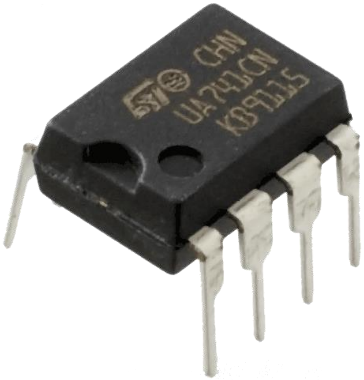
Lecture 4

- Operational Amplifiers

The Op. Amp (OA)

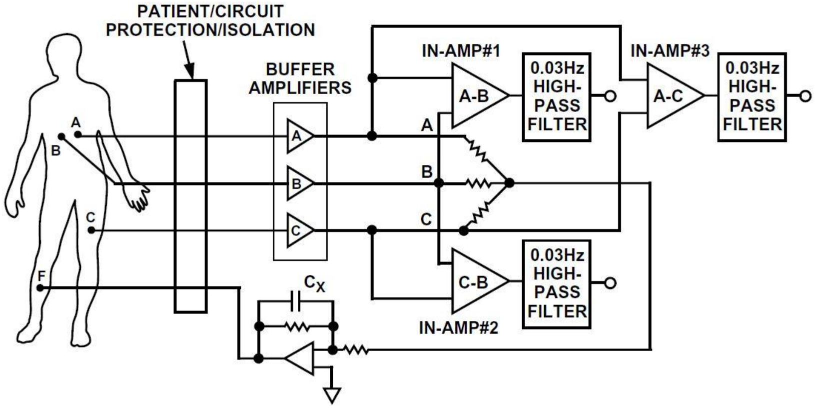
- When combined with resistors, capacitors, and inductors, OA can perform various functions:
  - amplification/scaling
  - sign changing
  - addition/subtraction/multiplication/division
  - integration
  - differentiation
  - analog filtering
  - nonlinear functions (exponential, log, sqrt)

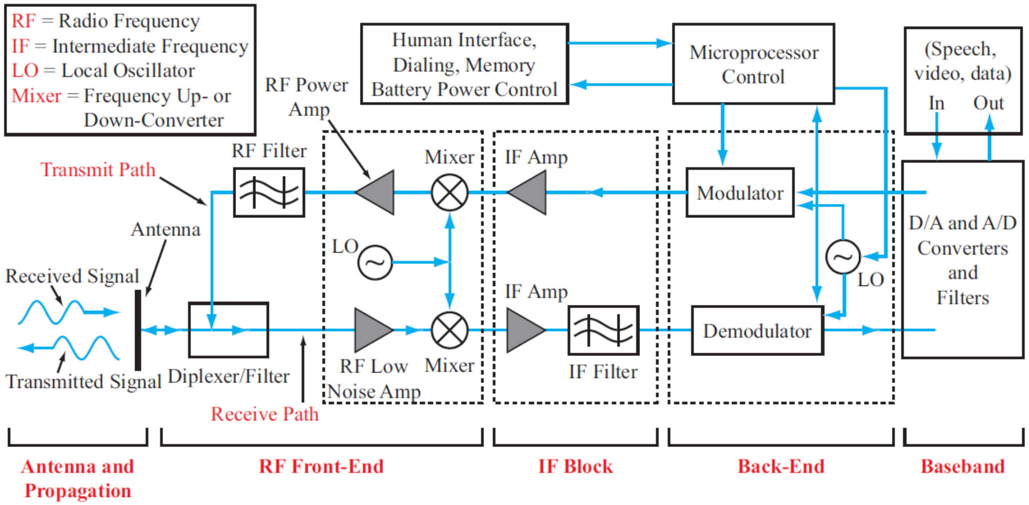


[Source: Berkeley]

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





[Source: Berkeley]

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.

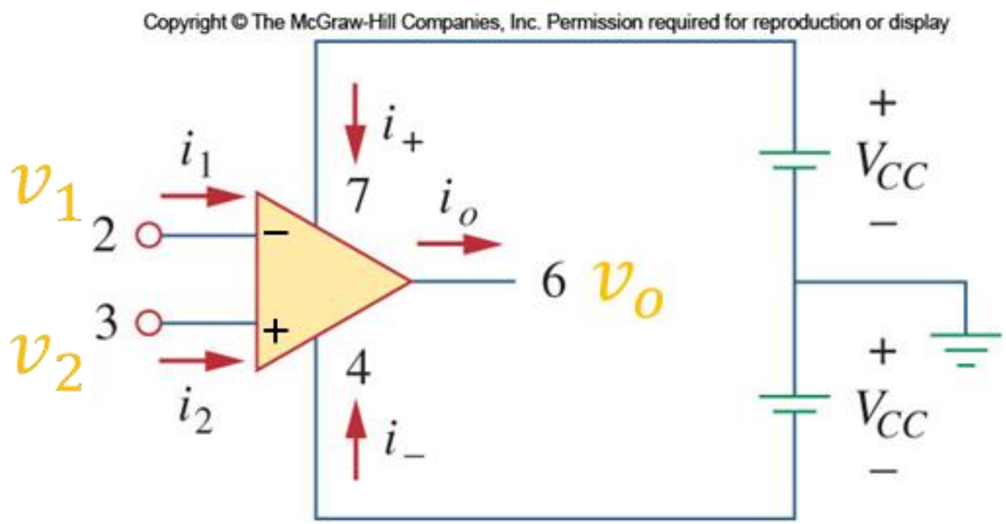
https://en.wikipedia.org/wiki/Operational_amplifier

