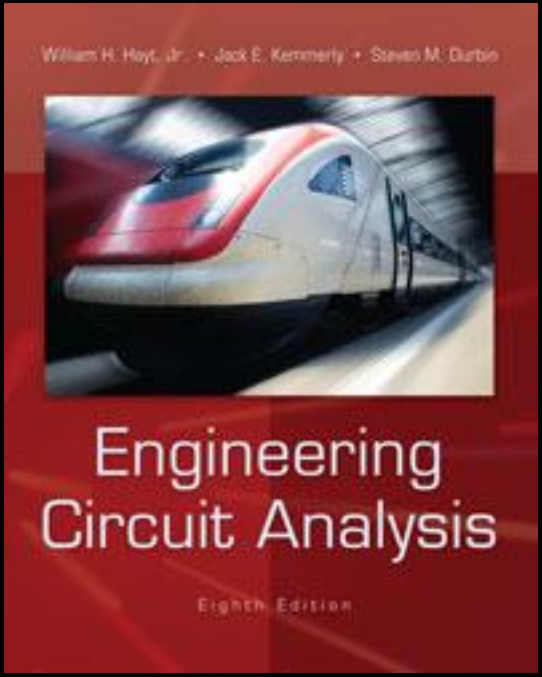
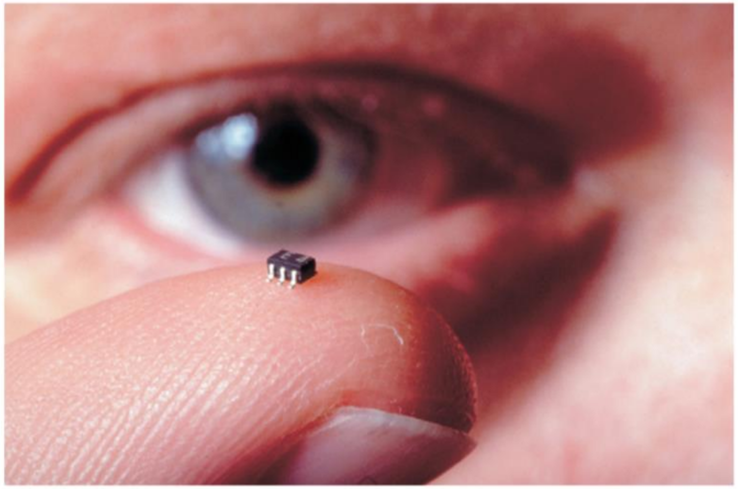
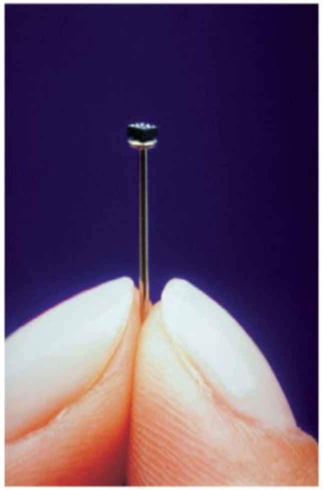
Chapter 6
The Operational Amplifier



The Operational Amplifier

- The *operational amplifier* or op amp for short, finds daily usage in a large variety of electronic applications.

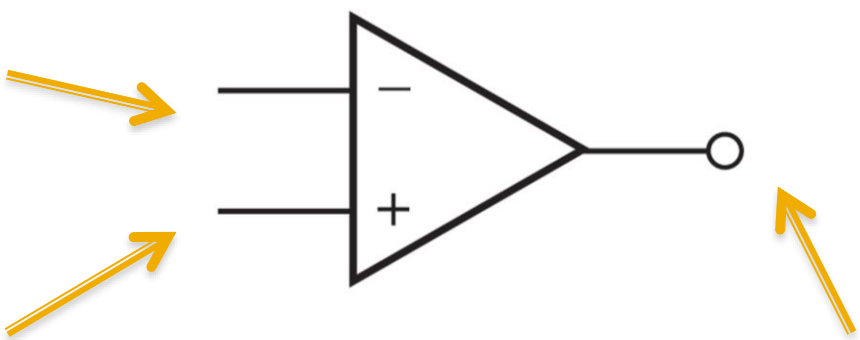




The Op Amp Circuit Element

- op amps have three principal terminals:

the inverting input



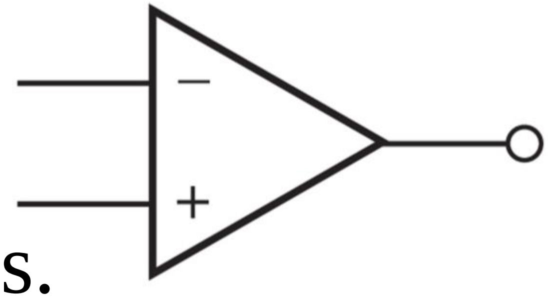
the non-inverting input

the output

The Ideal Op Amp

Ideal Op Amp Rules

- No current ever flows into either input terminal.
- There is no voltage difference between the two input terminals.



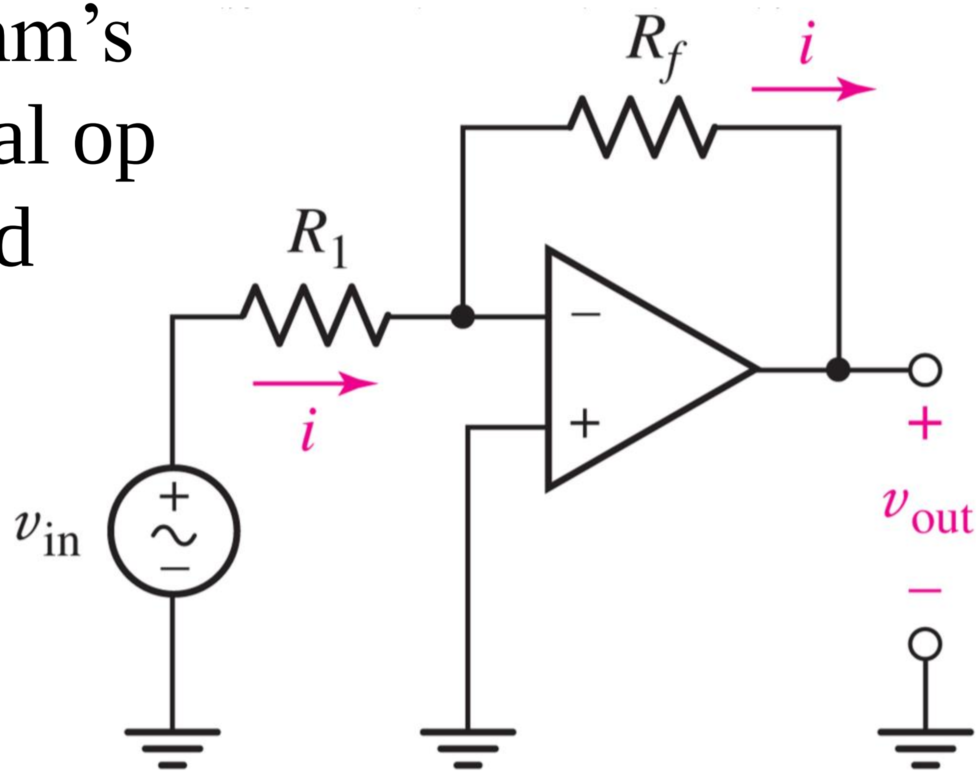
The op amp *acts* to make this happen!

