BLM1612 Circuit Theory

The Operational Amplifier

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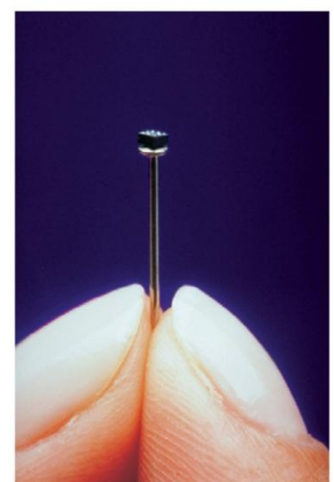
The Operational Amplifier

• An operational amplifier (Op-Amp) is a DC-coupled high-gain electronic voltage amplifier with a differential input and, usually, a single-ended output.

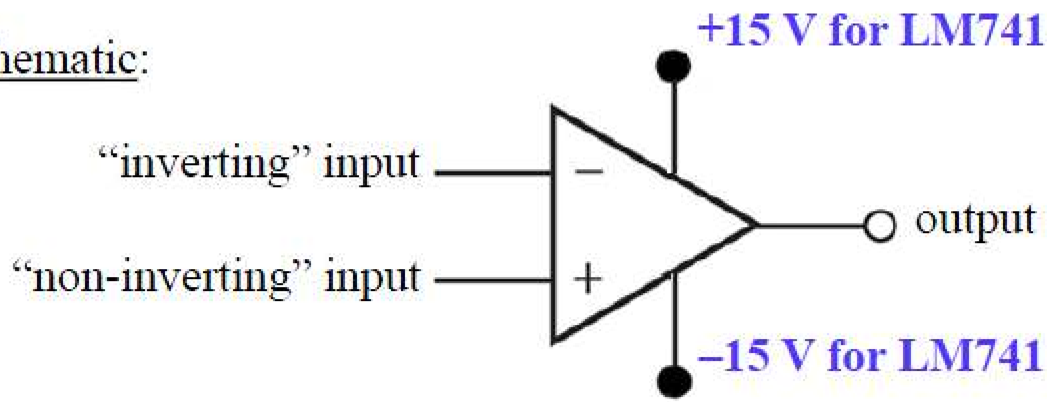
• An Op-Amp produces an output potential (relative to circuit ground) that is typically hundreds of thousands of times larger than the potential difference between its input terminals.

• The operational amplifier finds daily usage in a large variety of electronic applications.



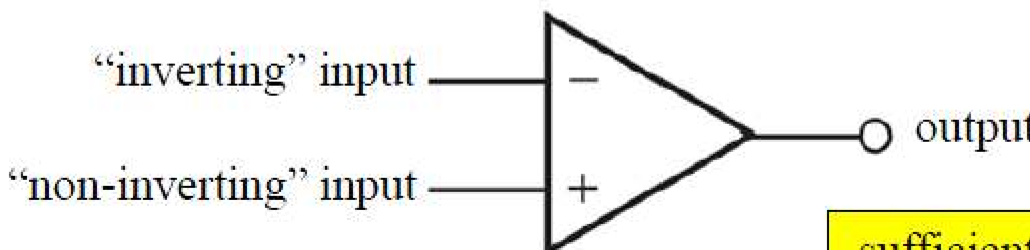
The Operational Amplifier

Full schematic:



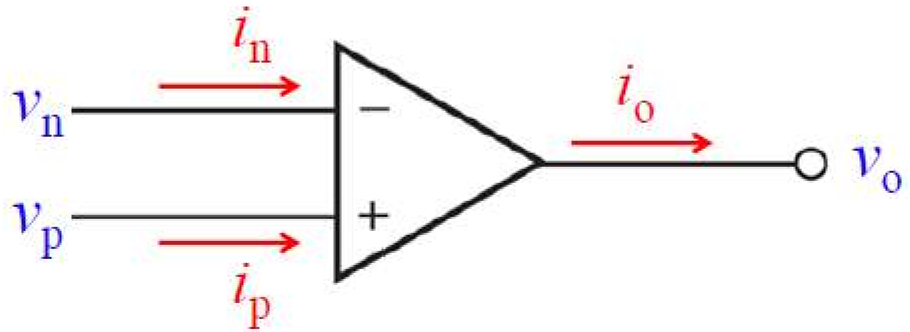
The op-amp chip needs external power in order to function.

Simplified schematic:



sufficient for circuit analysis

The Operational Amplifier



$$A_v = \frac{v_o}{v_p - v_n}$$

<u>Function of the op amp</u>:

to amplify the voltage difference $v_p - v_n$ by $A_v > 10^6$ with external feedback such that

$$\boxed{v_n \approx v_p} \qquad \boxed{i_n = i_p \approx 0}$$

Ideal Op-Amp Rules

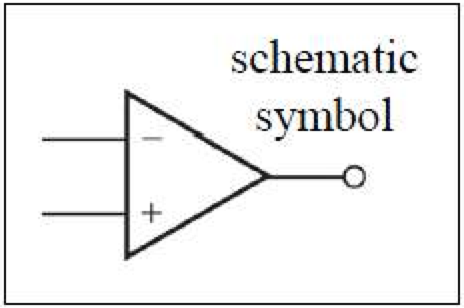
– No current ever flows into either input terminal.

–There is no voltage difference between the two input terminals.

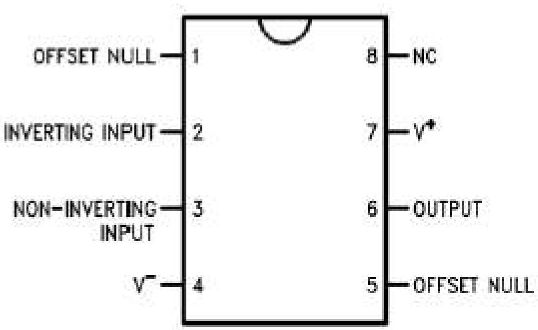
The Operational Amplifier

"Op Amp"

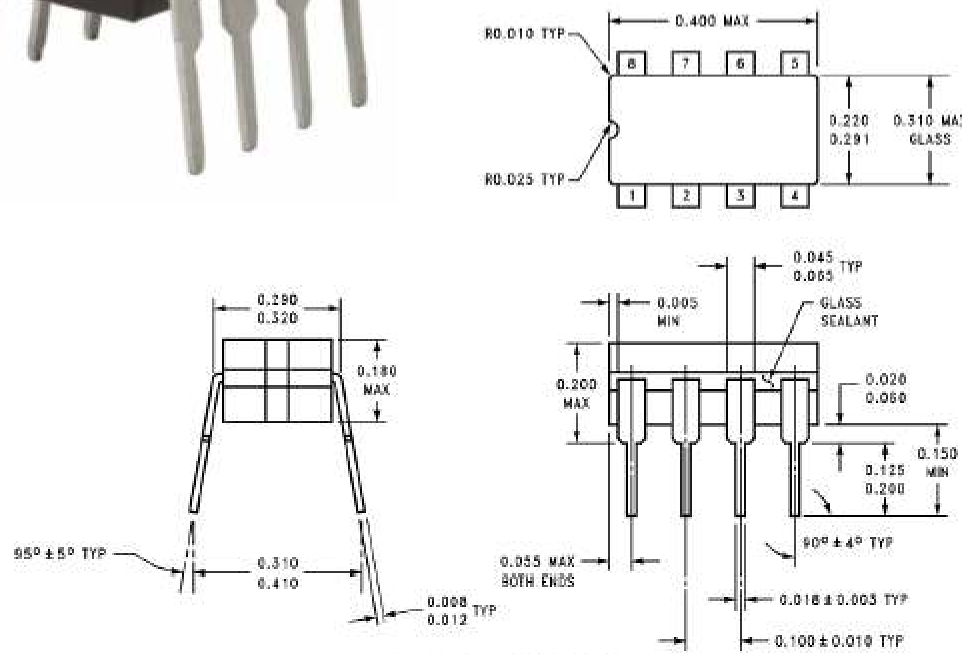
National Semiconductor **LM741** datasheet



Dual-In-Line or S.O. Package



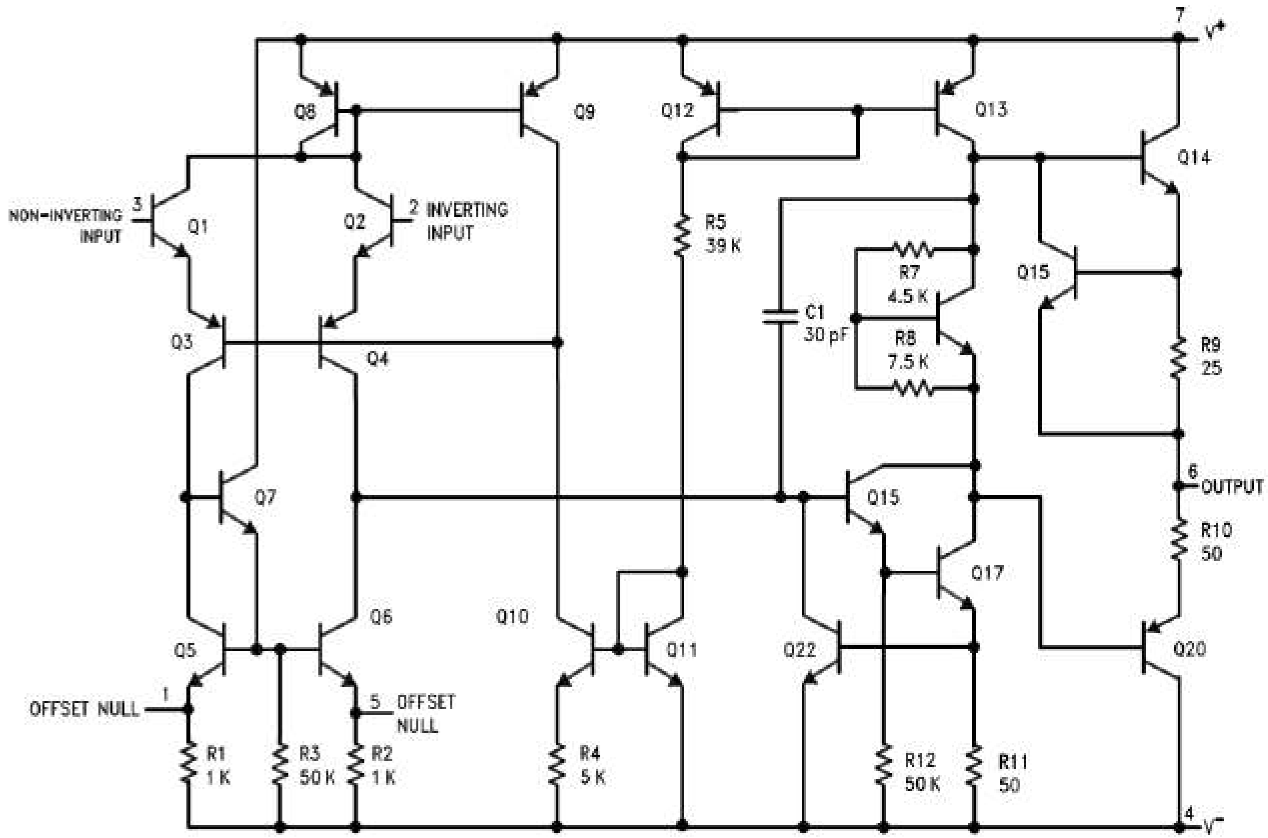
Order Number LM741J, LM741J/883, LM741CM, LM741CN or LM741EN



