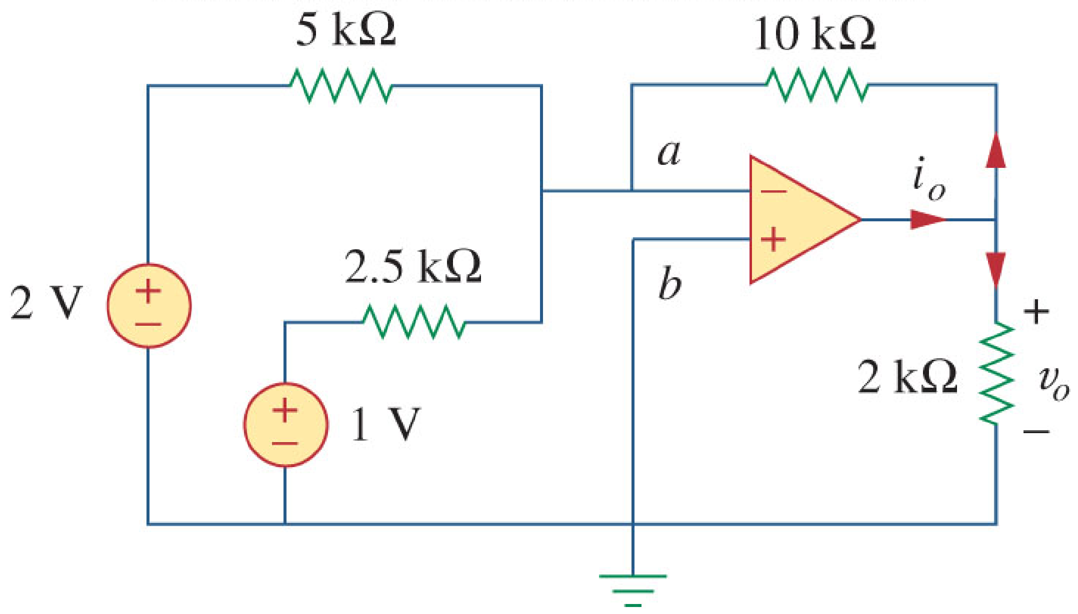
Example

Design a circuit that performs the operation

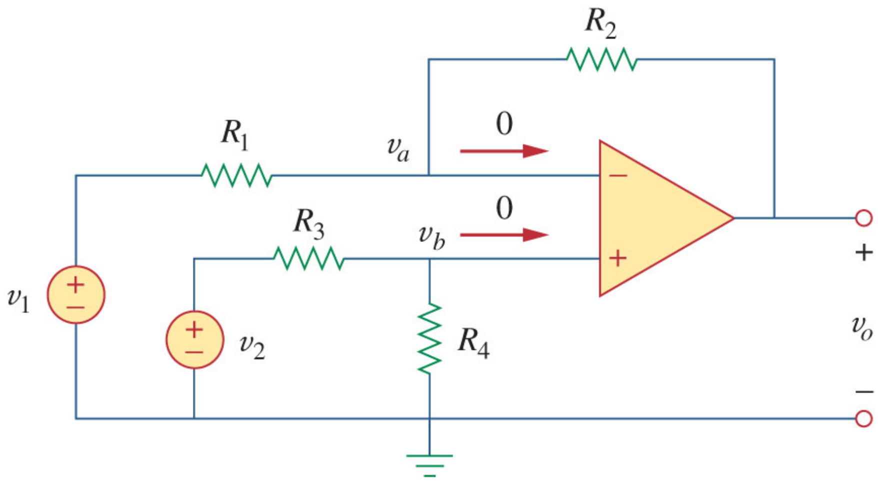
$$v_o = 4v_1 + 7v_2.$$

Practice

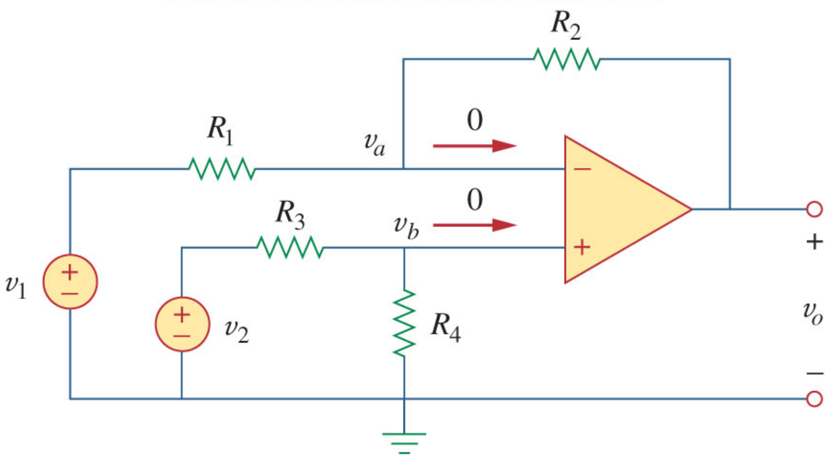