The Inverting Amplifier

More appropriately KCL

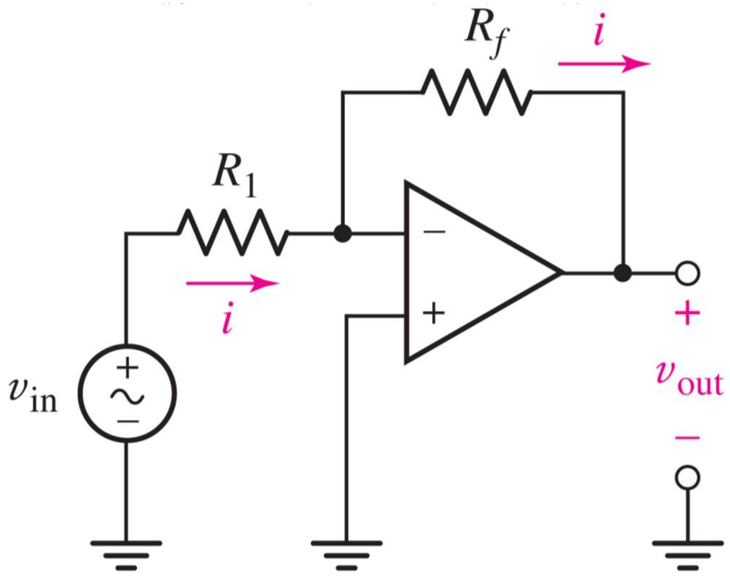
- Apply KVL, Ohm's law, and the ideal op amp rules to find

$$v_{out} = -\frac{R_f}{R_1} v_{in}$$

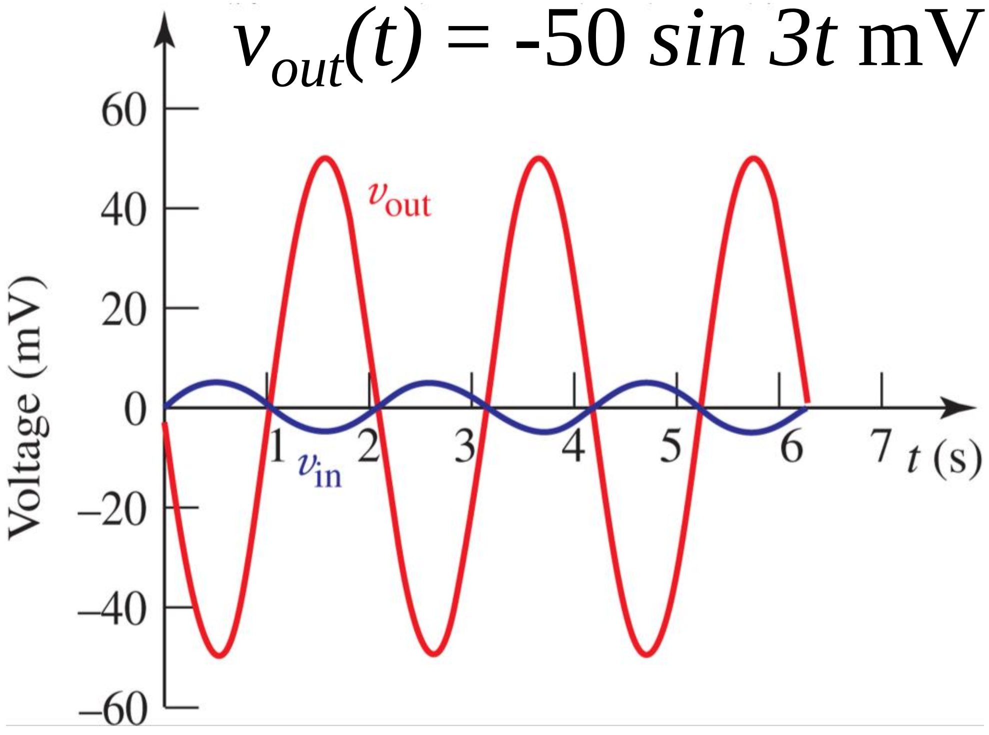


The Inverting Amplifier

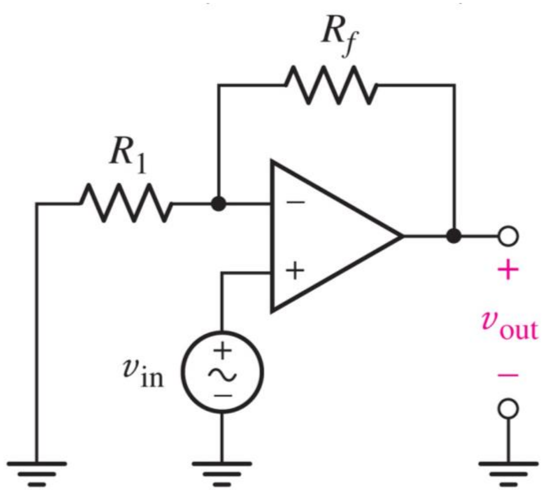
Example: $v_{in}(t)$=5 *sin 3t* mV, R_f=47 kΩ, R_1=4.7 kΩ