Input and Output

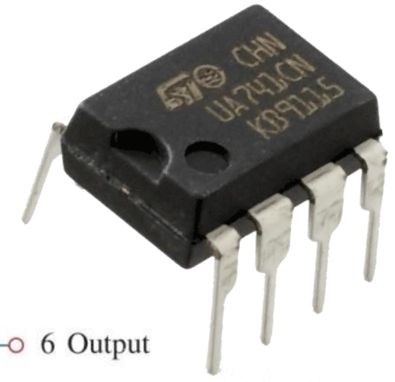
- The voltage output of an op-amp is **proportional** to the **voltage difference** between the noninverting and inverting inputs

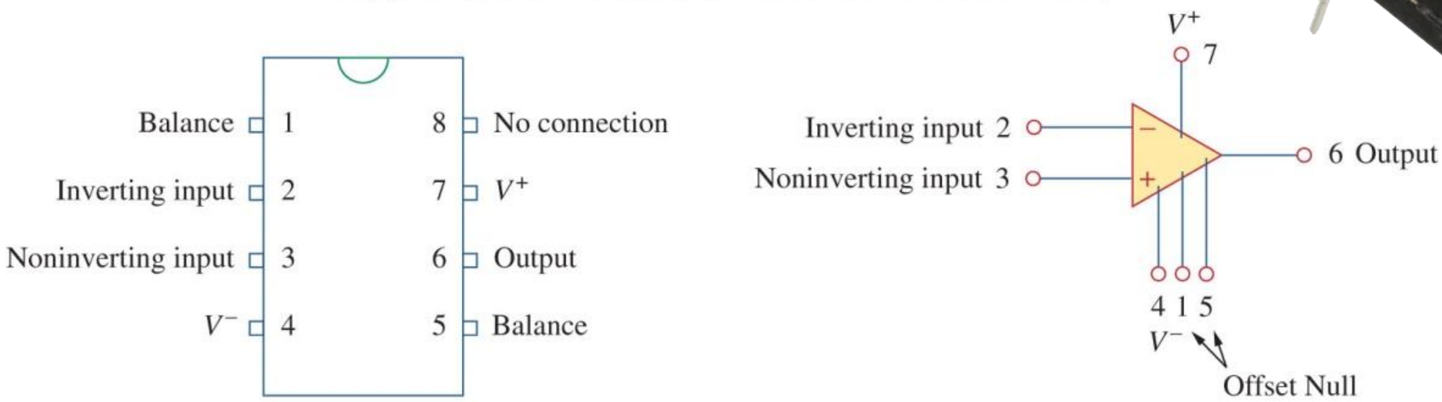
$$\boxed{v_o = Av_d = A(v_2 - v_1)}$$

Here, *A* is called the open loop gain.



Op Amp Terminals





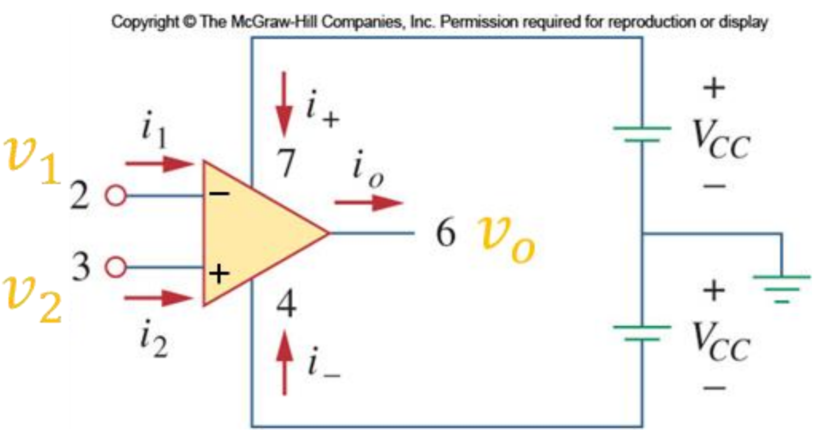
(a) (b)

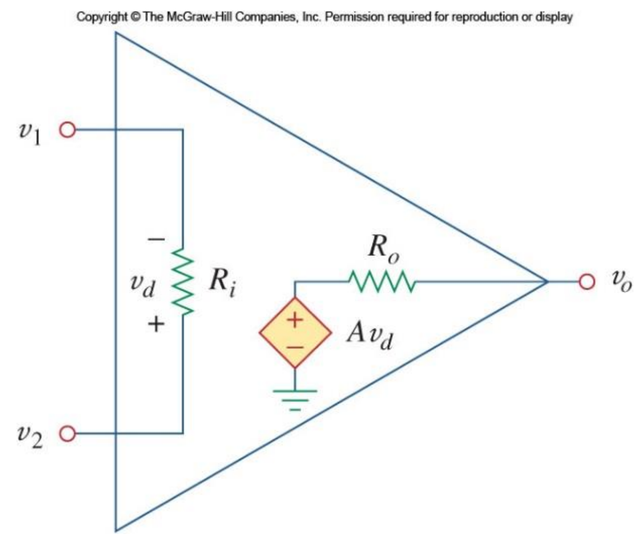
- **Five** important terminals
  - The inverting input
  - The noninverting input
  - The output
  - The positive (+) power supply
  - The negative (-) power supply
- The rest three terminals
  - 2 Offset Null (Balance)
    - May used in auxiliary circuit to compensate for performance degradation due to aging etc.
  - 1 No Connection (NC)
    - Unused, not connected to the amplifier circuit.