- Find v_o and i_o in the circuit shown below



Difference Amplifier



Common Mode Rejection

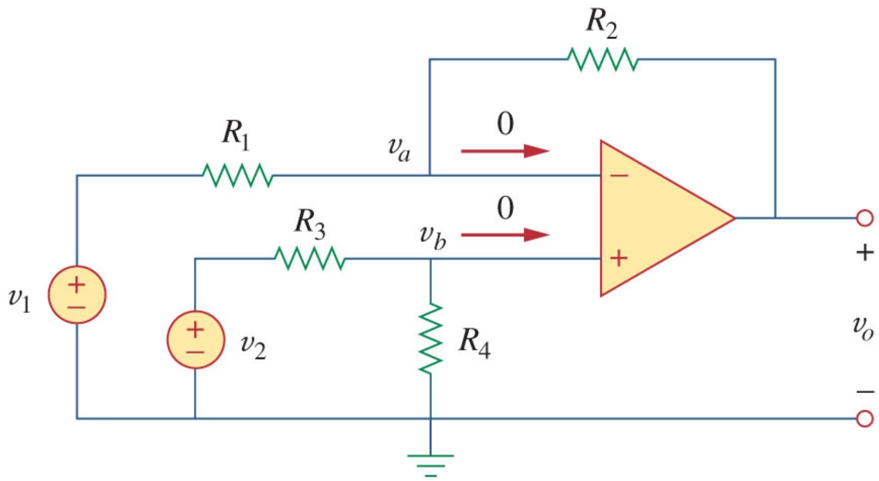


$$v_o = \frac{R_2\left(1+R_1/R_2\right)}{R_1\left(1+R_3/R_4\right)}v_2 - \frac{R_2}{R_1}v_1$$