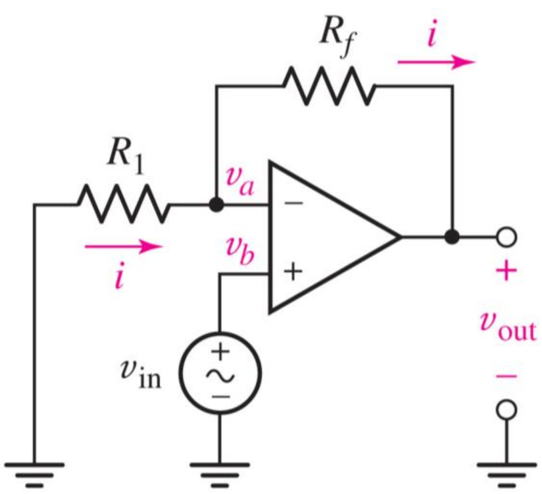
$v_{out}(t)$ = -50 *sin 3t* mV



The Non-inverting Amplifier



$$v_{out} = \left(1 + \frac{R_f}{R_1}\right) v_{in}$$

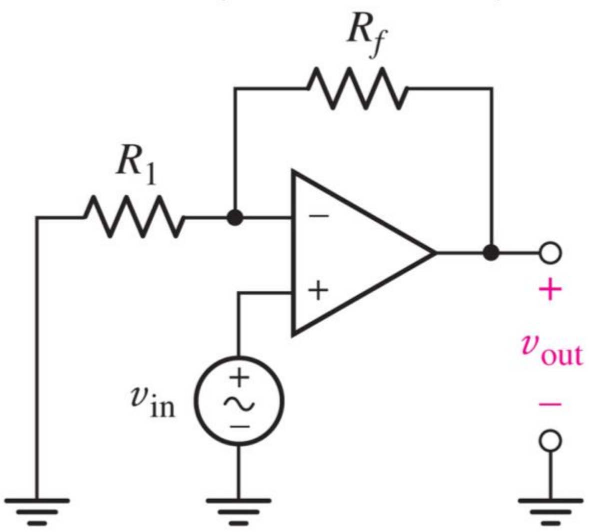


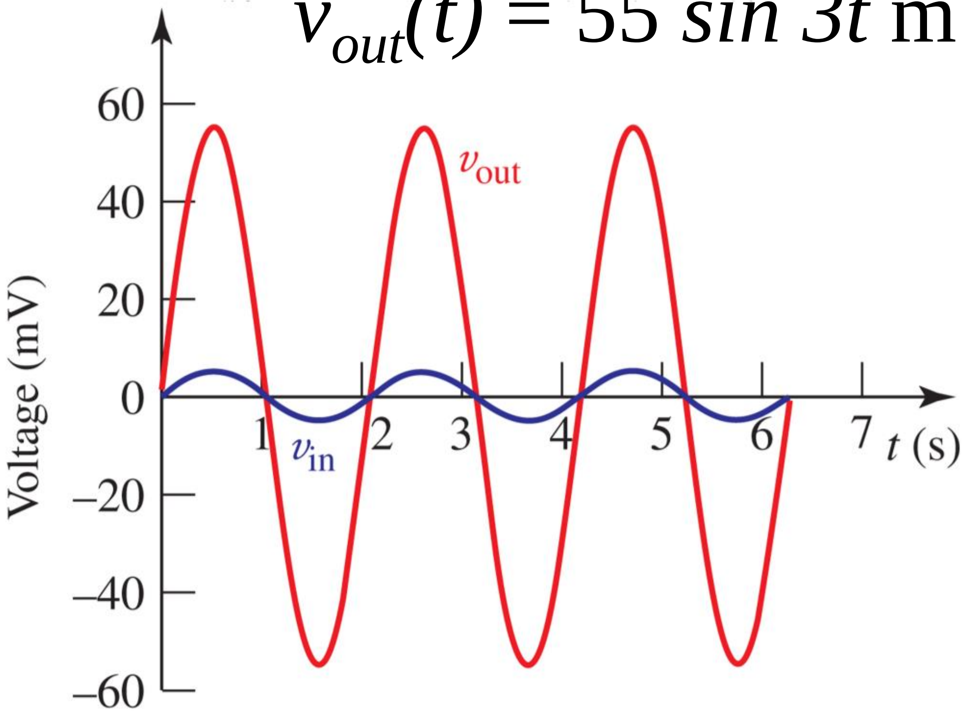
To solve, use KVL, KCL, and op amp rules.
Suggested circuit variables to perform the circuit analysis

The Non-inverting Amplifier

Example: $v_{in}(t)$=5 $sin\ 3t$ mV, R_f=47 kΩ, R_1=4.7 kΩ

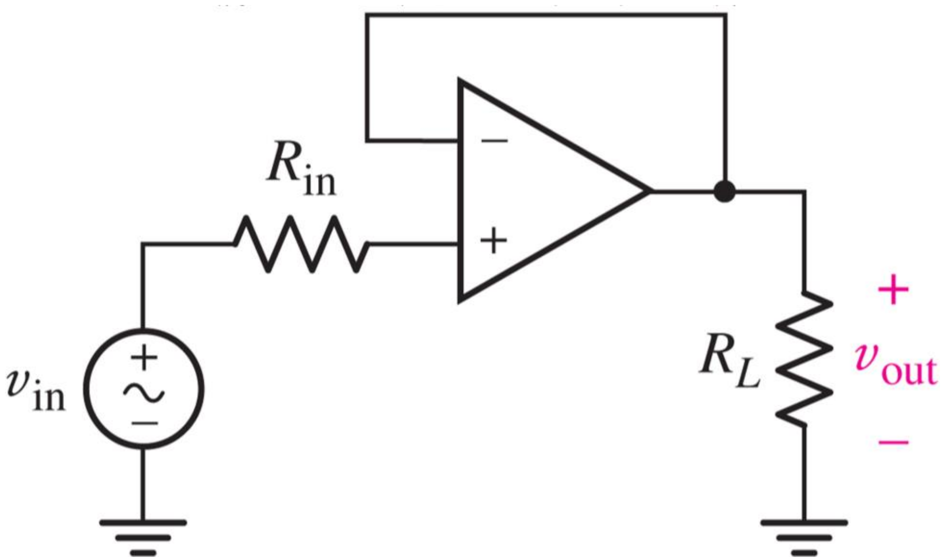
$v_{out}(t)$ = 55 $sin\ 3t$ mV





The Voltage Follower

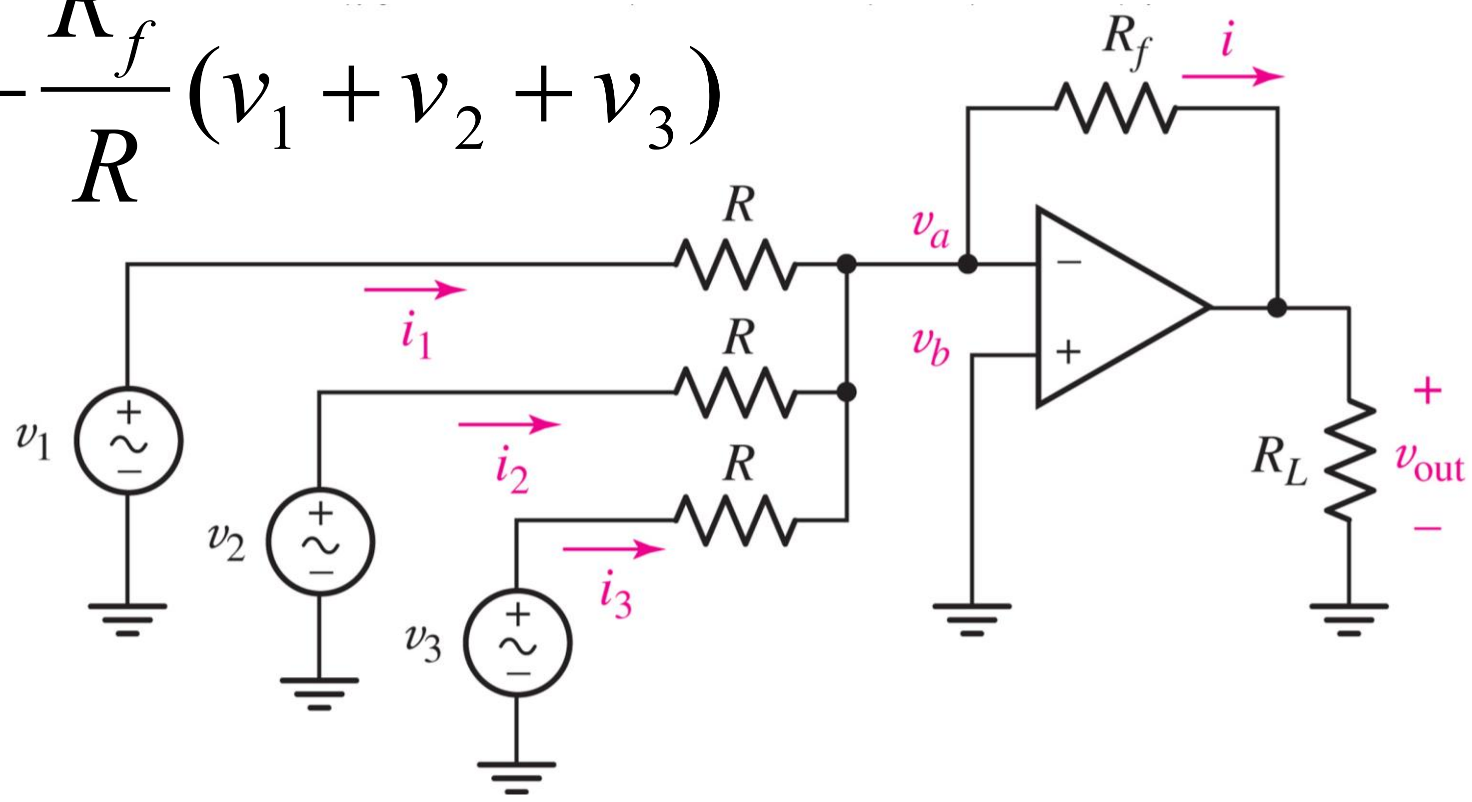
- $v_{out}(t) = v_{in}(t)$



- this design allows connection of a practical voltage source to a load without experiencing voltage droop!