Op Amp Terminals-2

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

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

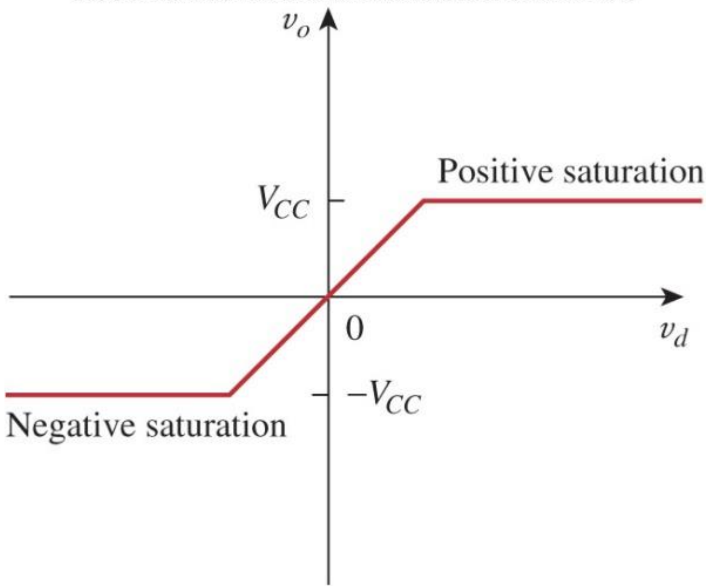


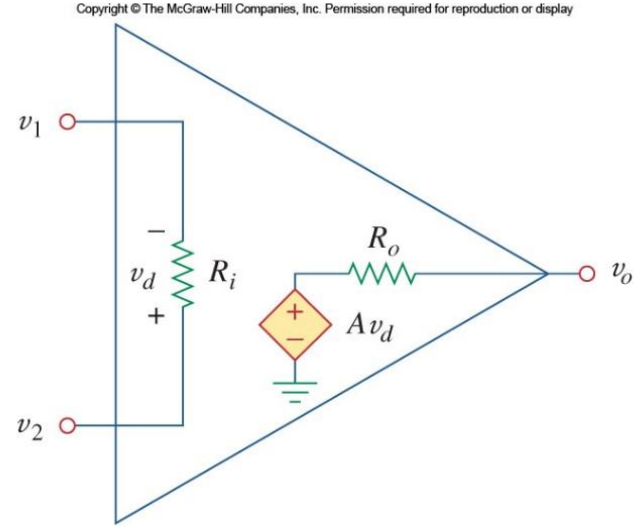


$$\boxed{v_o = Av_d = A(v_2 - v_1)}$$

Output Voltage Saturation

- Is the output voltage unlimited?



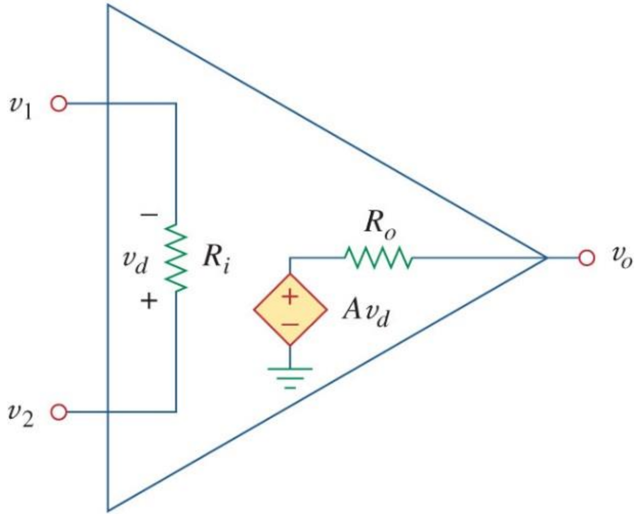


$$\boxed{v_o = Av_d = A(v_2 - v_1)}$$

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

Output Voltage

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



- Ideally A is infinite. In real devices, it is still high: 10^5 to 10^8.