Ceramic Dual-In-Line Package (J)
Order Number LM741CJ or LM741J/883

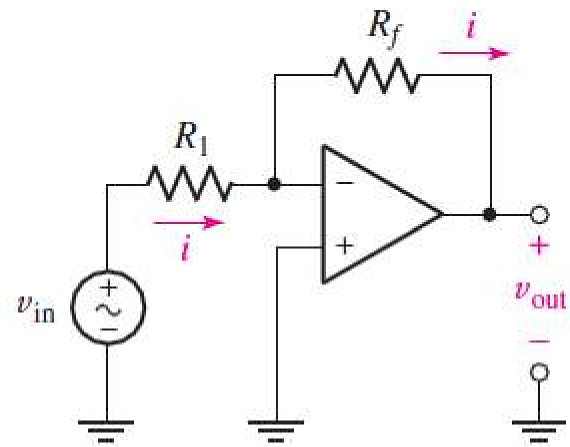
Inside of LM741

National Semiconductor LM741 datasheet

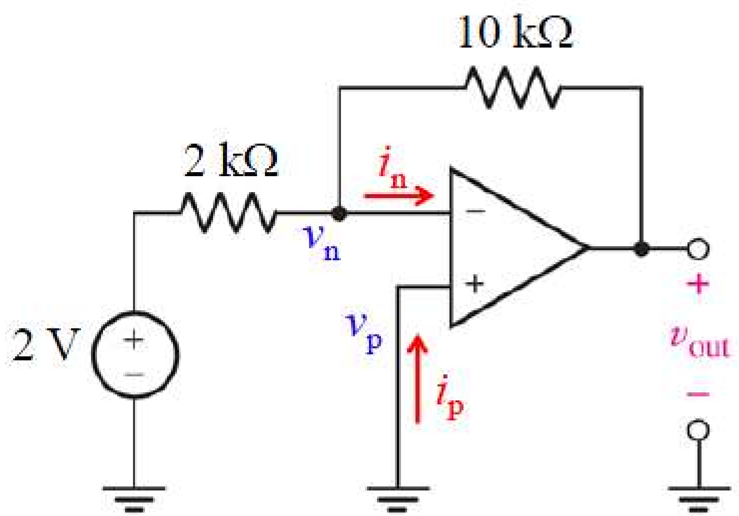


Op Amp Circuit #1

Determine v_{out} if v_{in} = 2 V, R_f = 10 kΩ, and R_1 = 2 kΩ.



$$\boxed{v_n = v_p} \qquad \boxed{i_n = i_p = 0}$$



$$\text{KCL @ } v_n\text{:} \quad \frac{v_{out} - v_n}{10} + \frac{2 - v_n}{2} - i_n = 0$$

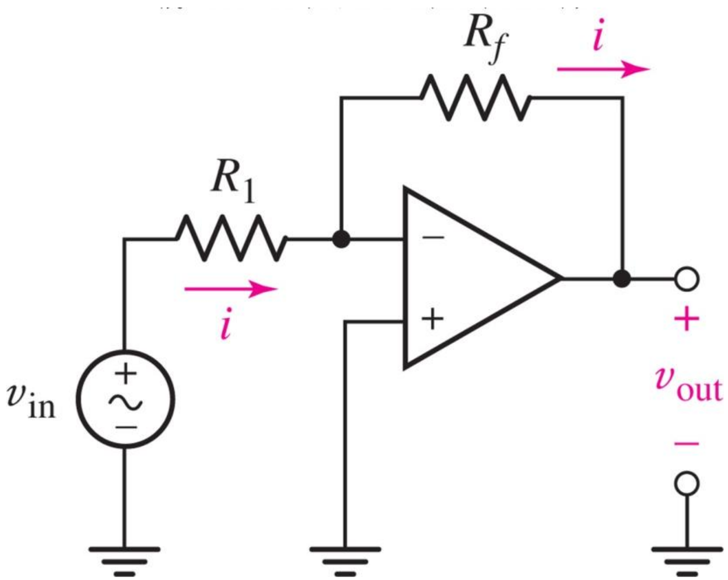
$$v_p = 0$$

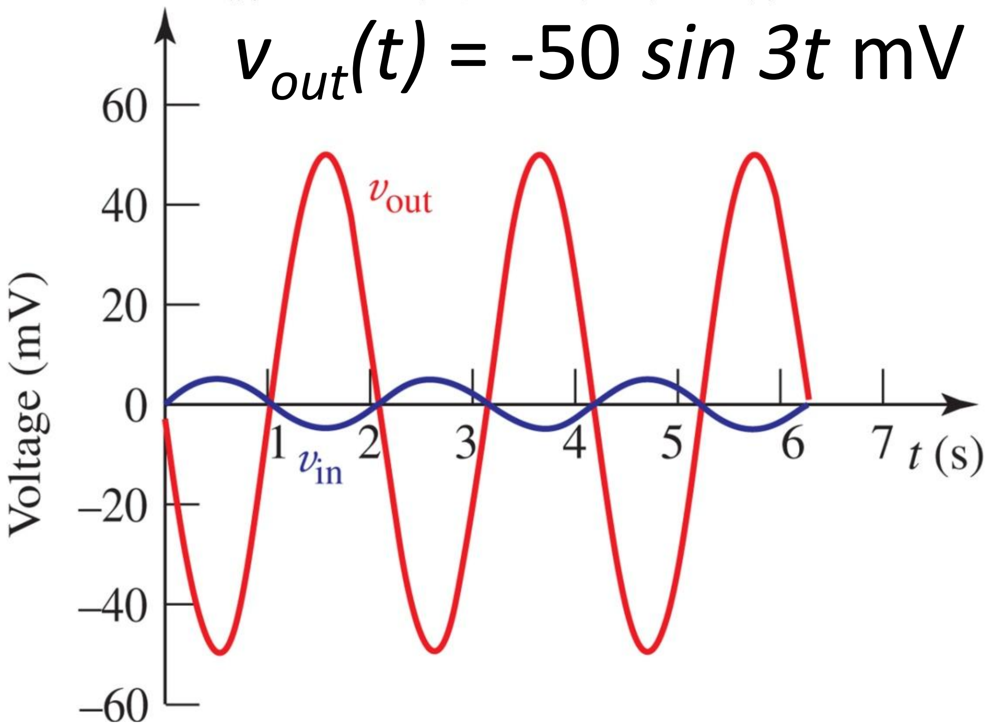
$$\boxed{v_{out} = -10\text{ V}}$$

(inverting amplifier)

Example

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

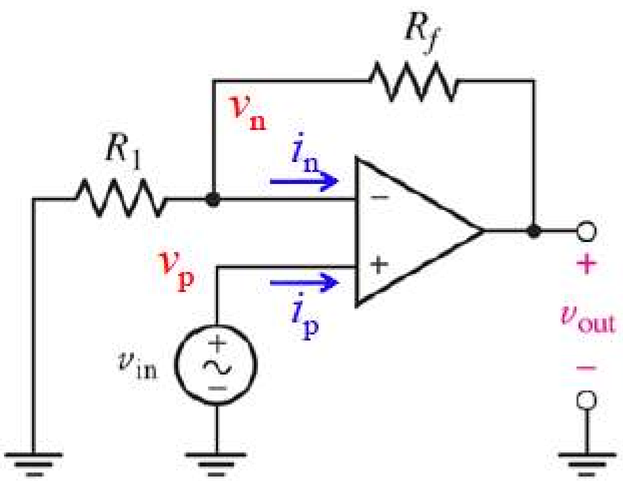




$$v_{out} = -\frac{R_f}{R_1} v_{in}$$

Op Amp Circuit #2

- Write v_{out} *in terms of* v_{in}, R_f , *and* R_1.



$\boxed{v_n = v_p}$ $\boxed{i_n = i_p = 0}$ $v_p = v_{in}$

$v_p = v_{in}$

$$\frac{-v_{in}}{R_1} + \frac{v_{out} - v_{in}}{R_f} = 0$$

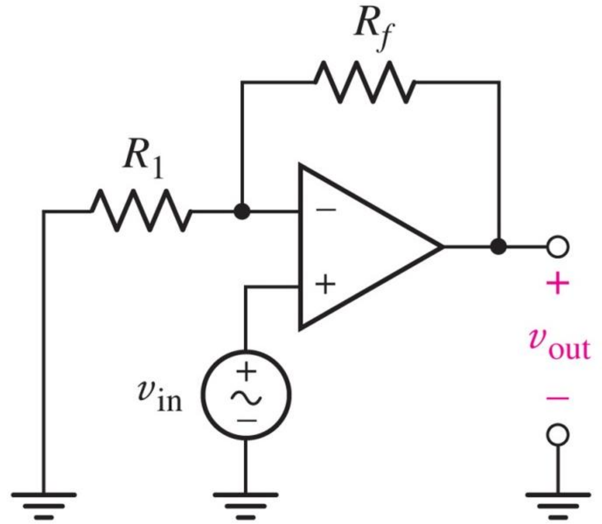
$$\frac{v_{in}}{R_1} + \frac{v_{in}}{R_f} = \frac{v_{out}}{R_f}$$