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

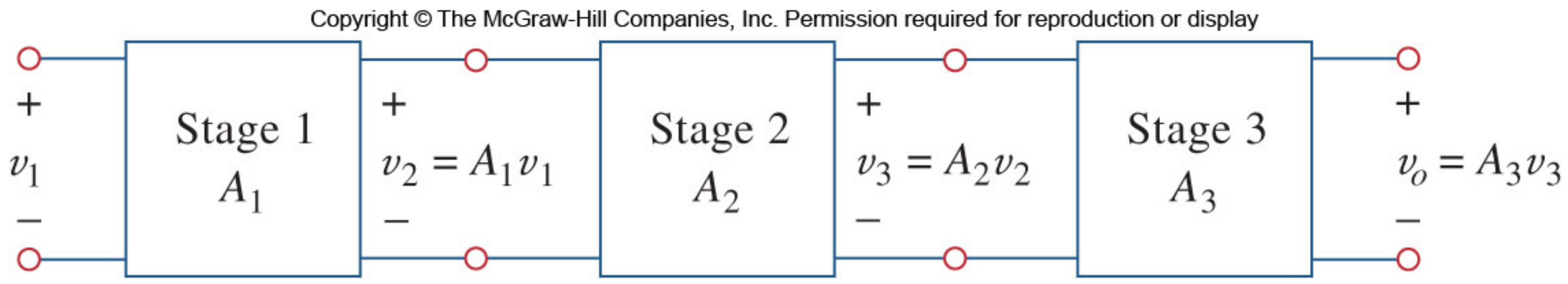
Example

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



Cascaded Op Amps

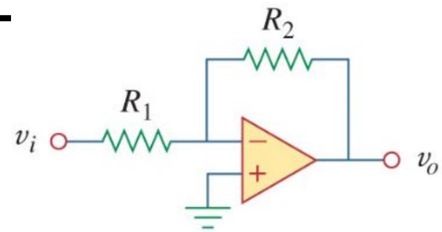
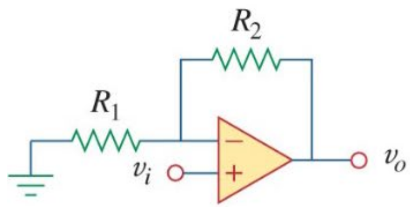
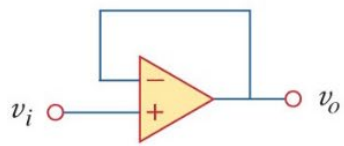
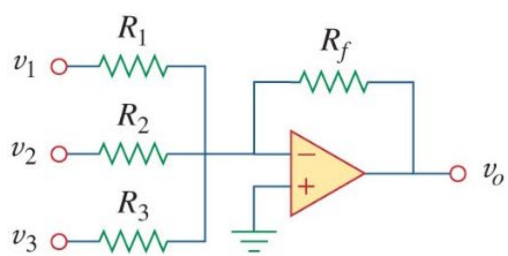
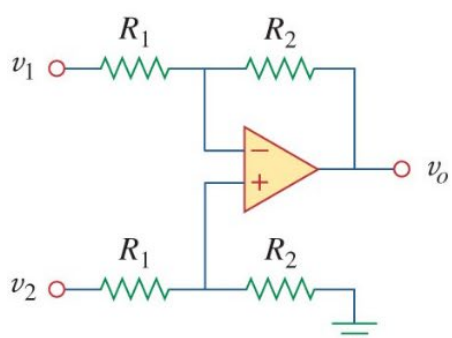
- This head to tail configuration is called "cascading".
  - Each amplifier is then called a "stage".



