# BME2301 - Circuit Theory

## The Instructors:

Dr. Görkem SERBES (C317)

gserbes@yildiz.edu.tr

https://avesis.yildiz.edu.tr/gserbes/

## Lab Assistants:

Nihat AKKAN

nakkan@yildiz.edu.tr

https://avesis.yildiz.edu.tr/nakkan

# Operational Amplifiers

(Op-Amps)

# Objectives of Lecture

- Describe how an ideal operational amplifier (op-amp) behaves.
- Define voltage gain, current gain, transresistance gain, and transconductance gain.
- Explain the operation of an ideal op amp in a voltage comparator and inverting amplifier circuit.
  - Show the effect of using a real op-amp.
- Apply the ‘almost ideal’ op-amp model in the following circuits:
  - Inverting Amplifier
  - Noninverting Amplifier
  - Voltage Follower
  - Summing Amplifier
  - Difference Amplifier
  - Cascaded Amplifiers

# The Operational Amplifier

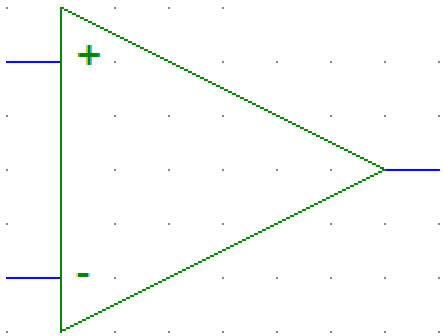
- An operational amplifier (Op-Amp) is a DC-coupled high-gain electronic voltage amplifier with a differential input and, usually, a single-ended output.
- An Op-Amp produces an output potential (relative to circuit ground) that is typically hundreds of thousands of times larger than the potential difference between its input terminals.
- The operational amplifier finds daily usage in a large variety of electronic applications.

# Op Amps Applications

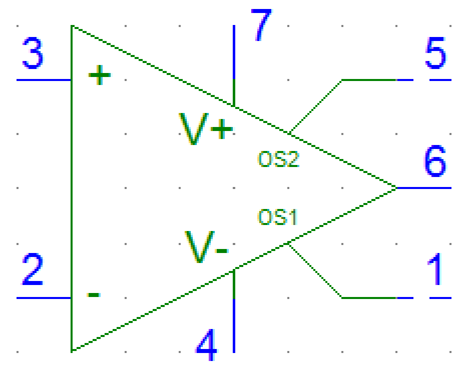
- Audio amplifiers
  - Speakers and microphone circuits in cell phones, computers, mpg players, boom boxes, etc.
- Instrumentation amplifiers
  - Biomedical systems including heart monitors and oxygen sensors.
- Power amplifiers
- Analog computers
  - Combination of integrators, differentiators, summing amplifiers, and multipliers