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

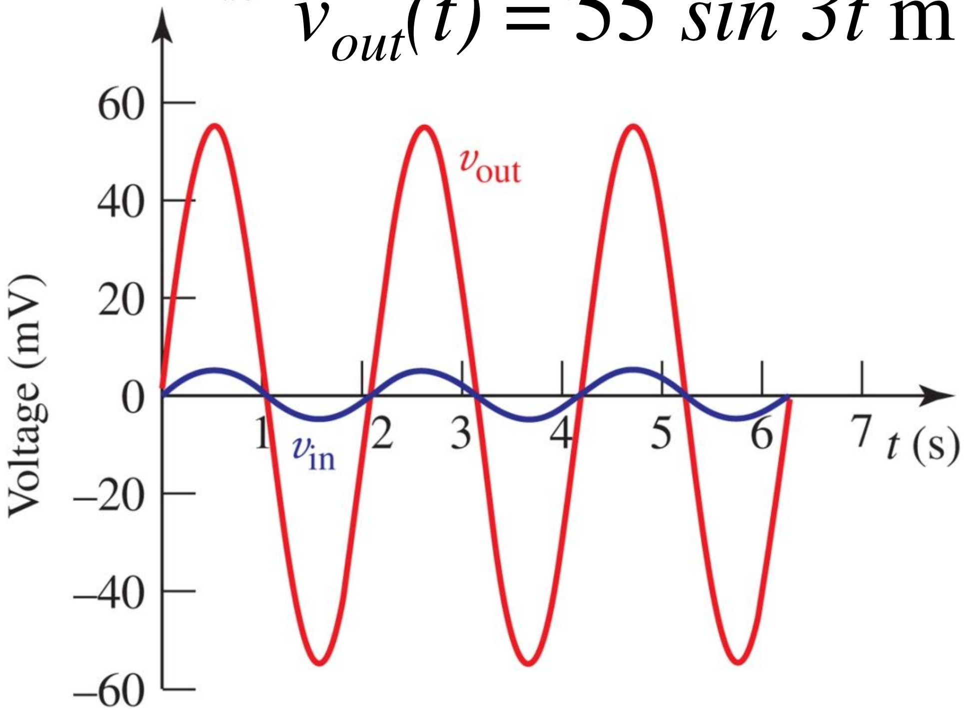
non-inverting amplifier

Example

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

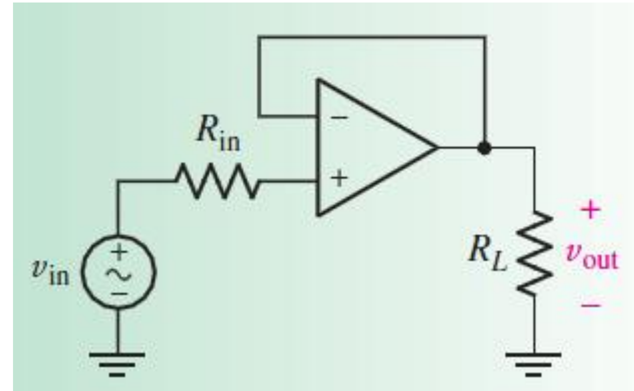


$$v_{out}(t) = 55\ sin\ 3t \text{ mV}$$



Op Amp Circuit #3

- represents a non-inverting amplifier with **R_1 set to infinity** and **R_f set to zero**, the output is identical to the input in both sign and magnitude.
- this new circuit is called as **Voltage Follower** $v_{out} = v_{in}$ (also known as a Unity Gain Amplifier)
- the input impedance of the op amp is very high, giving effective isolation of the output from the signal source. You draw very little power from the signal source, avoiding "loading" effects.

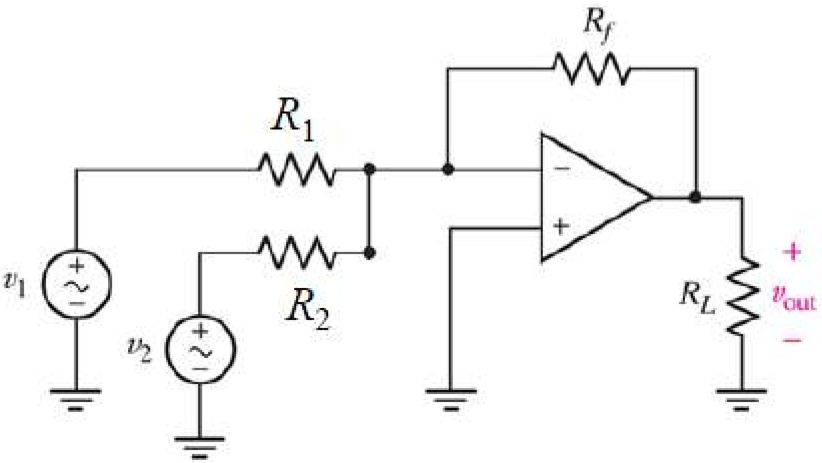


$$v_{out} = v_{in}$$

Op Amp Circuit #4

- Write v_{out} *in terms of* v_1, v_2, R_f, R_1, R_2, *and* R_L.

$$\boxed{v_n = v_p} \qquad \boxed{i_n = i_p = 0}$$



$$\frac{v_{out}}{R_f} + \frac{v_1}{R_1} + \frac{v_2}{R_2} = 0 \qquad v_{out} = -R_f\frac{v_1}{R_1} - R_f\frac{v_2}{R_2}$$

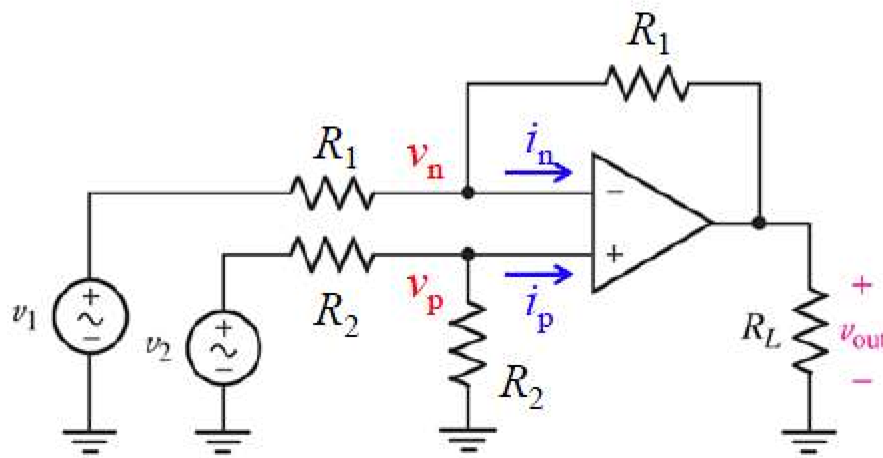
$$\boxed{v_{out} = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2\right)}$$

(inverting) summing amplifier

Op Amp Circuit #5

- Write v_{out} *in terms of* v_1, v_2, R_1, R_2, *and* R_L.

$\boxed{v_n = v_p}$ $\boxed{i_n = i_p = 0}$

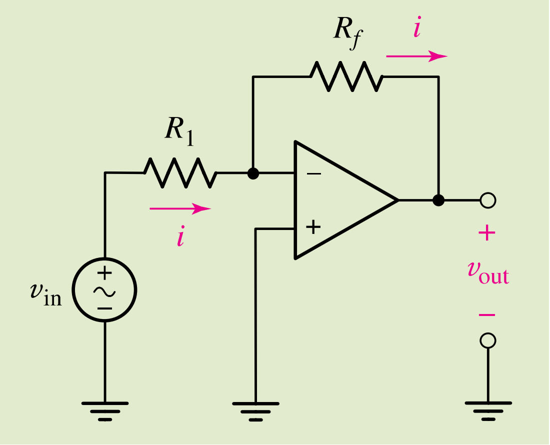


$$\boxed{v_{out} = v_2 - v_1}$$

difference amplifier

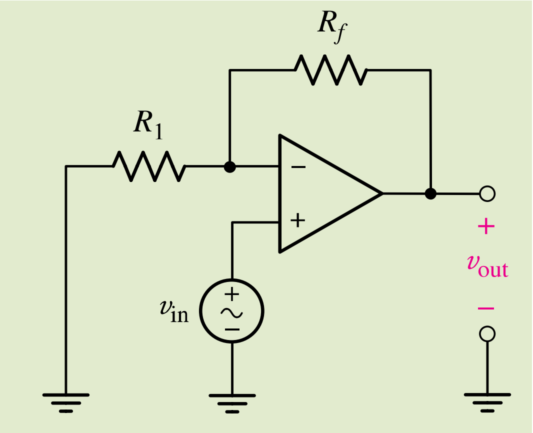
Summary of Basic Op Amp Circuits

Inverting Amplifier



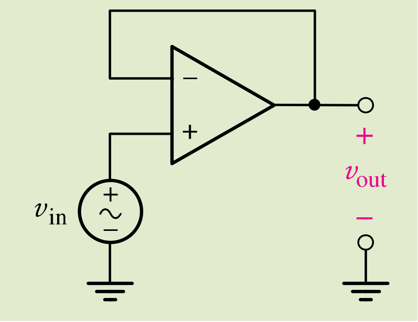
$$v_{out} = -\frac{R_f}{R_1} v_{in}$$

Noninverting Amplifier



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

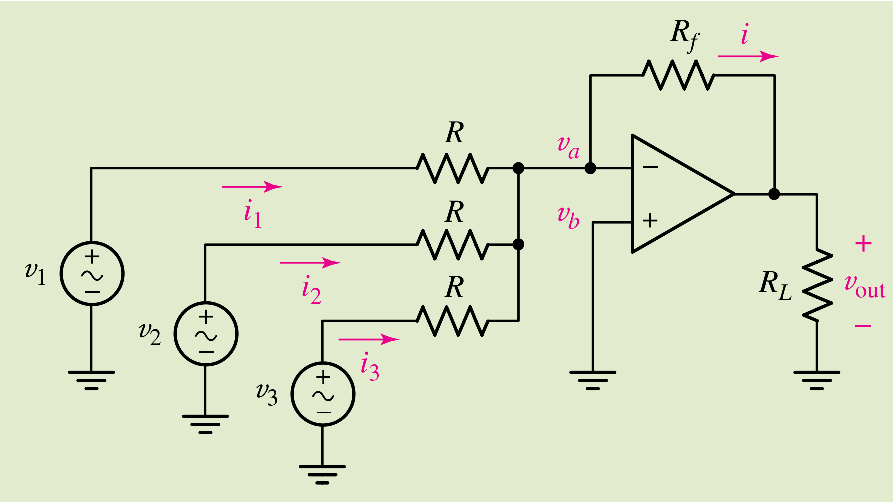
Voltage Follower (also known as a Unity Gain Amplifier)