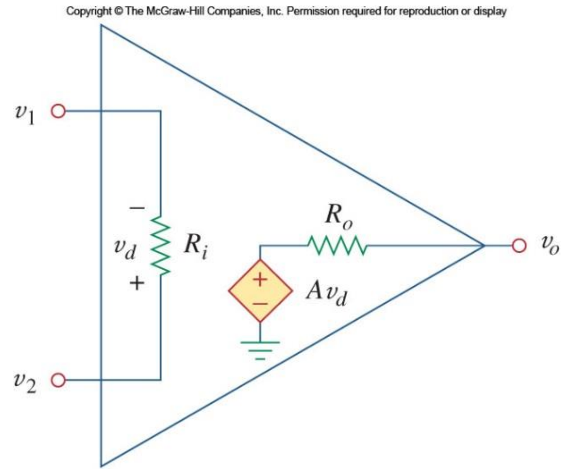
TABLE 5.1

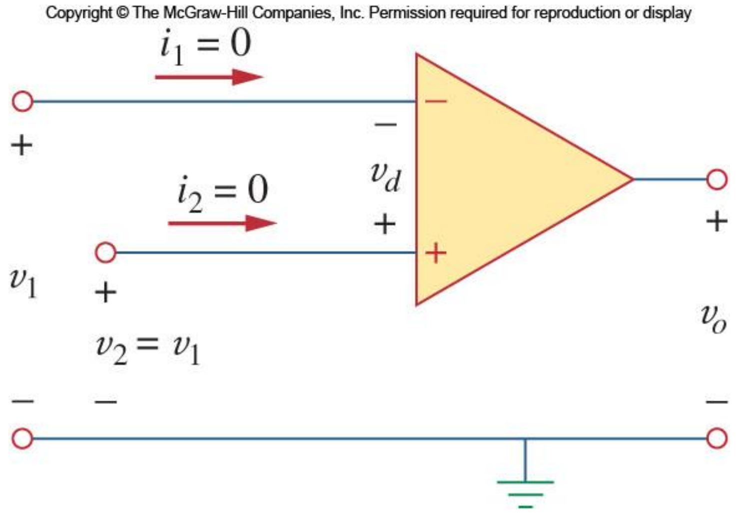
Typical ranges for op amp parameters.

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	

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, $R_i \simeq \infty$
    - Implies that $i_1 = i_2 = 0$.
  - zero output impedance, $R_o \simeq 0$
    - Implies that output voltage is **load independent.**