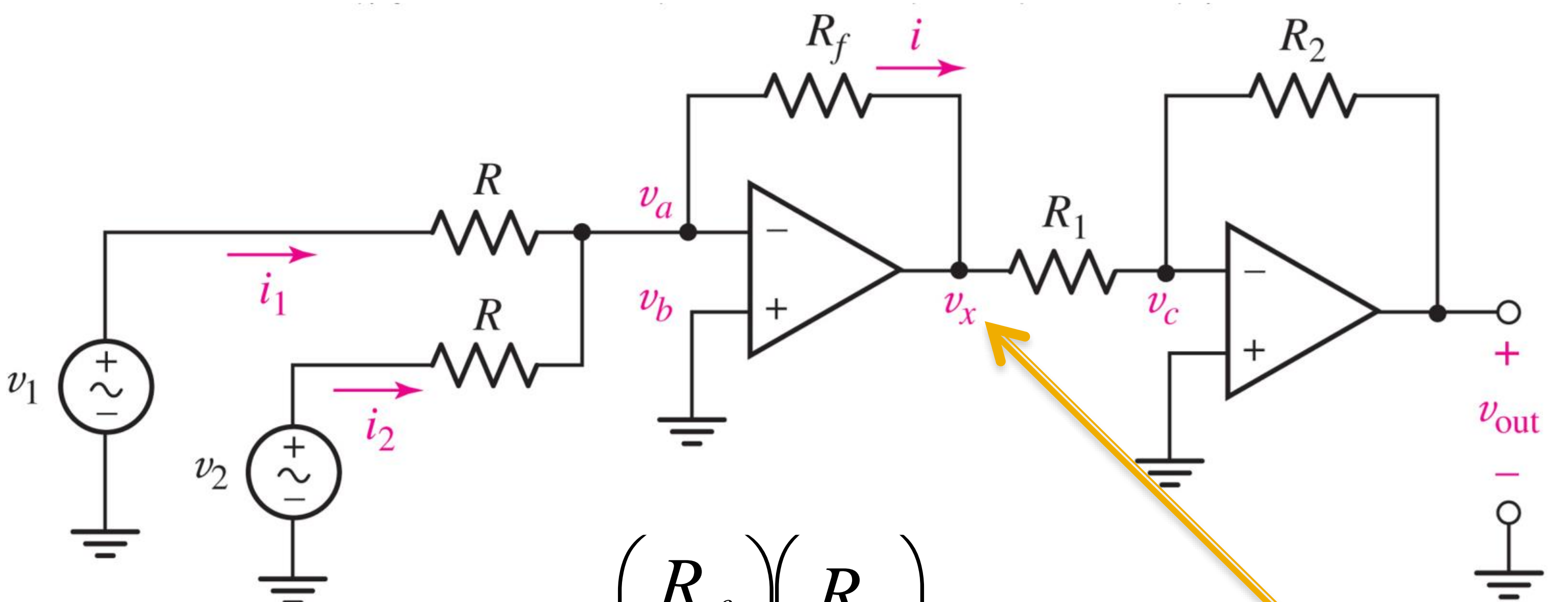
The Summing Amplifier

$$v_{out} = -\frac{R_f}{R}(v_1 + v_2 + v_3)$$



This amplifier performs the *operation* of adding.
It also introduces a gain of $-R_f/R$

Cascaded Stages



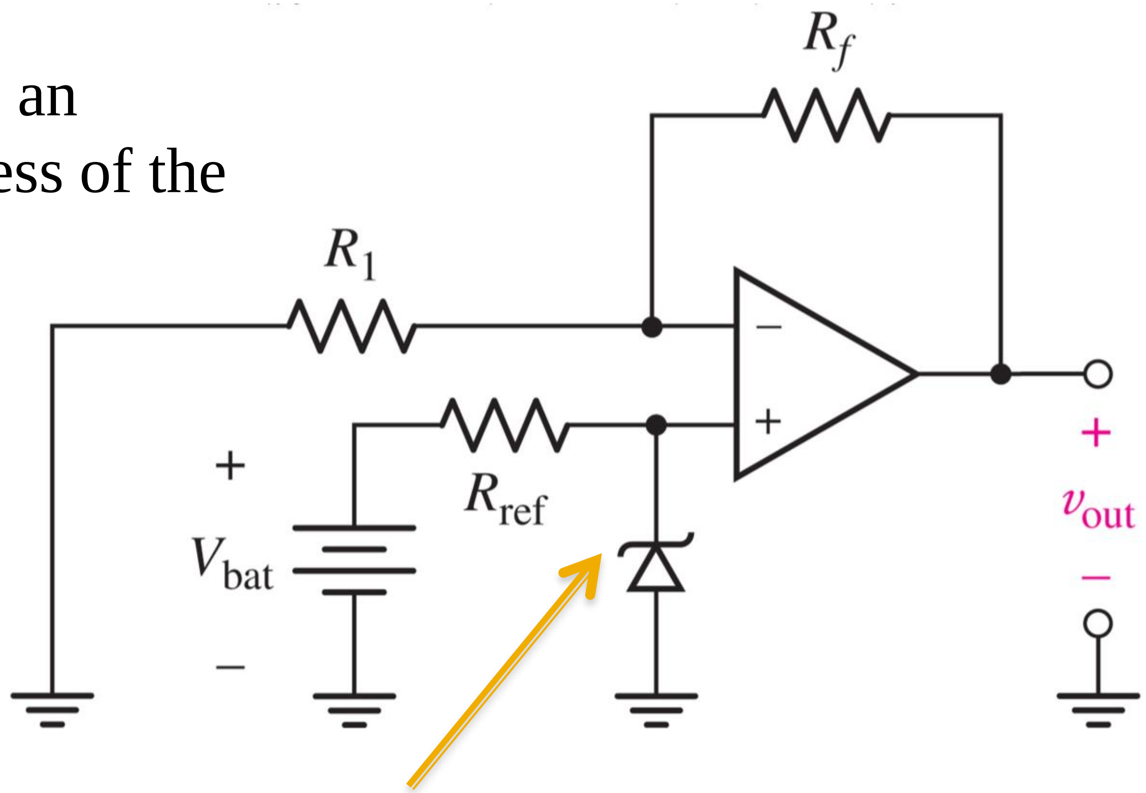
$$v_{out} = \left(\frac{R_f}{R}\right)\left(\frac{R_2}{R_1}\right)(v_1 + v_2)$$

This voltage is not affected by the circuit on the right.

Op amps can be combined in stages to create the desired relationship between the outputs and the inputs.

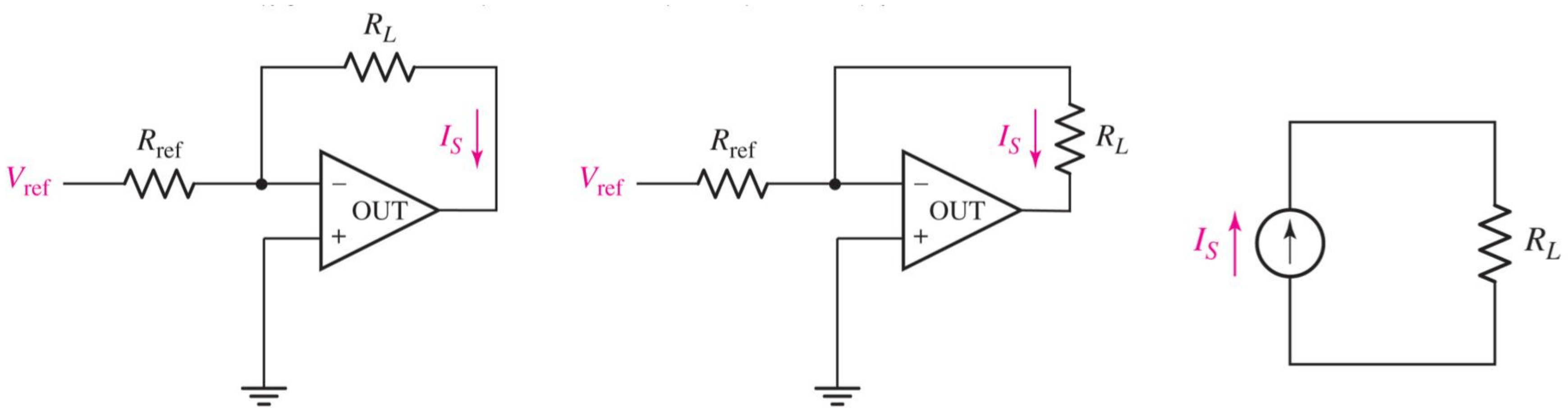
A Reliable Voltage Source

This circuit will produce an accurate voltage regardless of the age of the battery V_{bat}.