$$v_{out} = v_{in}$$

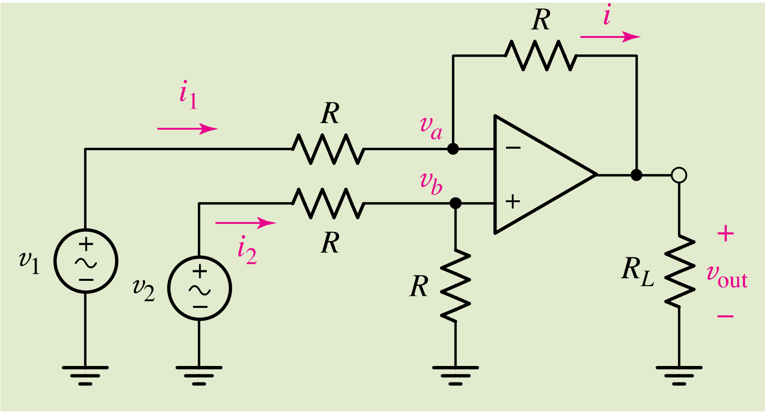
Summary of Basic Op Amp Circuits

Summing Amplifier



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

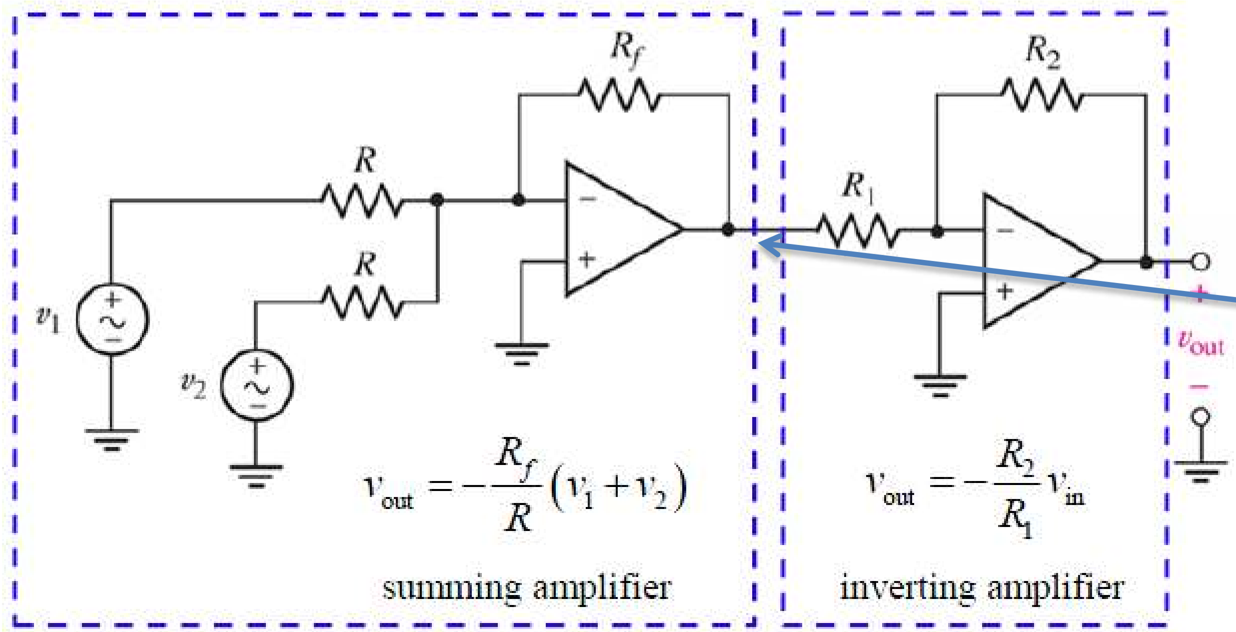
Difference Amplifier



$$v_{out} = v_2 - v_1$$

Op-Amp Cascades

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



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

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

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

Op Amp Circuit #6 – Design Example

Design a circuit to achieve: $v_{\text{out}} = 2v_1 - 3v_2 + 4v_3 - 6v_4$

$$\boxed{v_{\text{out}} = \left(\frac{R_y}{R_x} + 1\right) v_{\text{in}}}$$

non-inverting amp

$$\boxed{v_{\text{out}} = -\frac{R_b}{R_a} v_{\text{in}}}$$

inverting amp

$$\boxed{v_{\text{out}} = -\left(\frac{R_f}{R_1} v_1 + \frac{R_f}{R_2} v_2 + \dots\right)}$$

inverting sum

$$\boxed{v_{\text{out}} = v_2 - v_1}$$

difference

$$v_{\text{out}} = \underbrace{-\left\{\frac{R_f}{R_1}\underbrace{\left(-\frac{R_b}{R_a} v_1\right)}_{\text{invert}} + \frac{R_f}{R_2} v_2 + \frac{R_f}{R_3}\underbrace{\left(-\frac{R_d}{R_c} v_3\right)}_{\text{invert}} + \frac{R_f}{R_4} v_4\right\}}_{\text{inverting sum}}$$

$$v_{\text{out}} = \frac{R_f R_b}{R_1 R_a} v_1 - \frac{R_f}{R_2} v_2 + \frac{R_f R_d}{R_3 R_c} v_3 - \frac{R_f}{R_4} v_4$$

Op Amp Circuit #6 – Design Example

Design a circuit to achieve: $v_{\text{out}} = 2v_1 - 3v_2 + 4v_3 - 6v_4$

$$v_{\text{out}} = \frac{R_f R_b}{R_1 R_a} v_1 - \frac{R_f}{R_2} v_2 + \frac{R_f R_d}{R_3 R_c} v_3 - \frac{R_f}{R_4} v_4$$

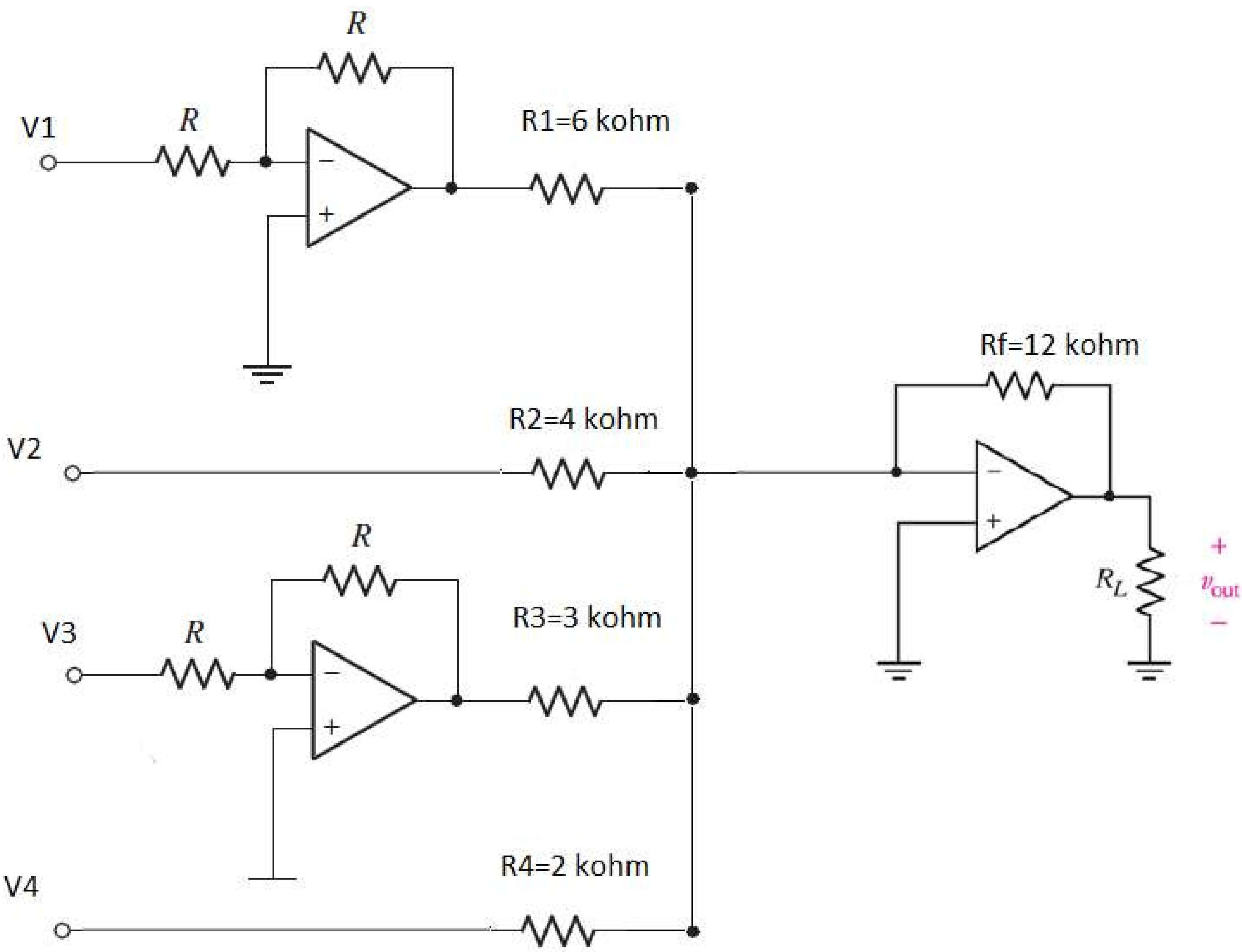
Choose $R_{\text{a}} = R_{\text{b}} = R_{\text{c}} = R_{\text{d}} = 2\ \text{k}\Omega$ ...

$$v_{\text{out}} = \frac{R_f}{R_1} v_1 - \frac{R_f}{R_2} v_2 + \frac{R_f}{R_3} v_3 - \frac{R_f}{R_4} v_4$$

Choose $R_f = 12\ \text{k}\Omega \rightarrow R_1 = 6\ \text{k}\Omega,\ R_2 = 4\ \text{k}\Omega,\ R_3 = 3\ \text{k}\Omega,\ R_4 = 2\ \text{k}\Omega$ ...

$$v_{\text{out}} = \frac{12}{6} v_1 - \frac{12}{4} v_2 + \frac{12}{3} v_3 - \frac{12}{2} v_4$$