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

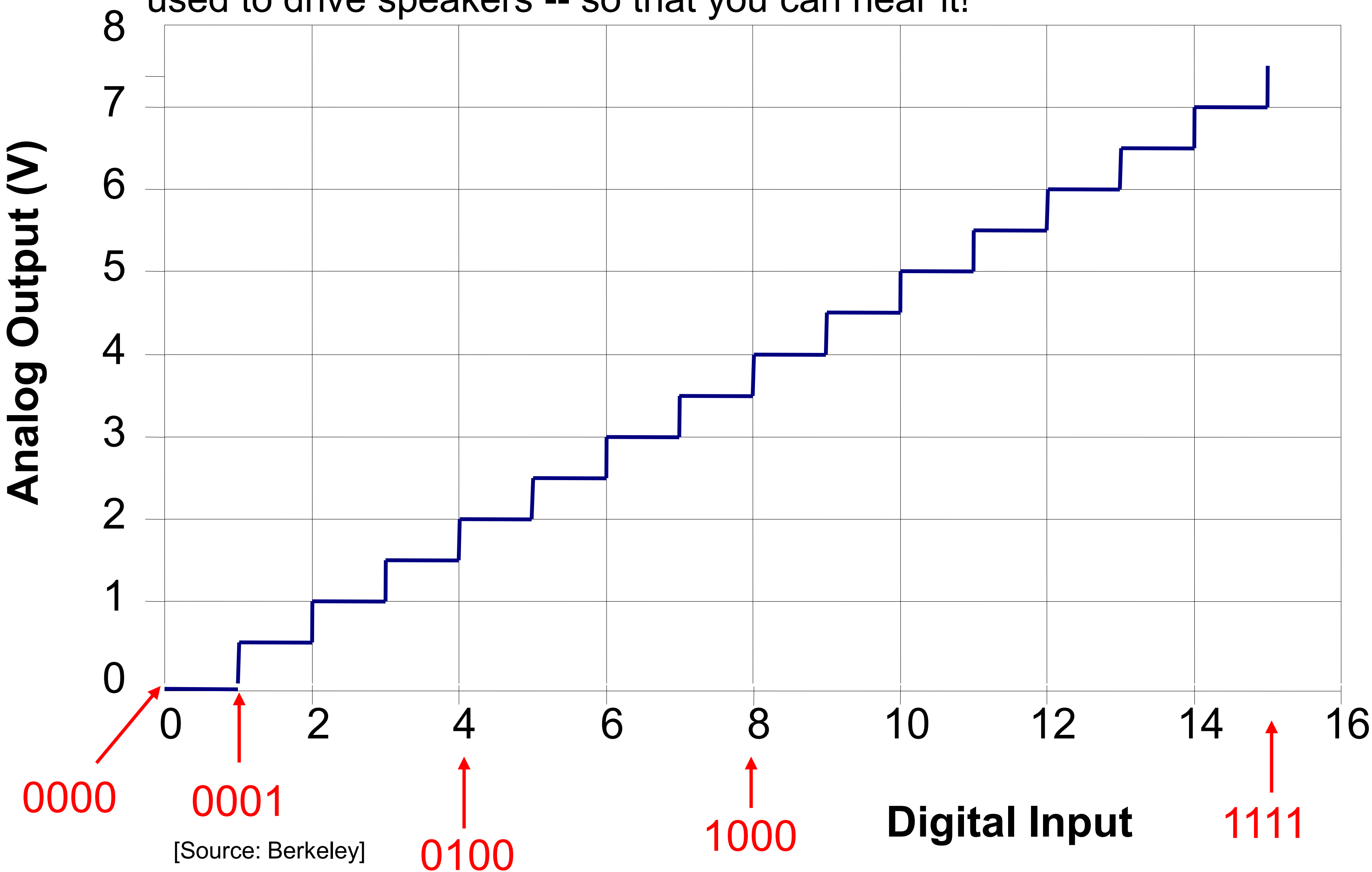
$$A = A_1 \cdot A_2 \cdot A_3$$

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!

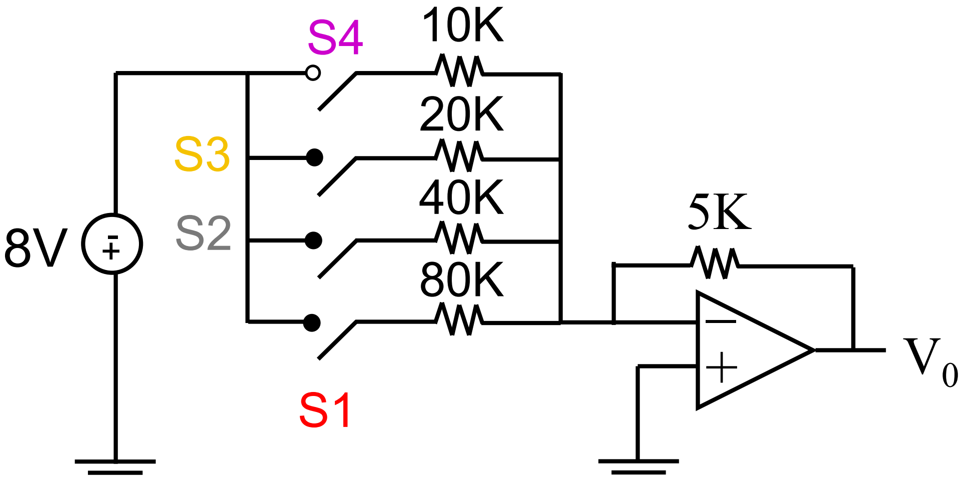


[Source: Berkeley]

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)

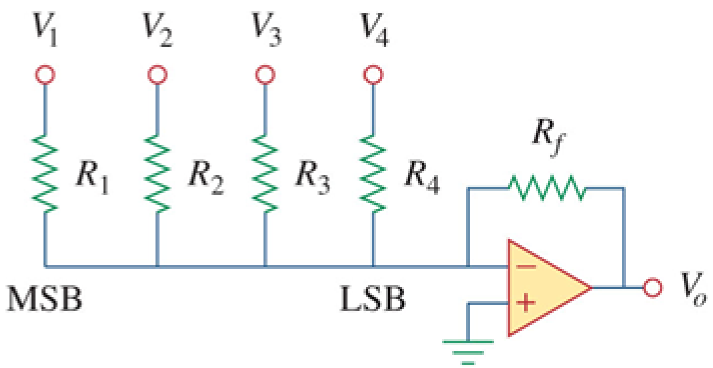
S1 closed if LSB =1
S2 " if next bit = 1
S3 " if " " = 1
S4 " if MSB = 1

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

[Source: Berkeley]

DAC



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