Zener diode: $i=0$ if $v<4.7$ volts

A Reliable Current Source

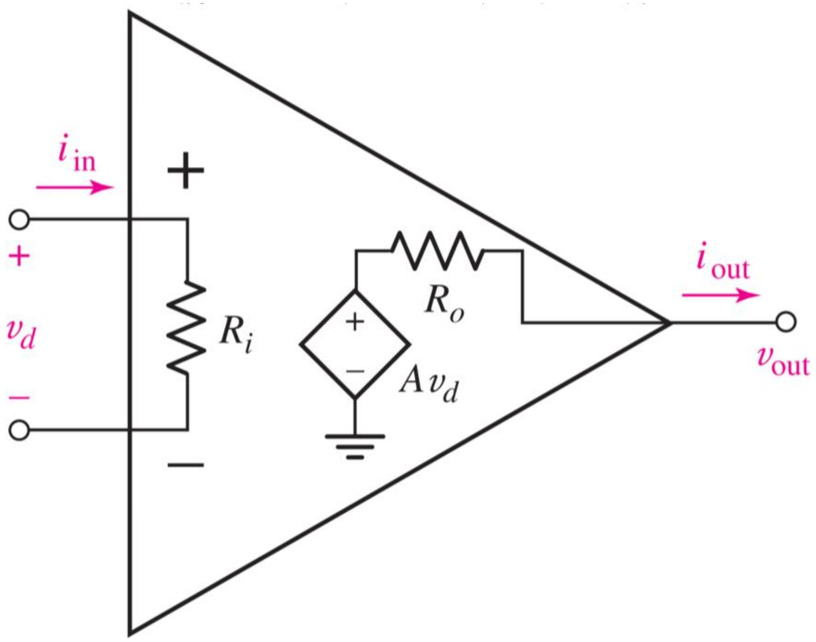


With a reference voltage source V_{ref}, we can drive a constant current $I_s = V_{ref} / R_{ref}$ through any load R_L.

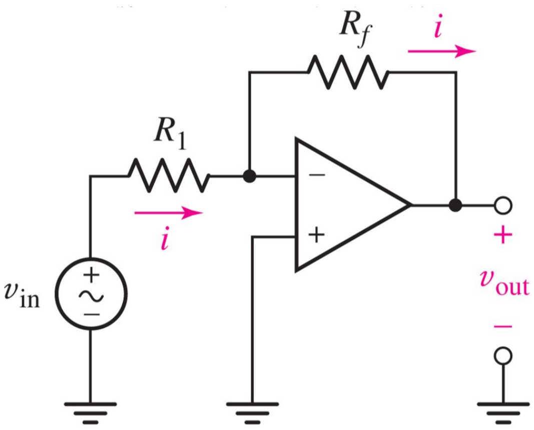
A More Detailed Op Amp Model

The op amp can be modeled as a dependent voltage source, with the following components as shown:

- input resistance R_i
- output resistance R_o
- open loop gain A



Inverting Amplifier with a Real Op Amp



For a 741op amp (A=200,000, R_i=2MΩ, R_o=75Ω

$v_{out}(t)$ = -49.997 sin 3t mV.

An ideal op amp produces $v_{out}(t)$ = -50 sin 3t mV.

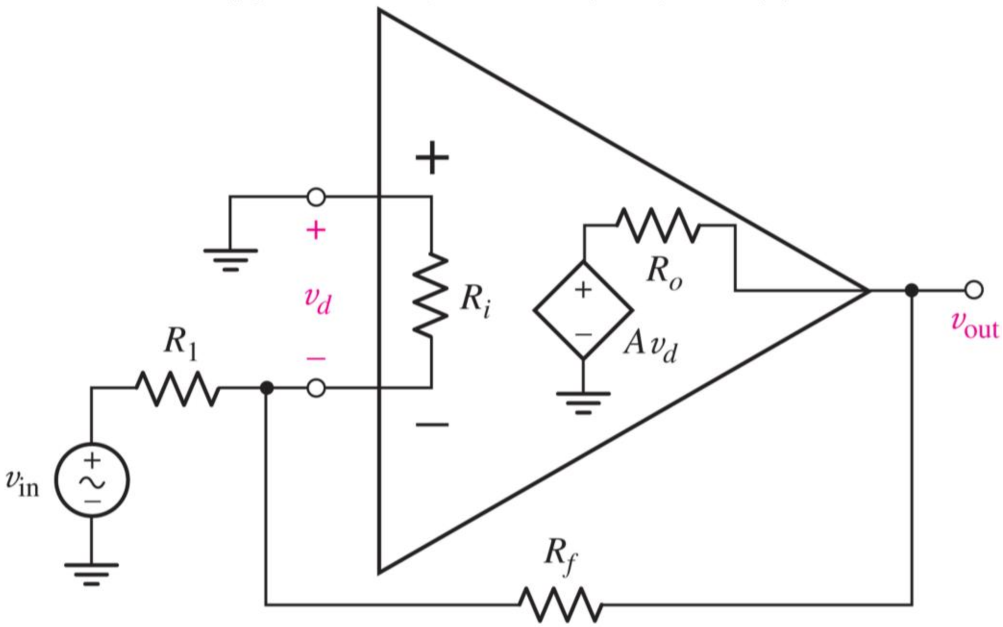
[Analyze the detailed op amp model using nodal analysis.]

Example:

$v_{in}(t)$=5 $sin\ 3t$ mV,

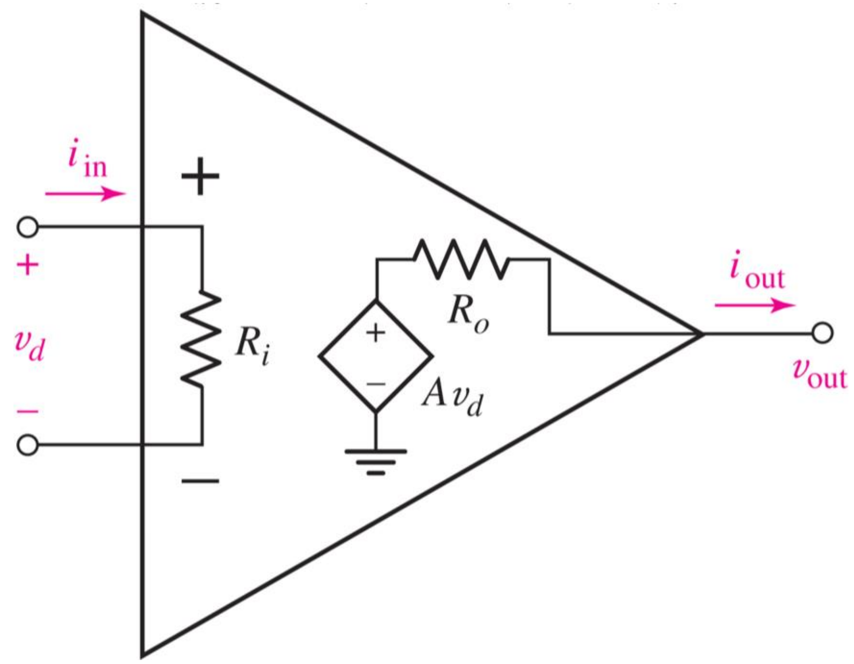
R_f=47 kΩ,

R_1=4.7 kΩ



An Ideal Op Amp

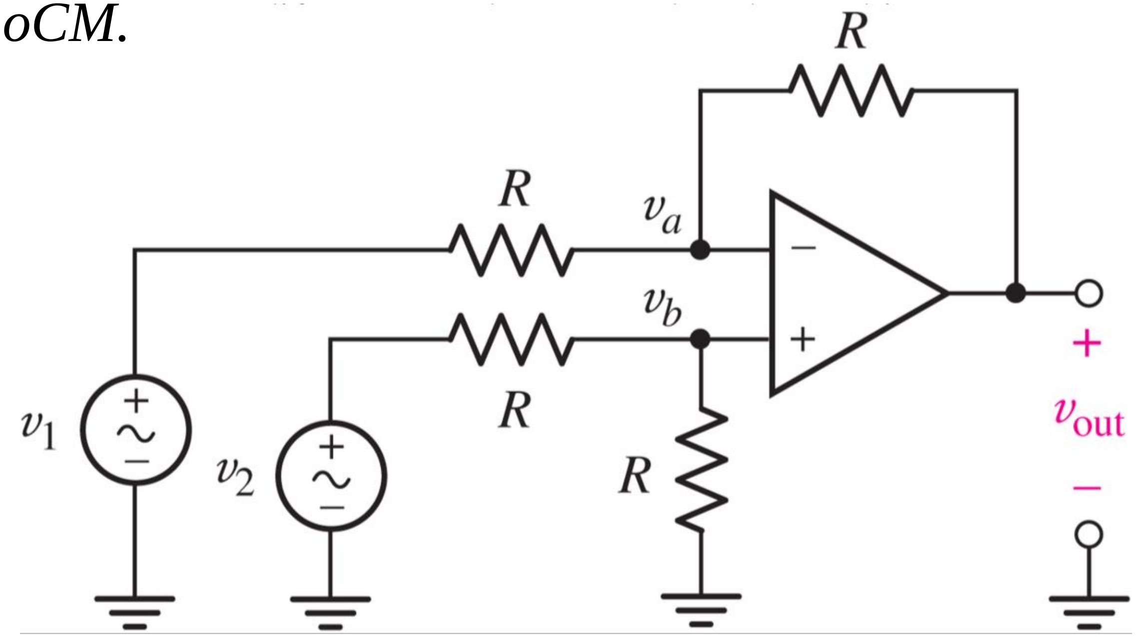
When A=∞, R_o=0 Ω, and R_i=∞ Ω, the op amp behaves according to the ideal op amp rules. ($v_d=0$ *and* $i_{in}=0$)



Common Mode Rejection

When $v_1 = v_2 = v_{CM,}$ the output should be zero, but real op amps produce a small "common mode" voltage $v_{oCM.}$

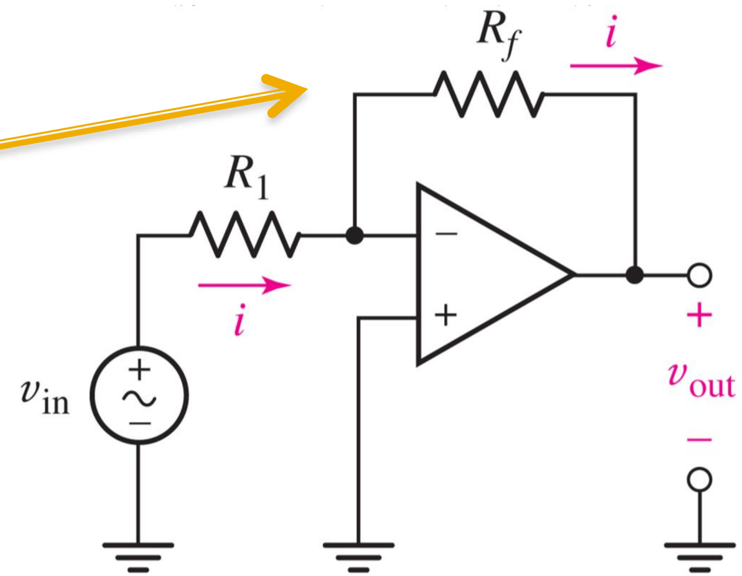
$A_{CM} = | v_{oCM} / v_{CM} |$



Negative Feedback

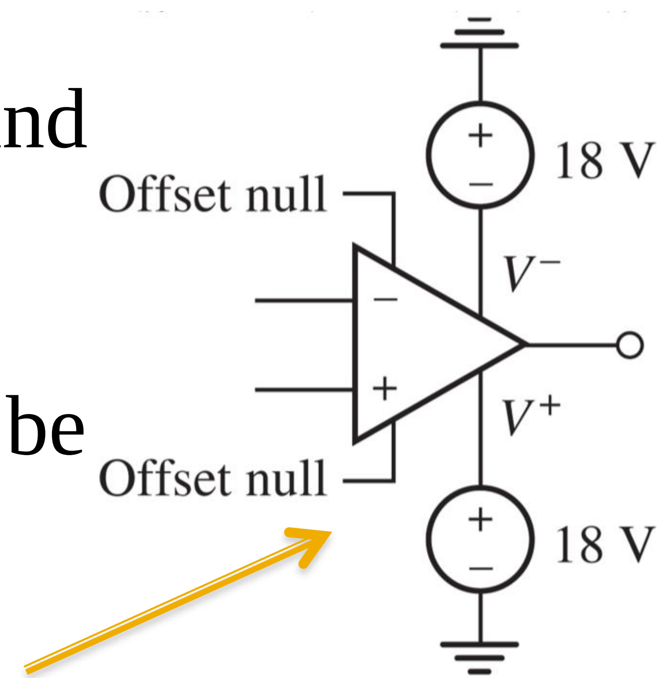
- The enormous but unpredictable gain of the op amp is made usable through negative feedback.
- When v_{in} goes up, v_d goes down, and the op amp reacts by lowering v_{out} until the "unwanted" non-zero v_d is pushed back to zero.

this "feedback" resistor allows the output to affect the input terminal.