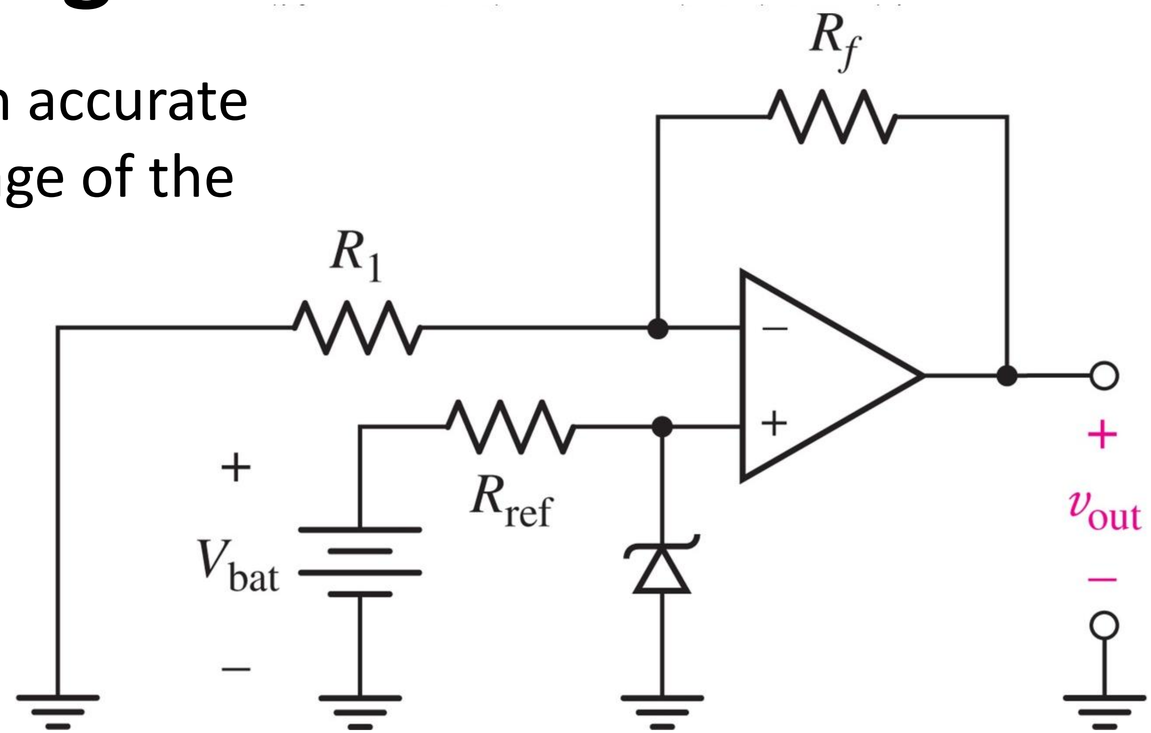
Op Amp Circuit #6 – Design Example



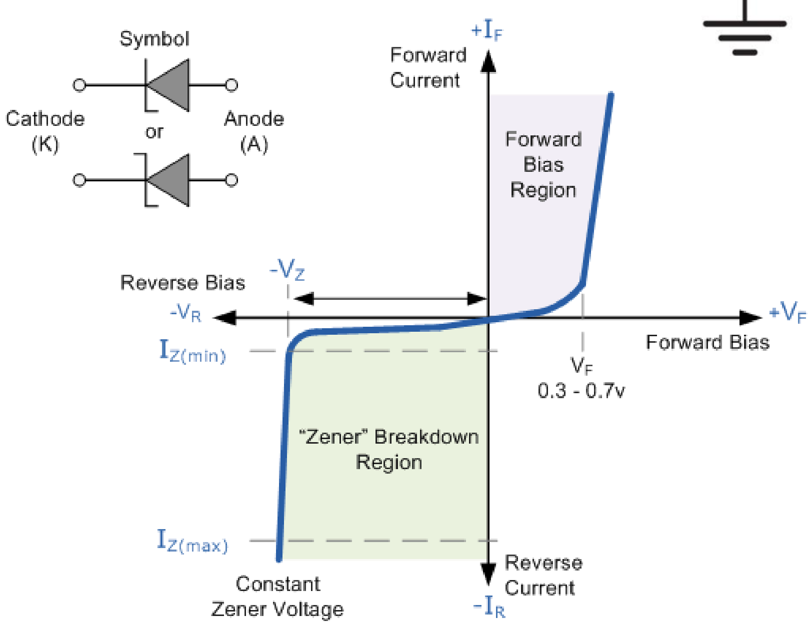
$$v_{out} = 2v_1 - 3v_2 + 4v_3 - 6v_4$$

A Reliable Voltage Source

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

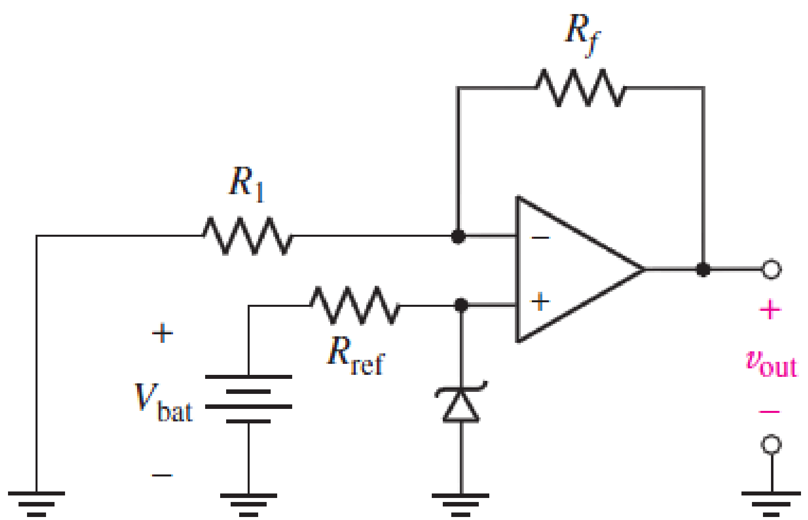


Zener diode: i=0 if v<4.7 volts
For 1N750 Zener Diode



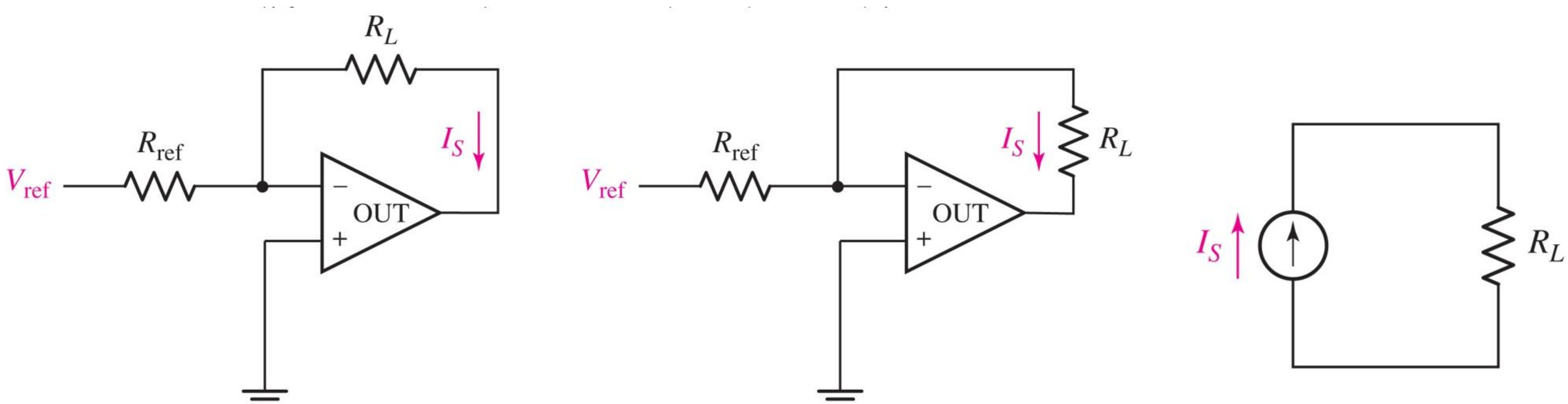
Practice 6.4

- Design a circuit to provide a reference voltage of 6 V using a 1N750 Zener diode and a noninverting amplifier. V_{bat} = 9 V, R_{ref} = 115 Ω



A Reliable Current Source

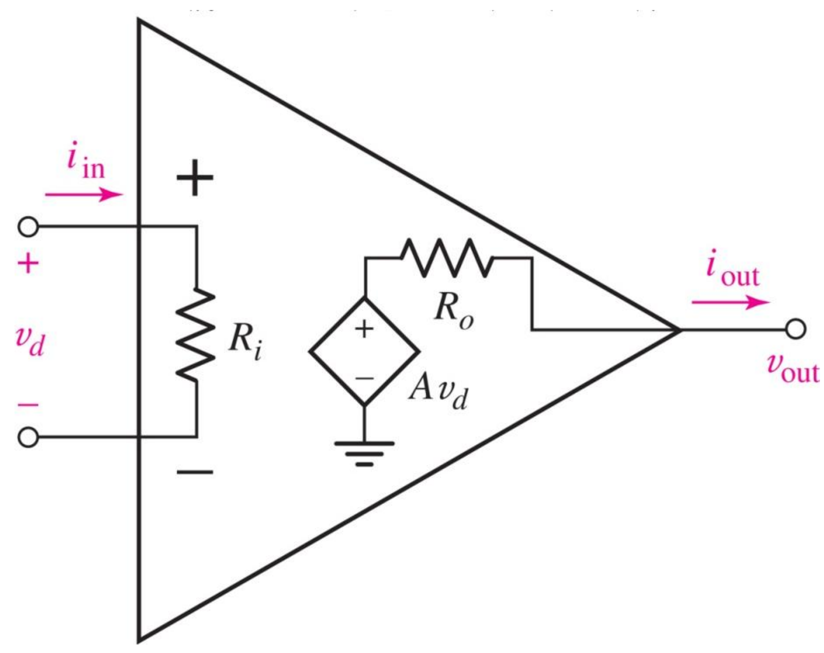
• With a reference voltage source V_{ref}, we can drive a constant current I_s=V_{ref}/ R_{ref} through any load R_L.
• the current supplied to R_L *does not depend on its* resistance—the primary attribute of an ideal current source.