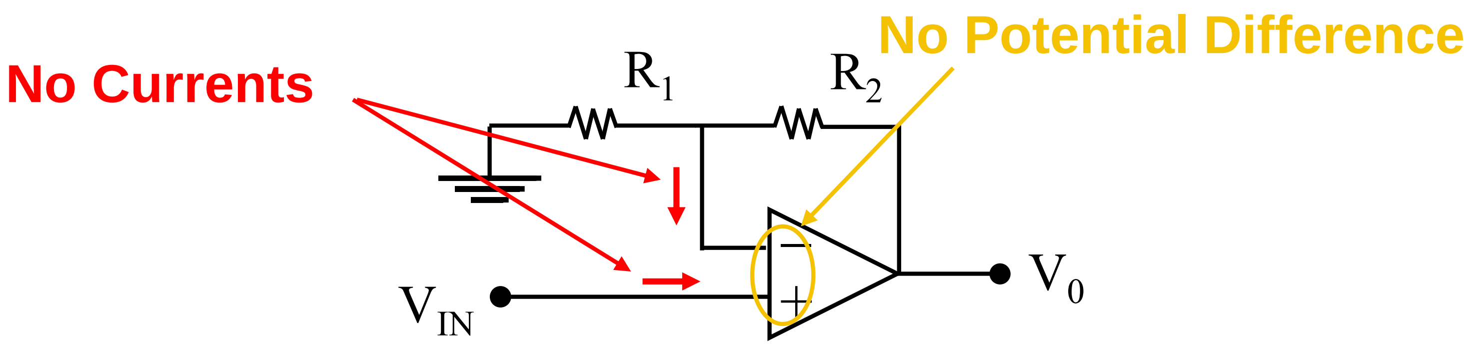




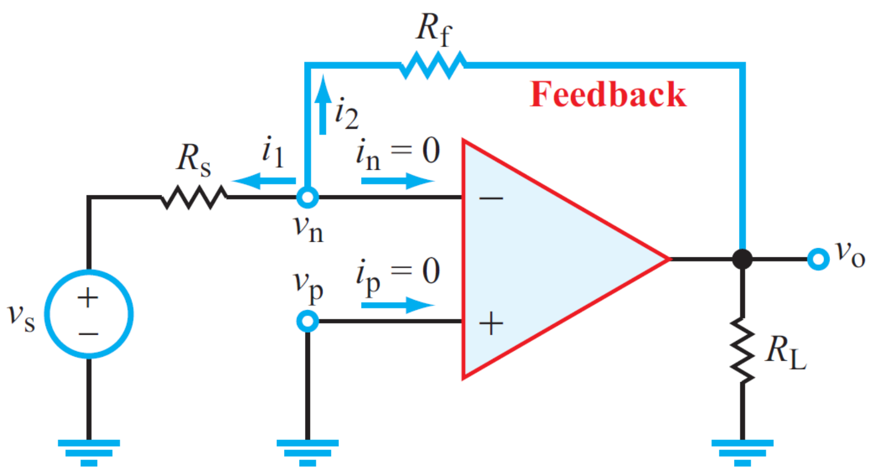
Ideal Op-Amp Analysis – Golden Rules

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

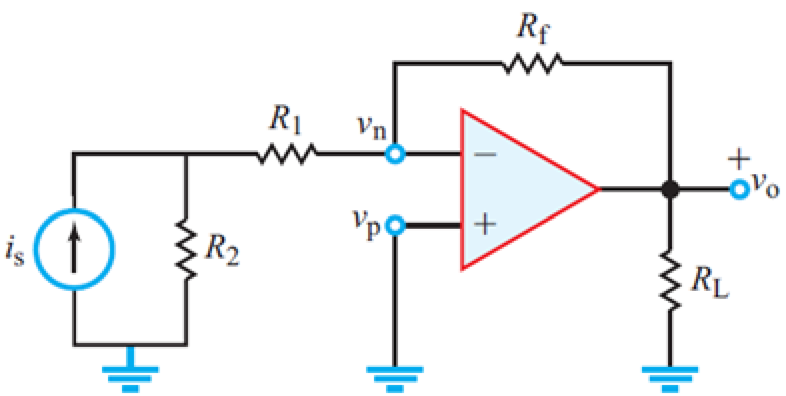
Assumption 2: The currents flowing into the op-amp's two input terminals both equal zero.



Inverting Amplifier



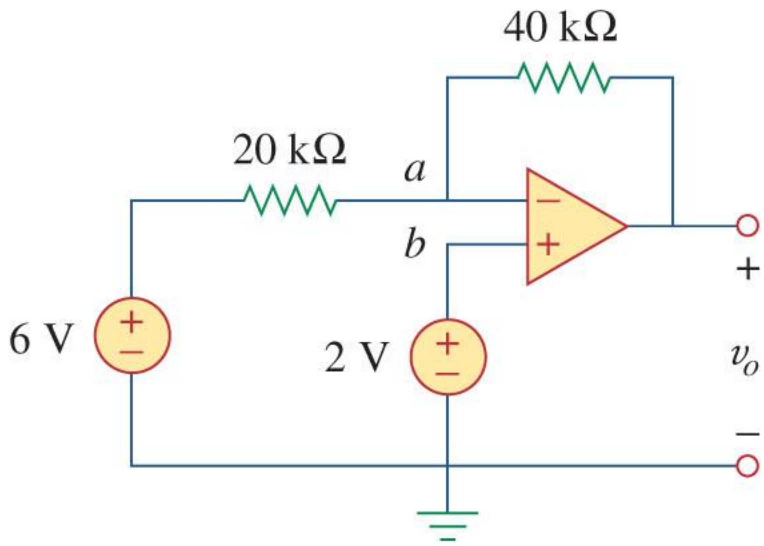
Example



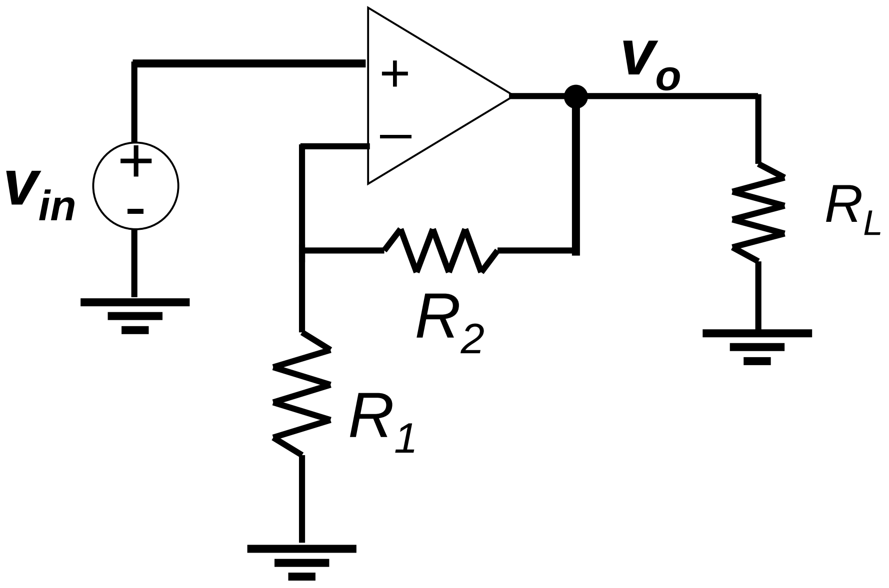
[Source: Berkeley]