Power Supplies

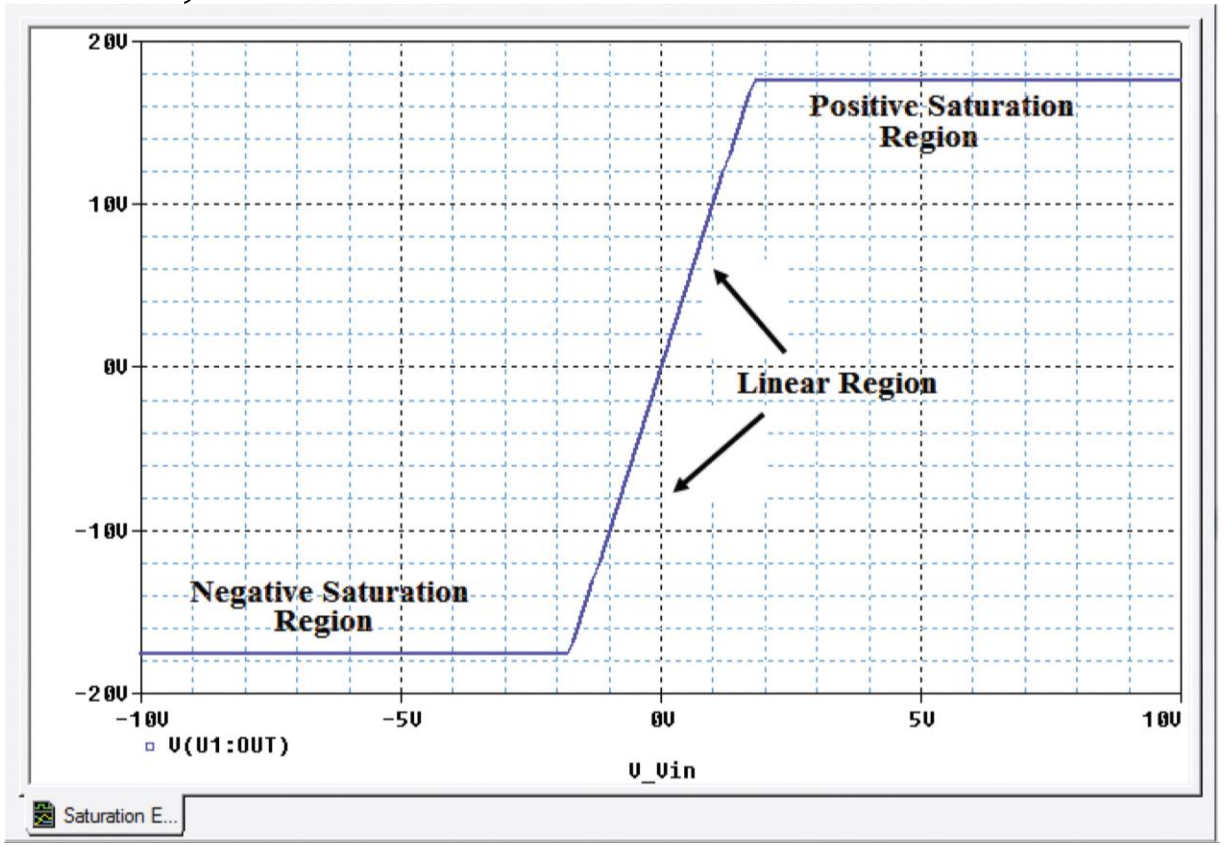
- An op amp requires power supplies.
- Usually, equal and opposite voltages are connect to the V^+ and V^- terminals.
- Typical values are 5 to 24 volts.
- The power supply ground must be the same as the signal ground.