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

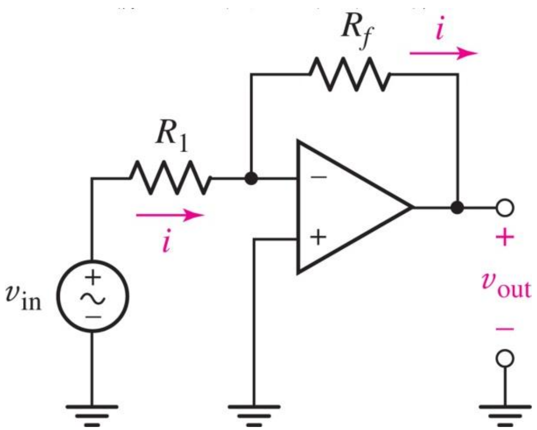


Op-Amp Parameters

TABLE 6.3 Typical Parameter Values for Several Types of Op Amps

Part Number	μA741	LM324	LF411	AD549K	OPA690
Description	General purpose	Low-power quad	Low-offset, low-drift JFET input	Ultralow input bias current	Wideband video frequency op amp
Open loop gain A	2×10^5 V/V	10^5 V/V	2×10^5 V/V	10^6 V/V	2800 V/V
Input resistance	2 MΩ	*	1 TΩ	10 TΩ	190 kΩ
Output resistance	75 Ω	*	$\sim$1 Ω	$\sim$15 Ω	*
Input bias current	80 nA	45 nA	50 pA	75 fA	3 μA
Input offset voltage	1.0 mV	2.0 mV	0.8 mV	0.150 mV	$\pm$1.0 mV
CMRR	90 dB	85 dB	100 dB	100 dB	65 dB
Slew rate	0.5 V/μs	*	15 V/μs	3 V/μs	1800 V/μs
PSpice Model	✓	✓	✓		

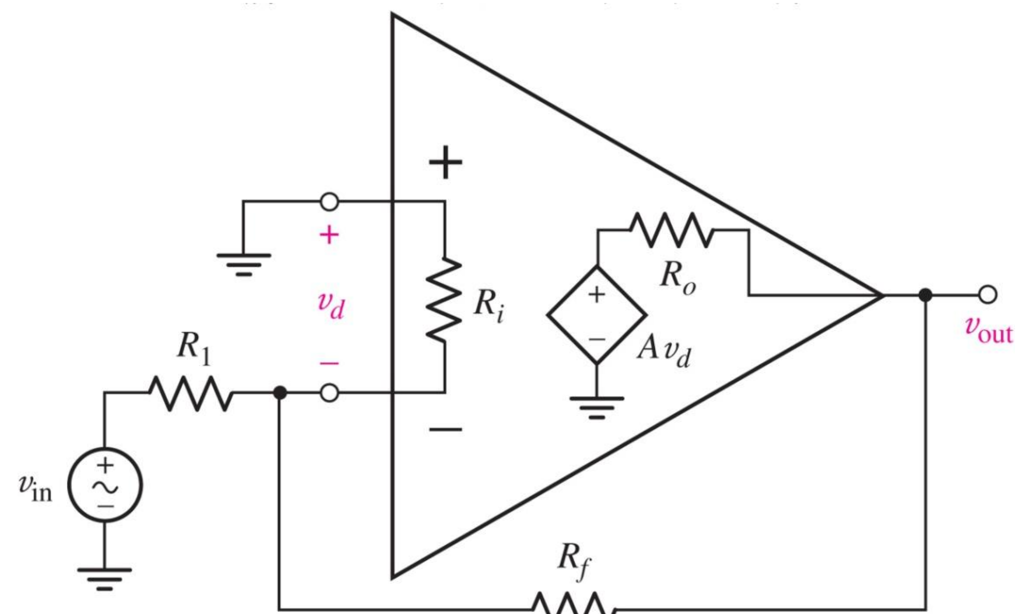
Example 6.6



- For a 741 Op-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

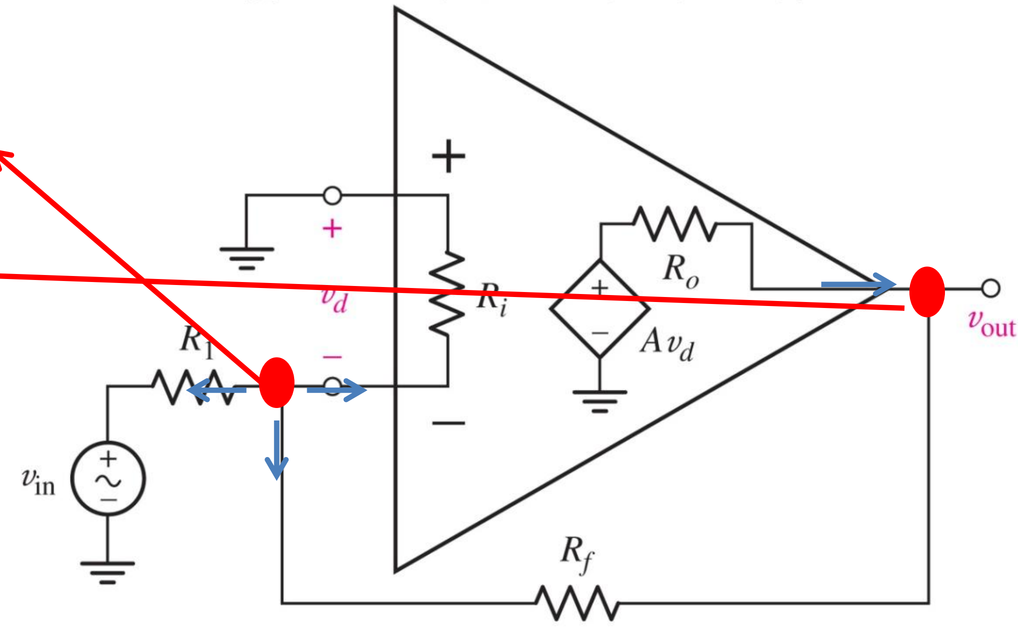


Example 6.6

- When A=infinity, R_o=0 Ω, and R_i=infinity Ω, the op amp behaves according to the ideal op amp rules. (v_d=0 and i_{in}=0)
- Note that we can no longer invoke the ideal op amp rules, since we are not using the ideal op amp model.

$$0 = \frac{-v_d - v_{\text{in}}}{R_1} + \frac{-v_d - v_{\text{out}}}{R_f} + \frac{-v_d}{R_i}$$

$$0 = \frac{v_{\text{out}} + v_d}{R_f} + \frac{v_{\text{out}} - Av_d}{R_o}$$



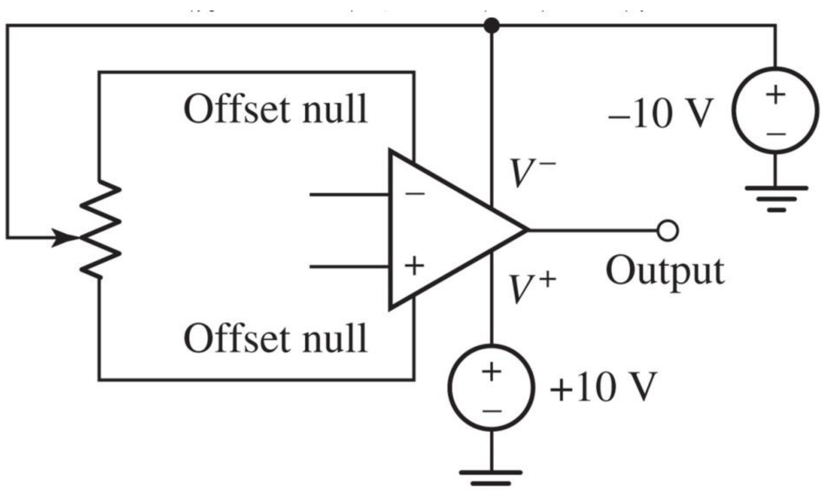
$$v_{\text{out}} = \left[\frac{R_o + R_f}{R_o - AR_f}\left(\frac{1}{R_1} + \frac{1}{R_f} + \frac{1}{R_i}\right) - \frac{1}{R_f}\right]^{-1} \frac{v_{\text{in}}}{R_1}$$

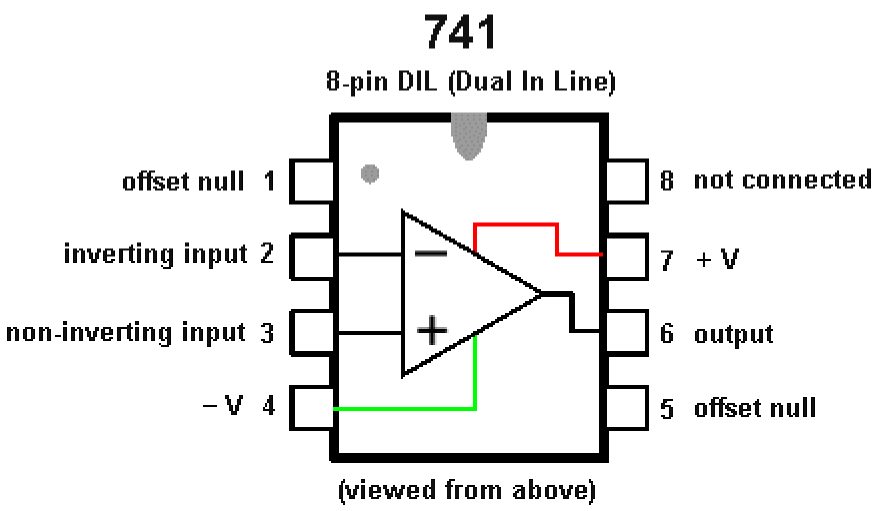
$$v_{\text{out}} = -9.999448 v_{\text{in}} = -49.99724 \sin 3t \quad \text{mV}$$

Input Bias Current and Input Offset Voltage

• Practical Op-Amps draw a small current (Input Bias Current) from each of their inputs due to bias requirements (in the case of BJT inputs) or leakage (in the case of MOSFET-based inputs). (I1+I2)/2

• An ideal op-amp amplifies the differential input; if this input is 0 volts (i.e. both inputs are at the same voltage with respect to ground), the output should be zero. However, due to manufacturing process, the differential input transistors of real op-amps may not be exactly matched. This causes the output to be zero at a non-zero value of differential input, called the input offset voltage.