Practice

- Determine v_o in the circuit shown below

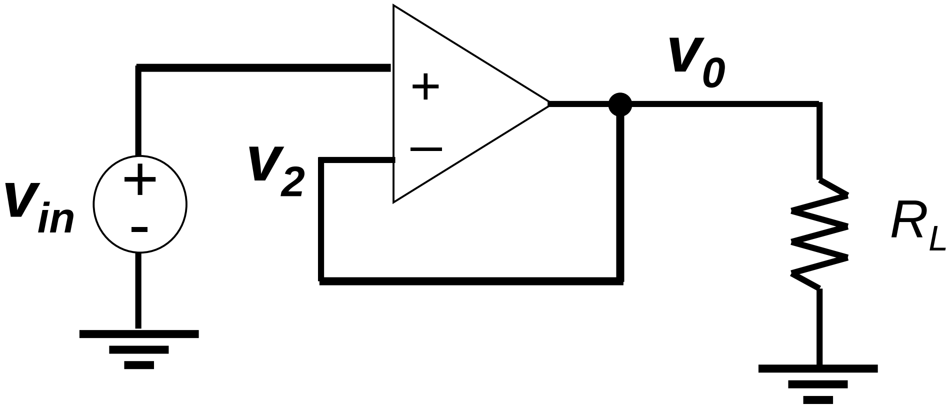


Non-Inverting Amplifier

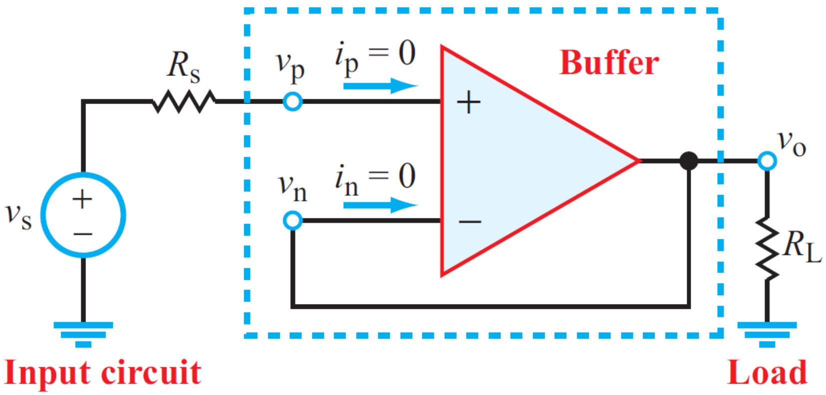


[Source: Berkeley]

Application: Voltage Follower



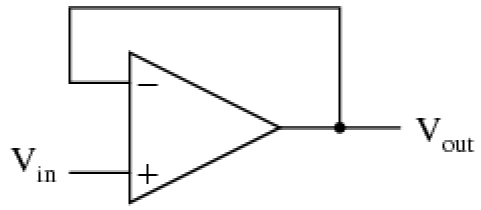
Application of Voltage Follower



“Buffer” sections of Circuit

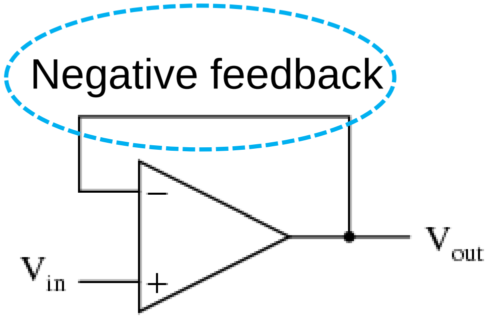
[Source: Berkeley]

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.

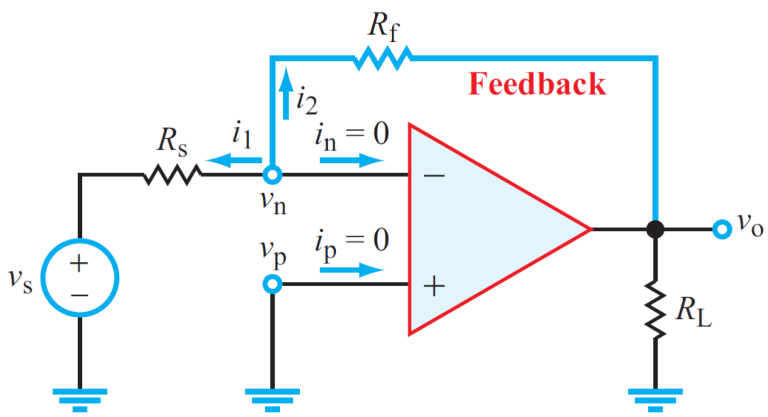
How Negative Feedback Works?

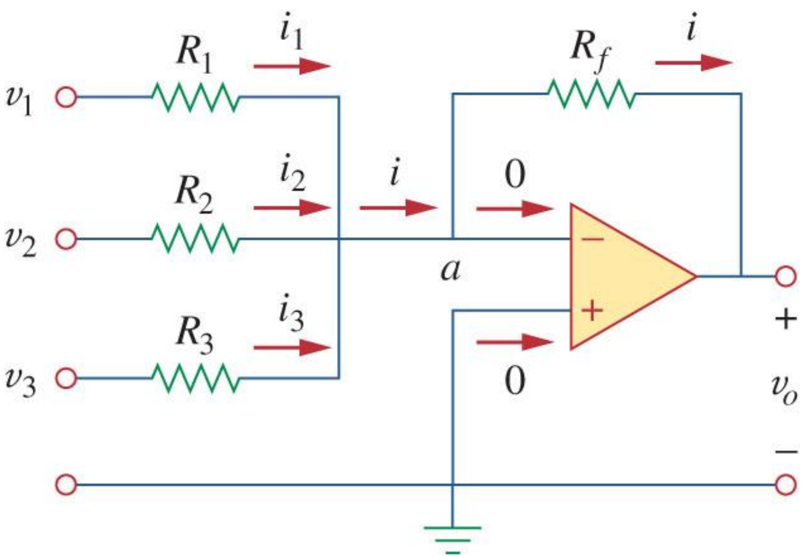


$$V_{in}\uparrow \Longrightarrow \text{voltage difference}\uparrow \Longrightarrow V_{out}\uparrow$$
$$\Longrightarrow \text{voltage difference}\downarrow \Longrightarrow V_{out}\downarrow$$
$$\Longrightarrow \cdots$$
$$\Longrightarrow V_{out} \rightarrow V_{in} \text{ but small difference exists}$$