in this example +18V is connected to V^+
and -18 V is connected to V^-

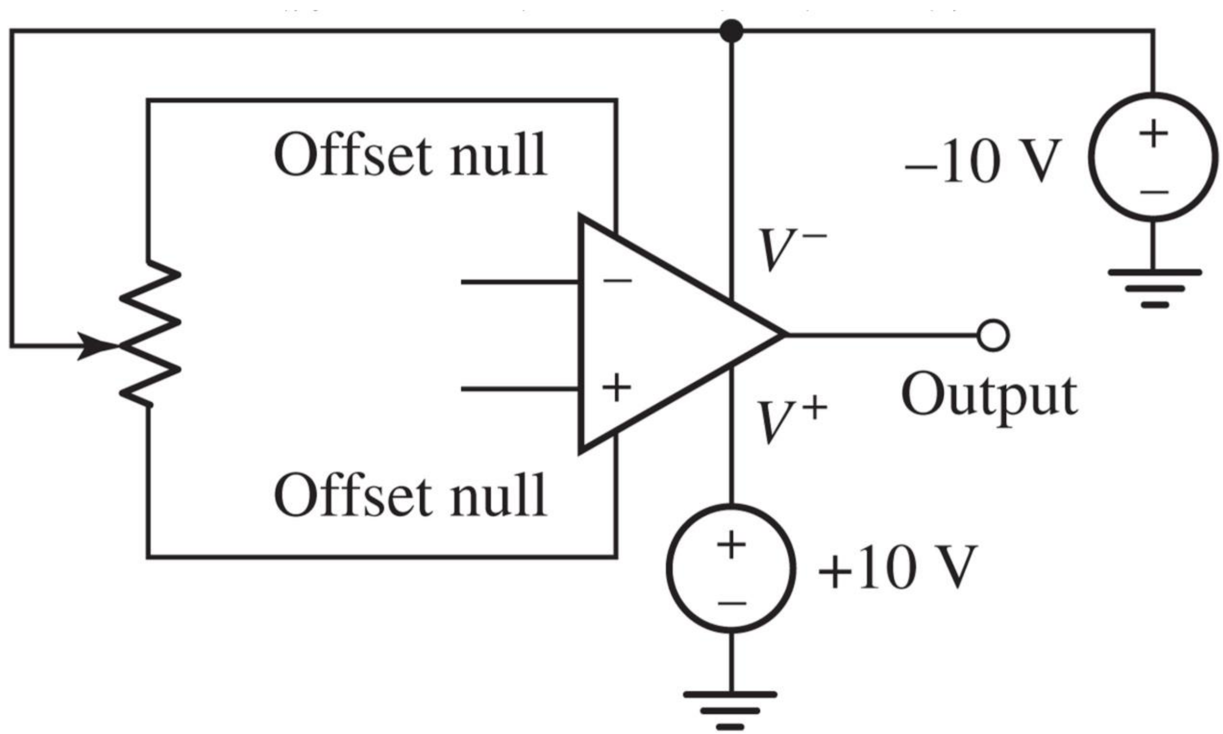
Saturation

$v_{out}=10v_{in},$ but only up to the $\pm$18 V supplies



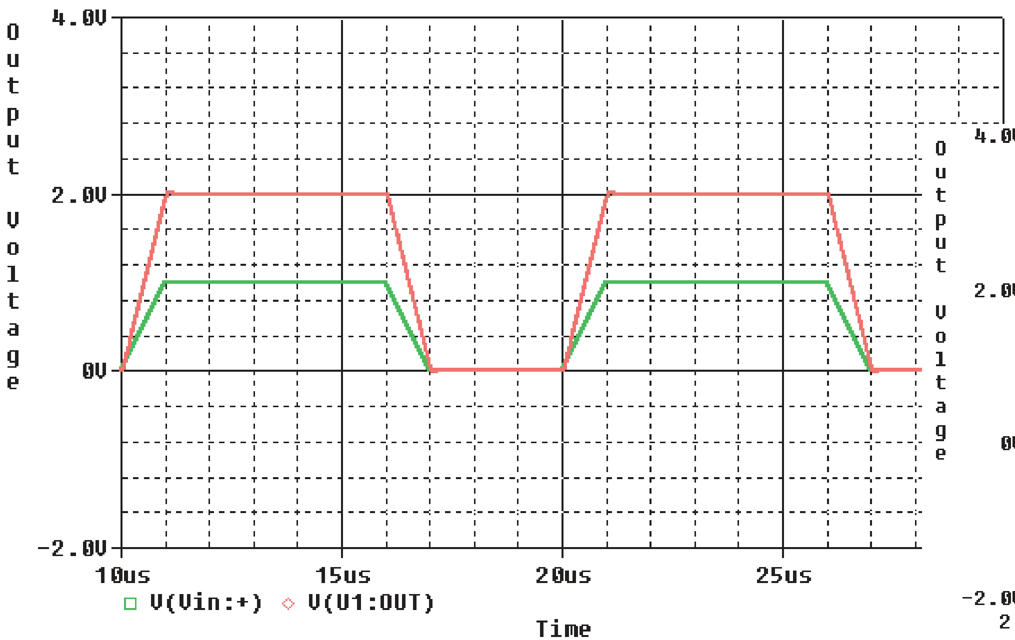
Input Offset Voltage

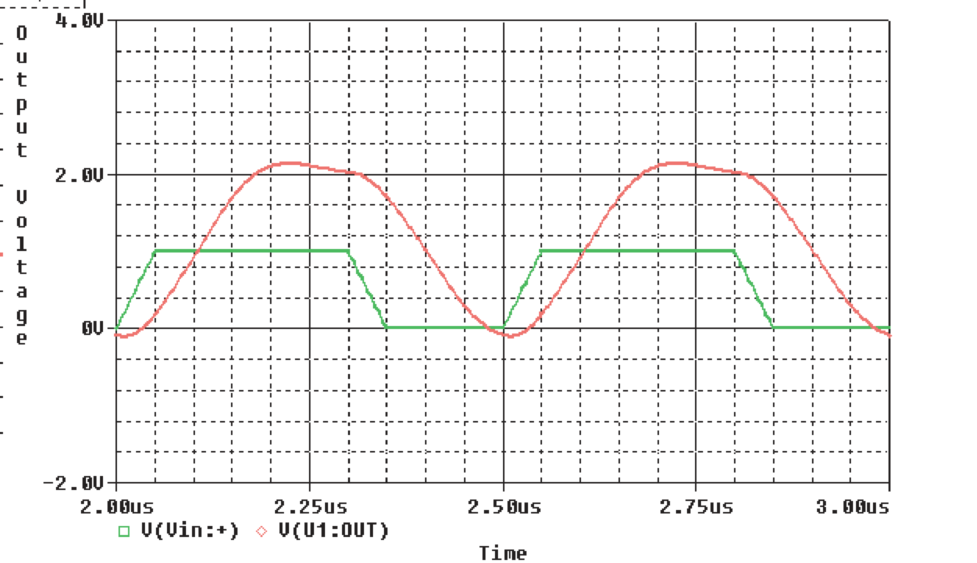
Non-zero output "offsets" can be removed:



Slew Rate and Input Frequency

Slew rate is the maximum V/µs for output.

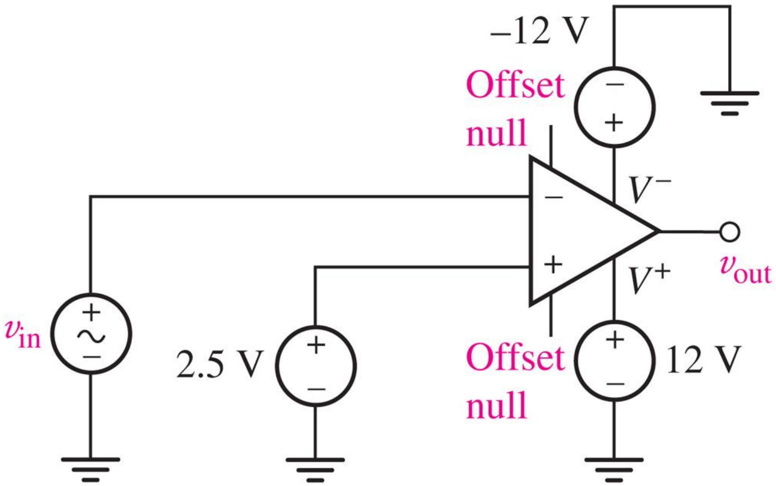


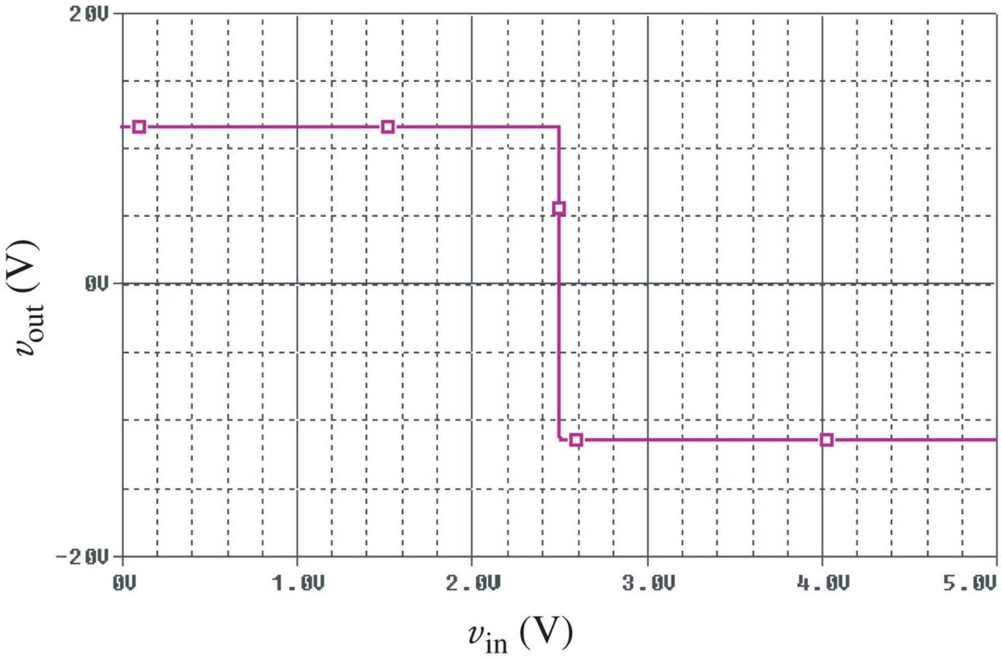


- examples: input (green) and output (red)

The Comparator

- Op amps in open loop can be used to make decisions. In this case, is v_{in}>2.5 V?

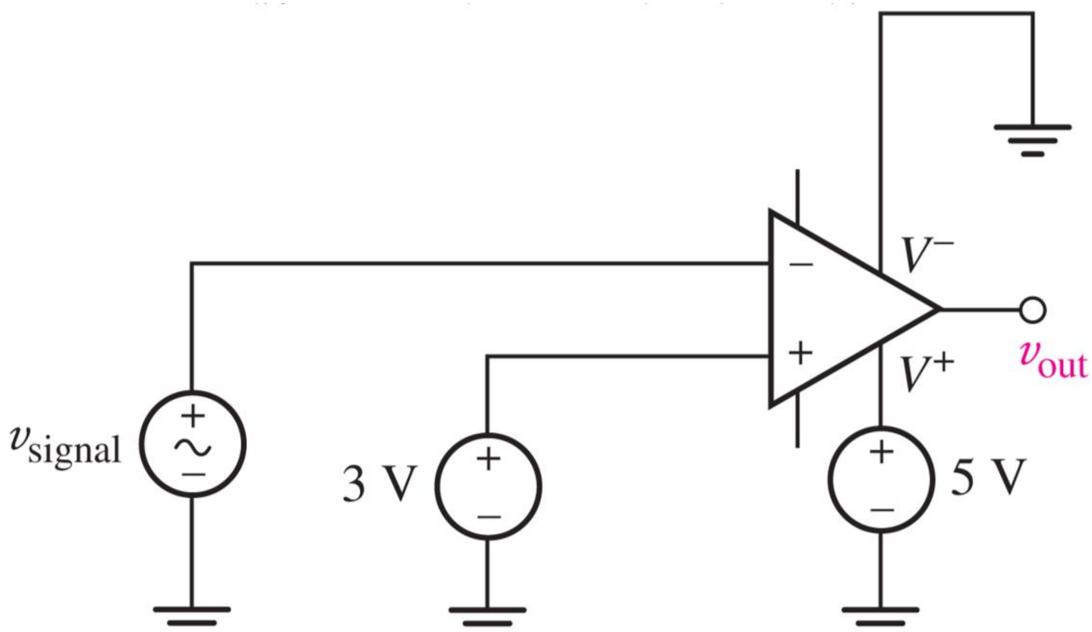




Example: Comparator Design

Design a circuit that provides a "logic 1" 5 V output if a certain voltage signal drops below 3 V, and zero volts otherwise.

Answer:



The Instrumentation Amplifier

This device allows precise amplification of small voltage differences:

$$v_{out}=K(v_+-v_-)$$