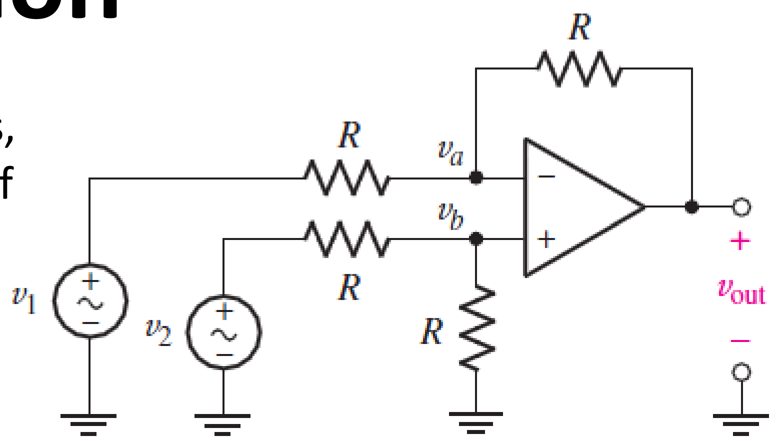




Common Mode Rejection

• if we apply identical voltages to both input terminals, we expect the output voltage to be zero. This ability of the Op-Amp is one of its most attractive qualities, and is known as ***common-mode rejection.***

•If v_1 = 2 + 3 sin 3t volts and v_2 = 2 volts, we would expect the output to be −3 sin 3t volts; the 2 V component common to v1 and v2 would not be amplified.



$$v_{out} = v_2 - v_1$$

•For practical op amps, we do in fact find a small contribution to the output in response to common-mode signals. In order to compare one Op-Amp type to another, it is often helpful to express the ability of an op amp to reject common-mode signals through a parameter known as the common-mode rejection ratio, or **CMRR.**

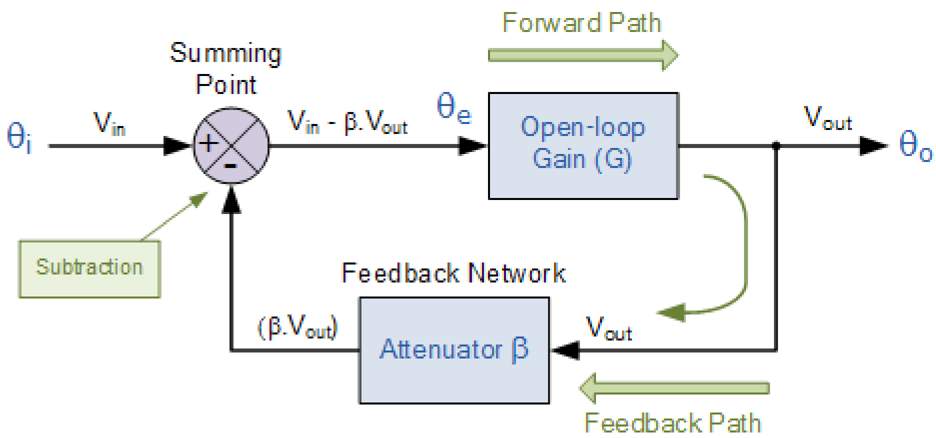
•Defining vo_{CM} as the output obtained when both inputs are equal ($v_1 = v_2 = v_{CM}$), we can determine ACM, the common-mode gain of the op amp

$$A_{CM} = \left| \frac{v_{o_{CM}}}{v_{CM}} \right| \qquad \text{CMRR} \equiv \left| \frac{A}{A_{CM}} \right| \qquad \text{CMRR}_{(\text{dB})} \equiv 20 \log_{10} \left| \frac{A}{A_{CM}} \right| \quad \text{dB}$$

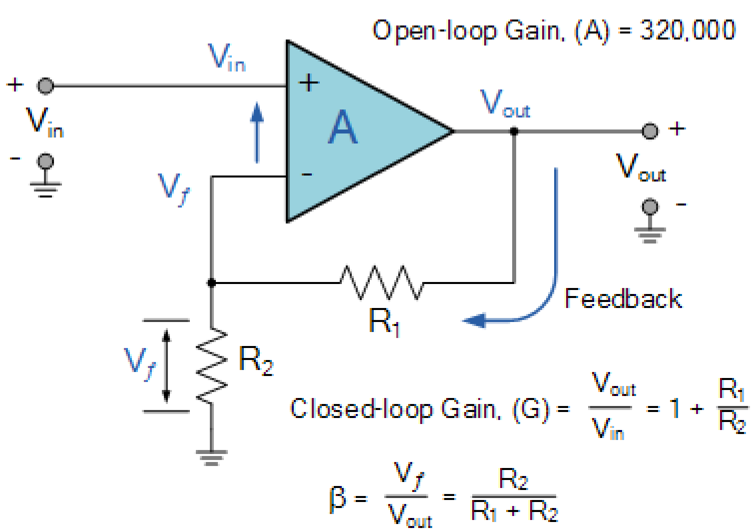
A is the differential gain, A_{CM} is the Common made gain

CMRR tells how well a differential input amplifier **rejects noise** that is common to both input lines.

Negative Feedback



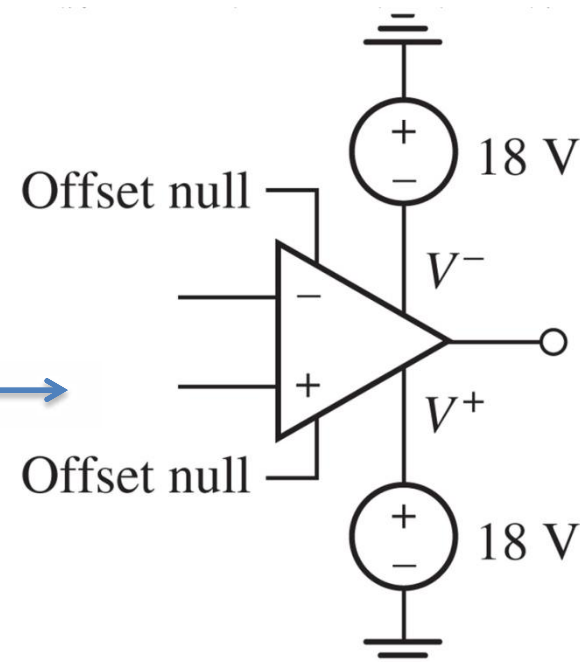
- the main advantages of using **Negative Feedback** in amplifier circuits is to greatly improve their stability, better tolerance to component variations, stabilization against DC drift as well as increasing the amplifiers bandwidth.



Saturation

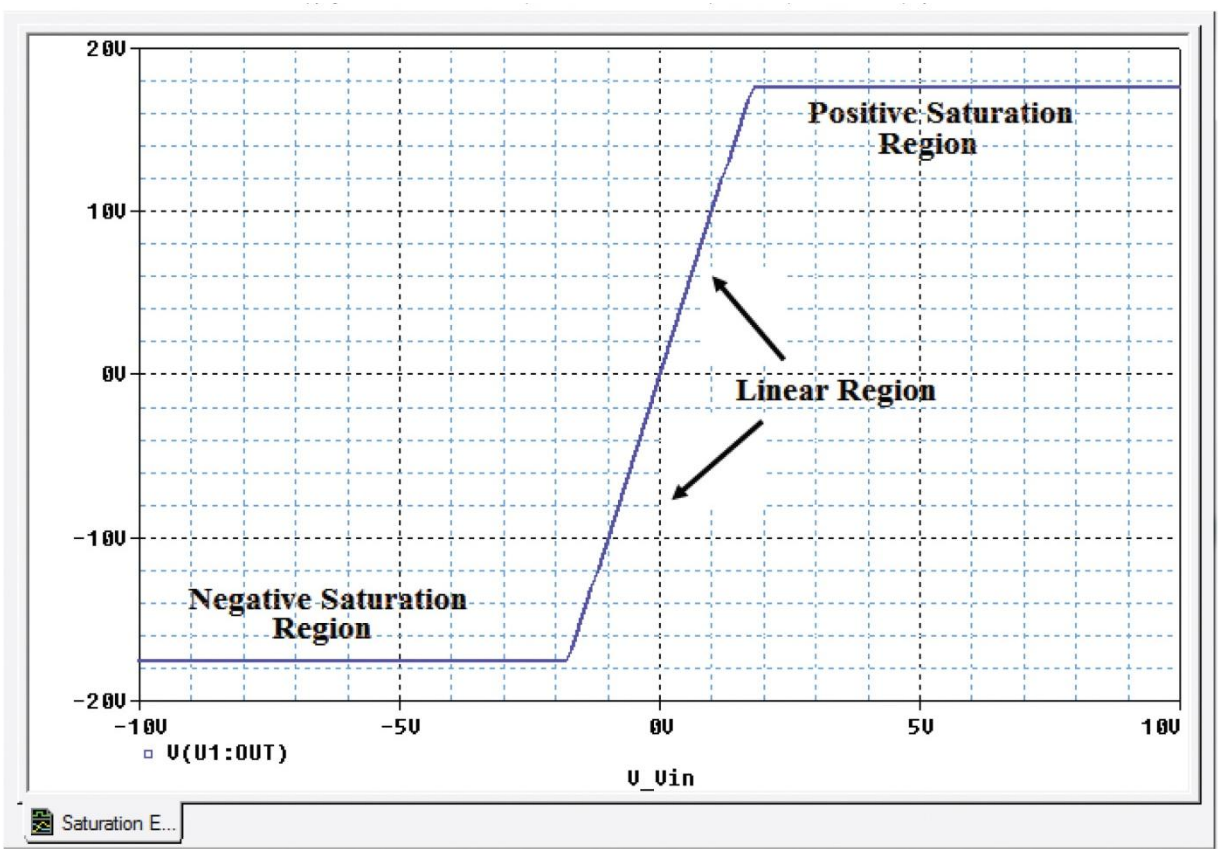
- An op amp requires power supplies.
- Usually, equal and opposite voltages are connect to the V^+ and V^- terminals.
- Typical values are 5 to 24 volts.
- The power supply ground must be the same as the signal ground.