Summing Amplifier

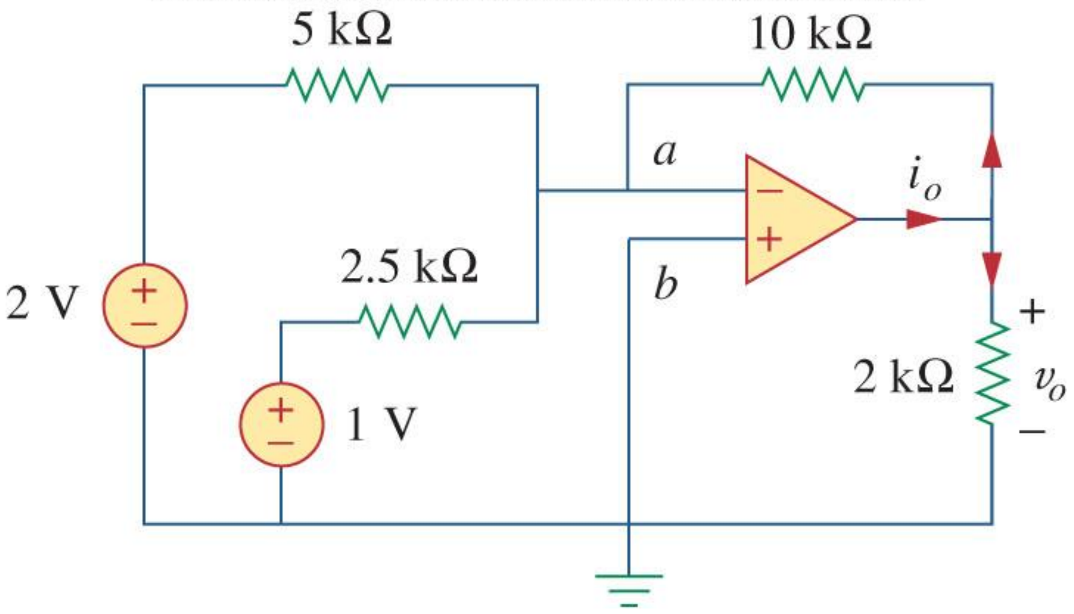
- Aside from amplification, the op-amp can be made to do addition very readily.



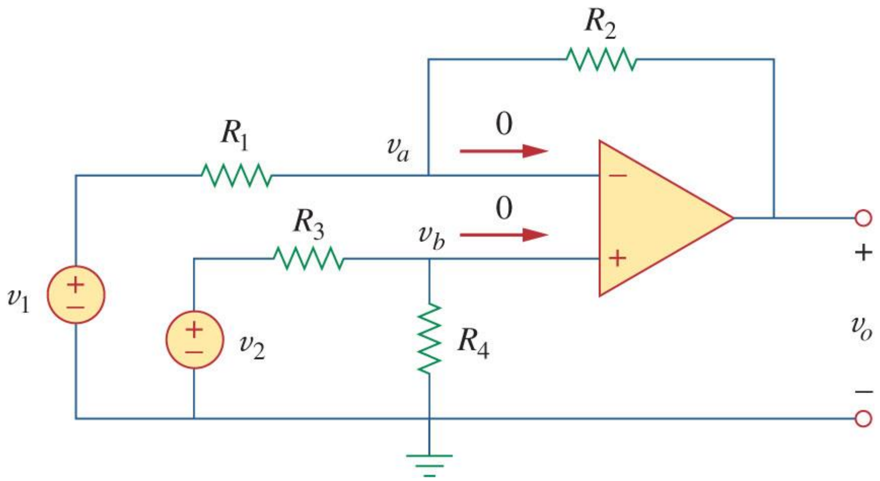


Practice

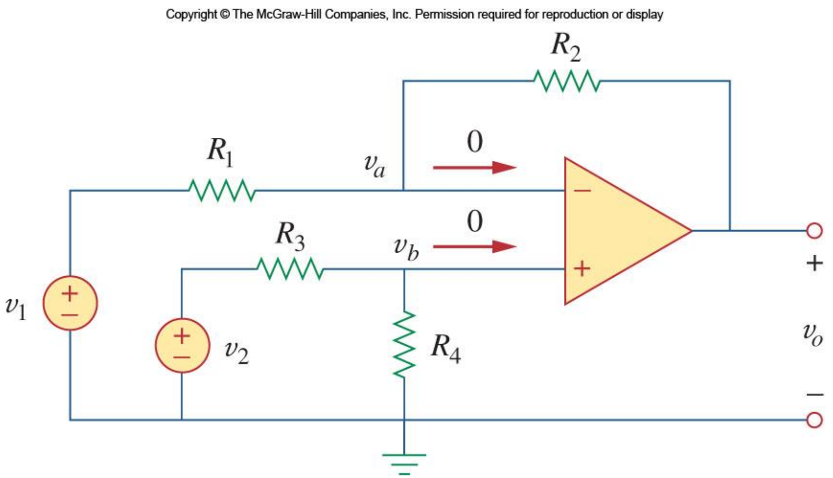
- Find v_o and i_o in the circuit shown below