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



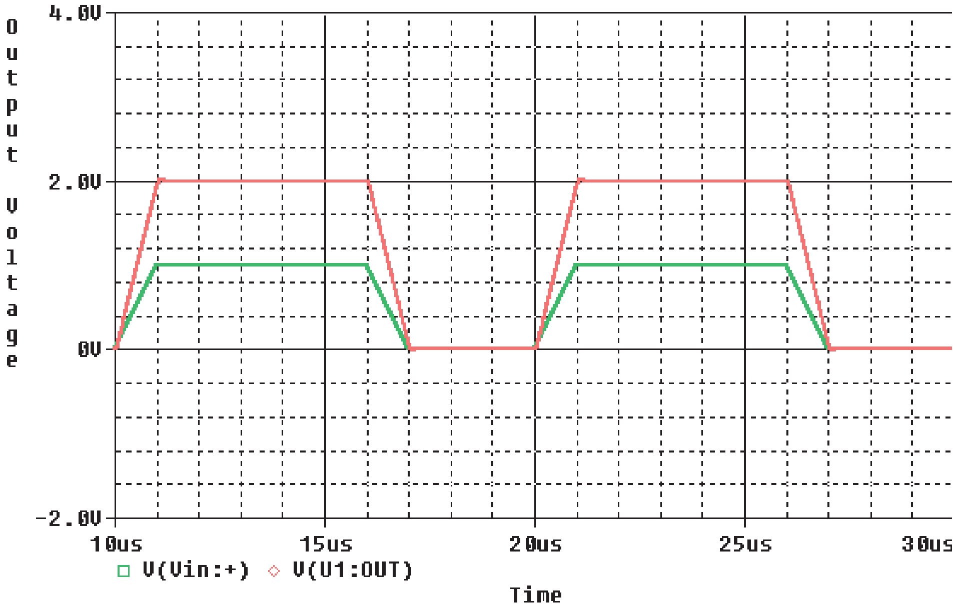
Saturation

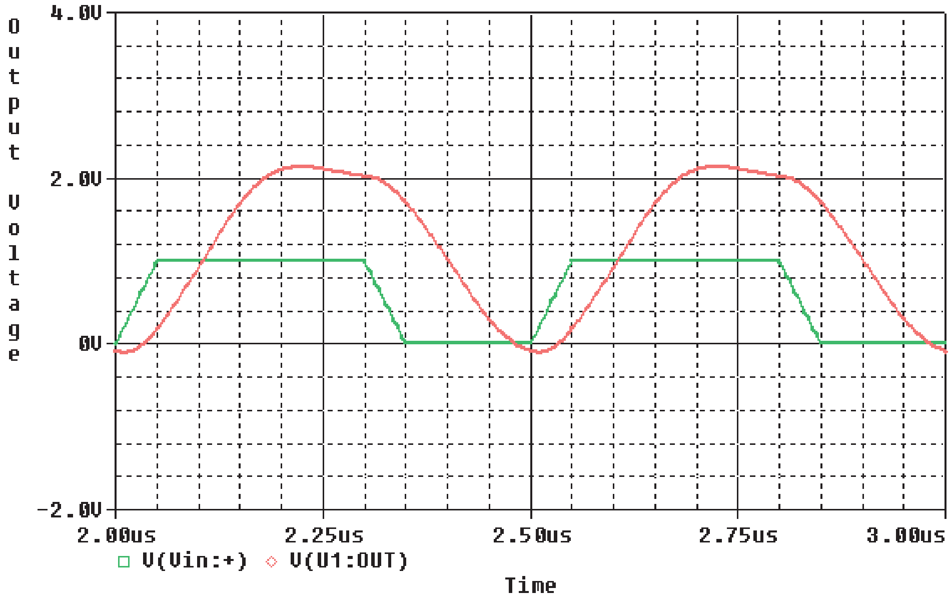
$v_{out}=10v_{in},$ but only up to the ±18 V supplies



Slew Rate

- One measure of the frequency performance of an op amp is its slew rate, which is the rate at which the output voltage can respond to changes in the input; it is most often expresses in V/μs . Slew rate is the maximum V/μs for output.





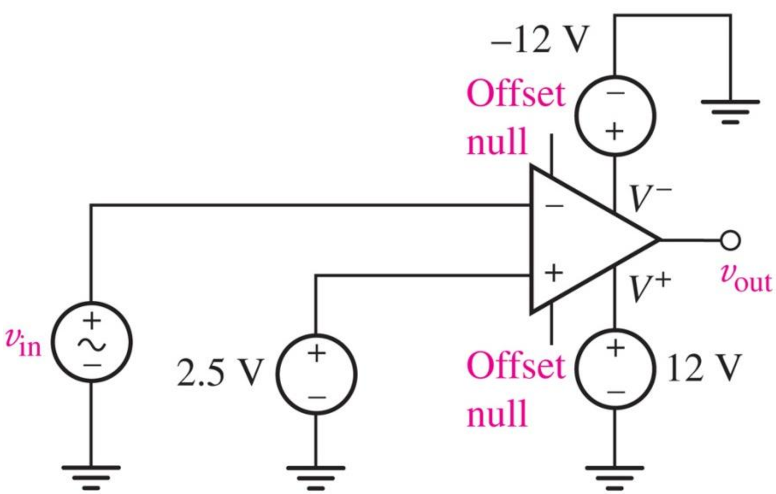
Rise and fall times 1 μs, pulse width 5 μs

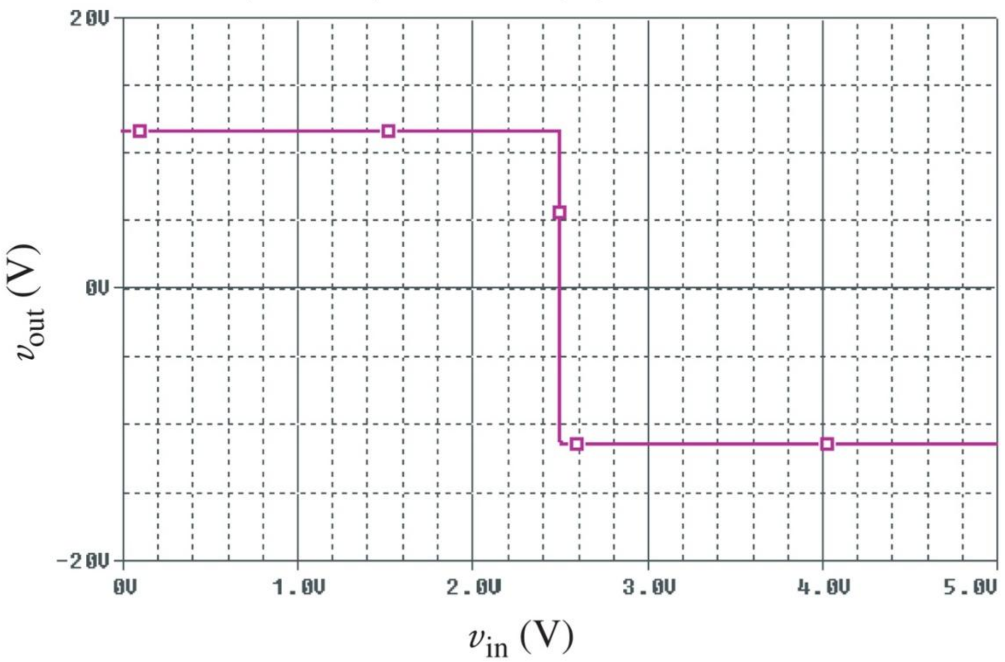
rise and fall times 50 ns, pulse width 250 ns

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?

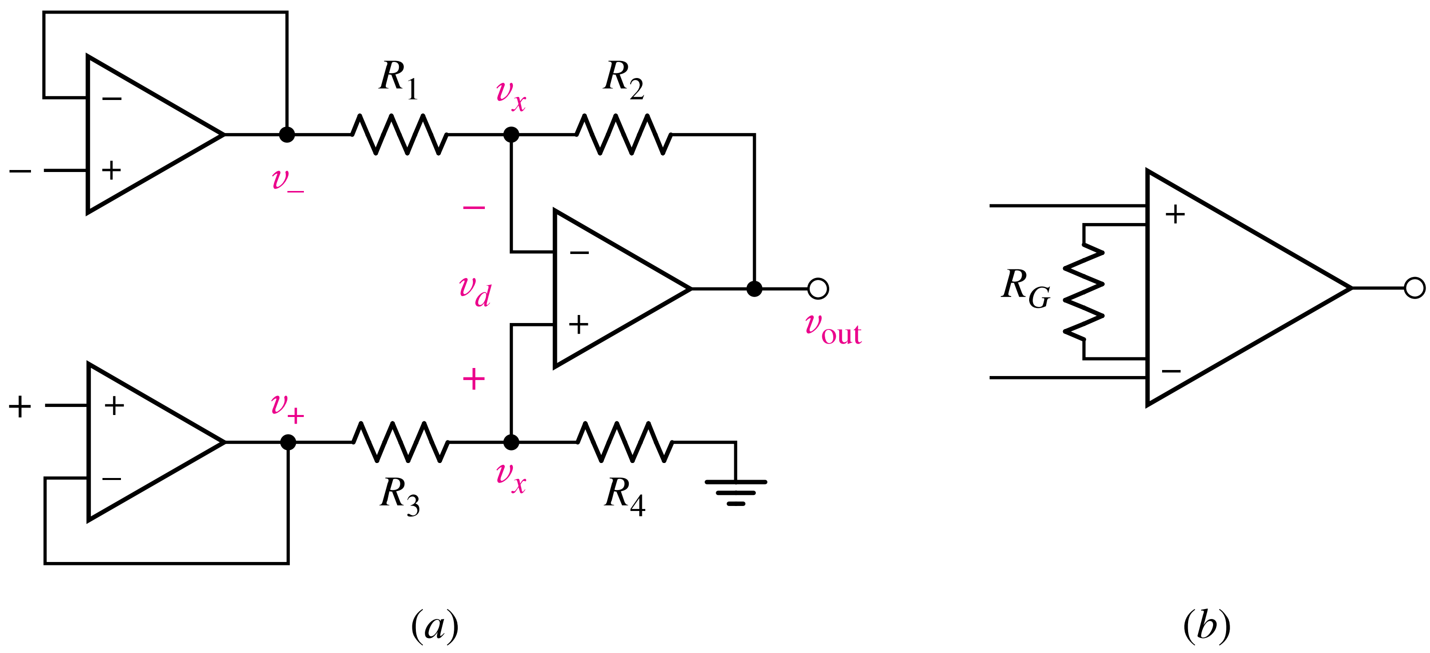




An instrumentation amplifier

- This device allows precise amplification of small voltage differences:

$$v_{out}=K(v_{+}-v_{-}) \qquad R_4/R_3 = R_2/R_1 = K$$



(a) The basic instrumentation amplifier. (b) Commonly used symbol.

Chapter 6 Summary & Review

- **Operational Amplifier**
  - a *linear circuit element* whose proper implementation (power, feedback) achieves the sum, difference, & amplification of any number of voltage/current inputs (up to the current-carrying capabilities & input-power levels of the particular op amp)
- **Op Amp Analysis**
  - two ideal op amp rules:
    - the voltage at the input terminals are equal ($v_n = v_p$),
    - the current into each input terminal is zero ($i_n = i_p = 0$)
  - the input and output of a single op-amp stage are related using *nodal analysis* (typically Kirchoff's Current Law at one/both of the op amp inputs)
- **Op Amp Cascades**
  - analyzed a single stage at a time, from input to output
  - the output of the previous stage becomes the input to the next stage
- **Op Amp Saturation**
  - dictates that the voltage output of an op amp cannot exceed +/– V_{CC}
  - is useful for generating digital signals from analog signals (*nonlinear* behavior)