Difference Amplifier



Common Mode Rejection

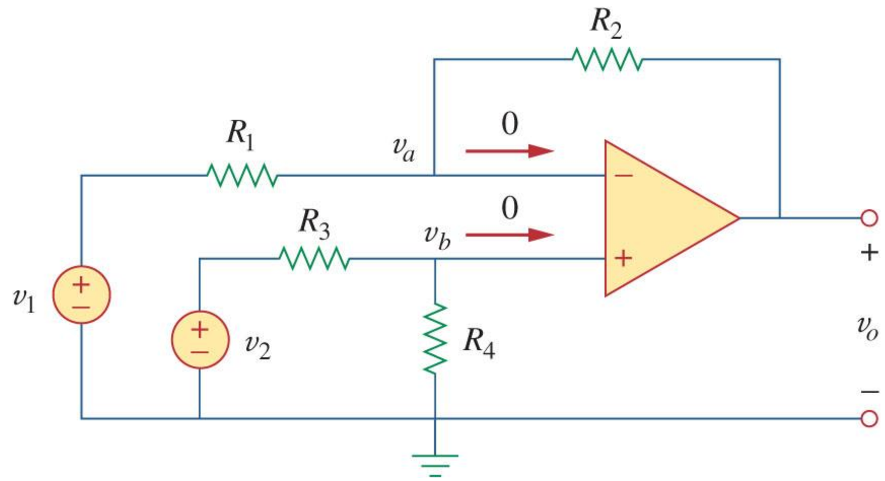


$$v_o = \frac{R_2(1+R_1/R_2)}{R_1(1+R_3/R_4)} v_2 - \frac{R_2}{R_1} v_1$$

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

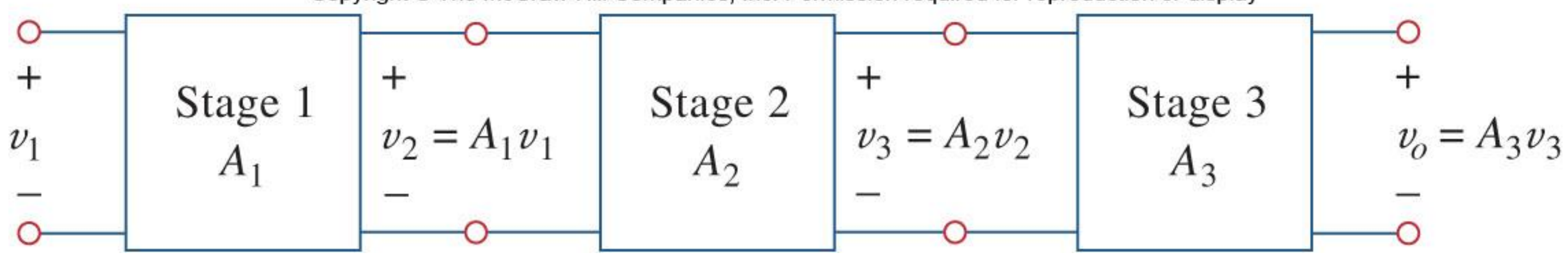
Example

- 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:

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

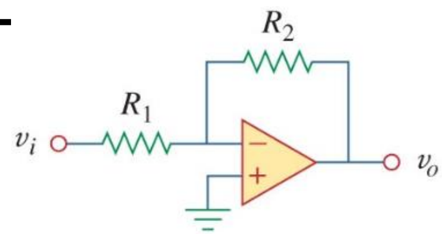
Example

Design a circuit that performs the operation

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

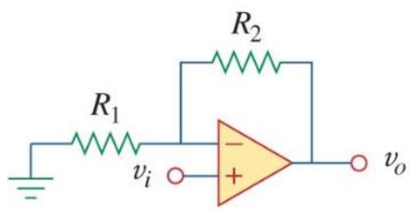
Summary

Op amp circuit	Name/output-input relationship



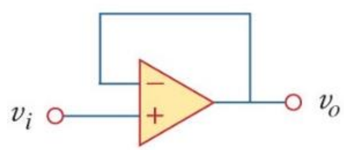
Inverting amplifier

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



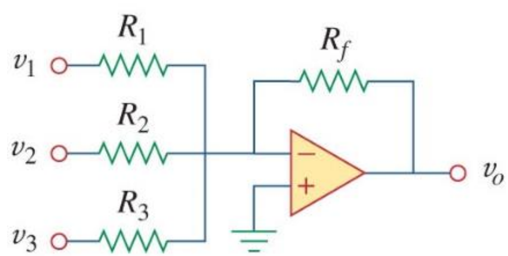
Noninverting amplifier

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



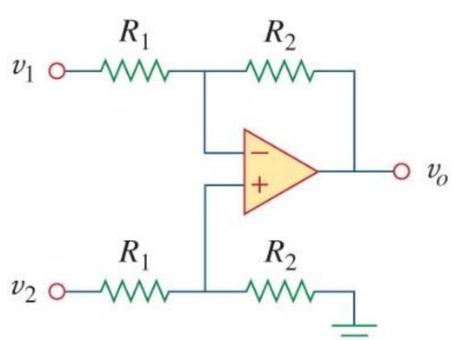
Voltage follower

$$v_o = v_i$$



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

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