# Symbols for Ideal and Real Op Amps

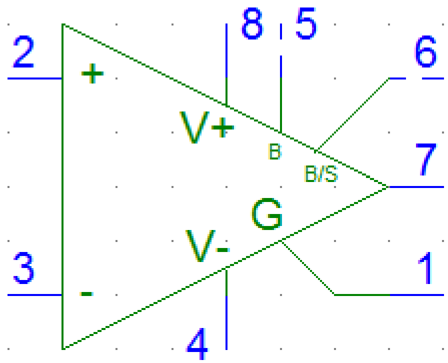
OpAmp



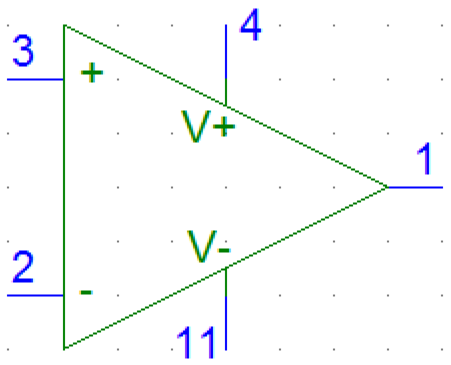

uA741




LM111

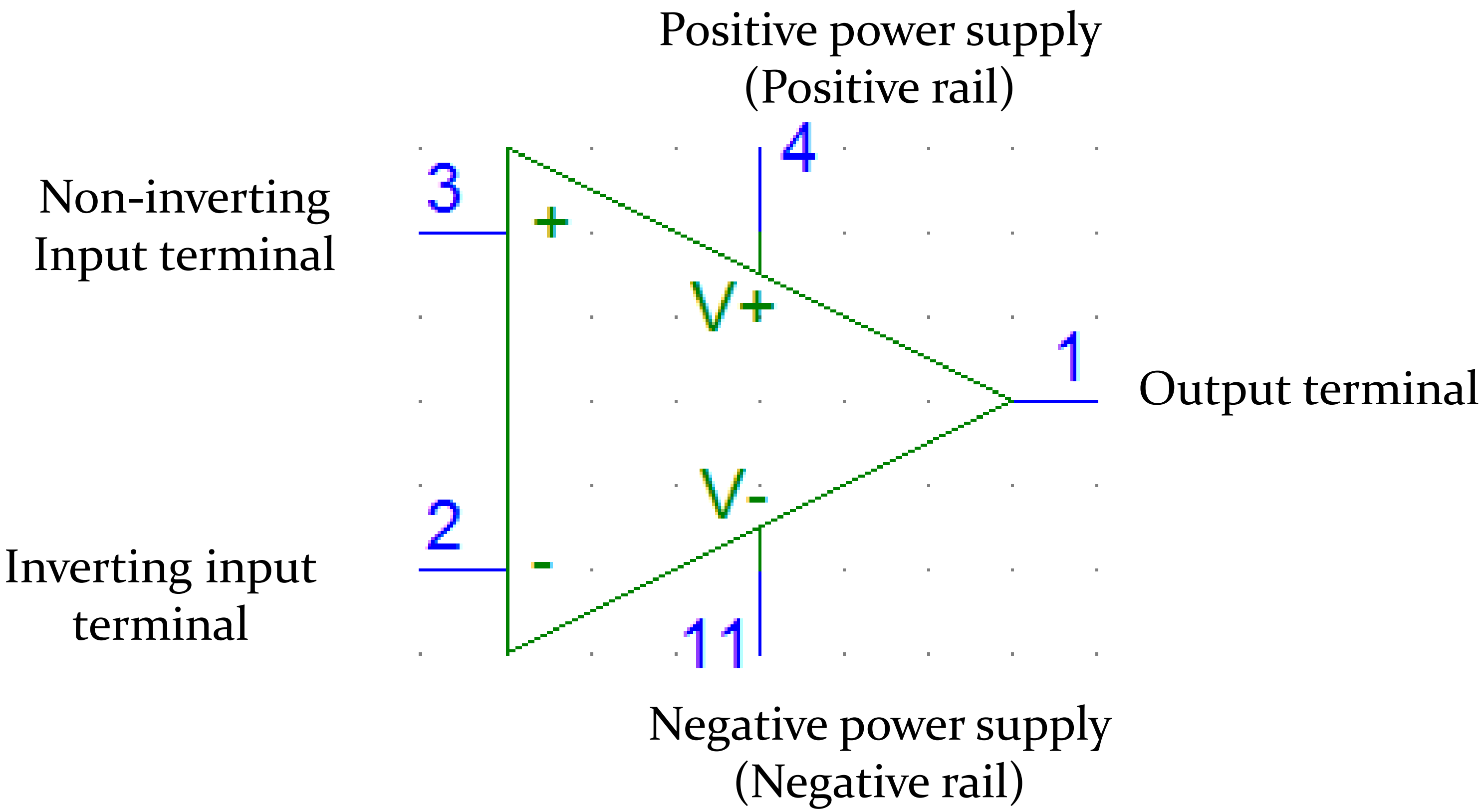



LM324



# Terminals on an Op Amp

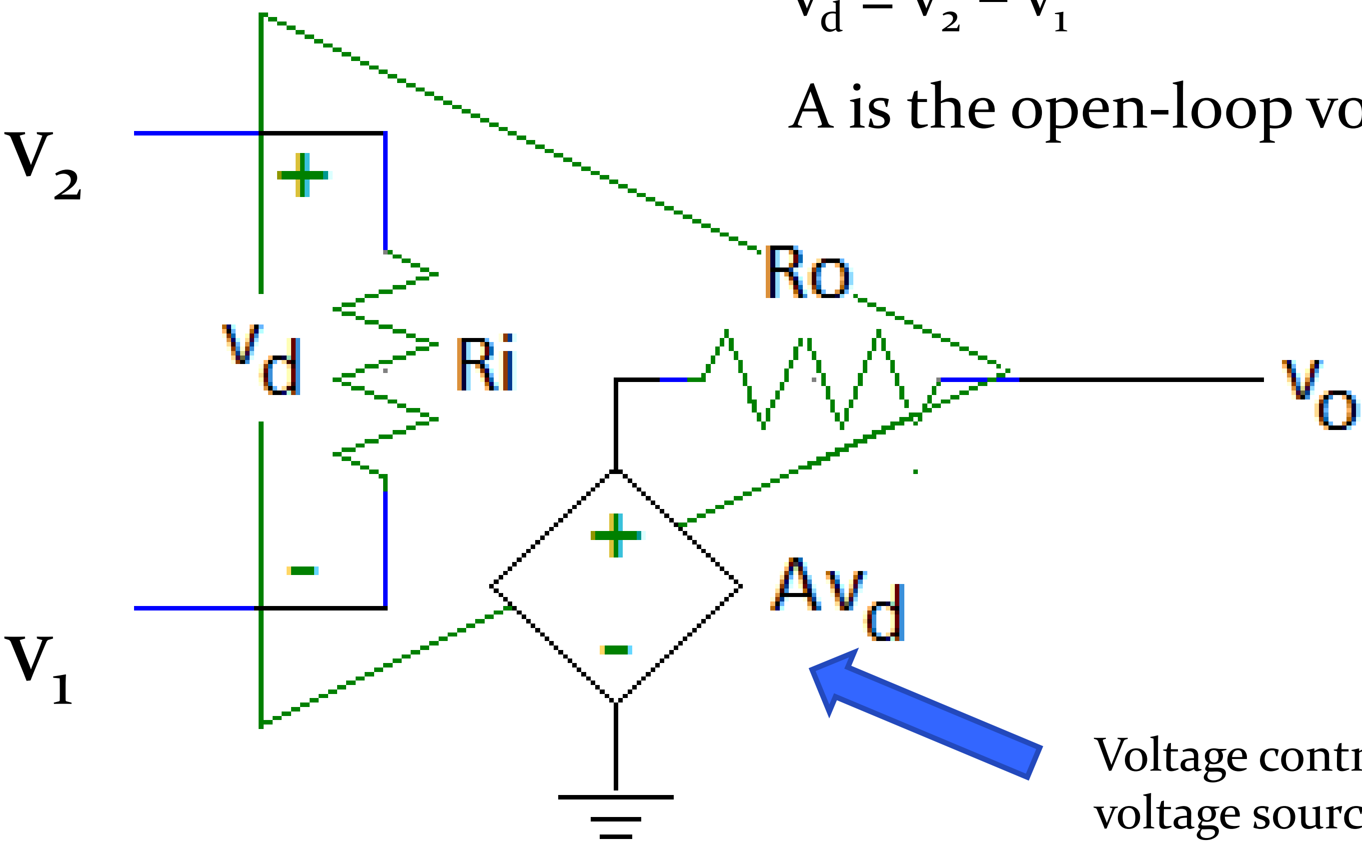
The op-amp chip needs external power in order to function.



# Op Amp Equivalent Circuit

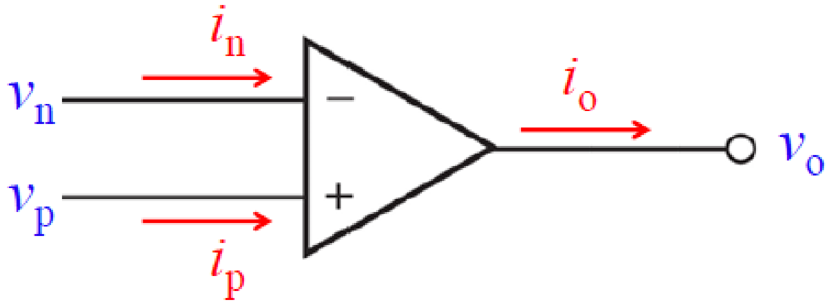
$v_d = v_2 - v_1$

A is the open-loop voltage gain




Voltage controlled voltage source

# The Operational Amplifier




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

Function of the op amp:

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

$$v_n \approx v_p$$

$$i_n = i_p \approx 0$$

**Ideal Op-Amp Rules**

– No current ever flows into either input terminal.

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

# Typical Op-Amp Parameters

| Parameter | Variable | Typical Ranges | Ideal Values |
|---|---|---|---|
| Open-Loop Voltage Gain | A | $10^5$ to $10^8$ | $\infty$ |
| Input Resistance | Ri | $10^5$ to $10^{13}$ Ω | $\infty$ Ω |
| Output Resistance | Ro | 10 to 100 Ω | 0 Ω |
| Supply Voltage | Vcc/$V^+$<br>-Vcc/$V^-$ | 5 to 30 V<br>-30V to 0V | N/A<br>N/A |

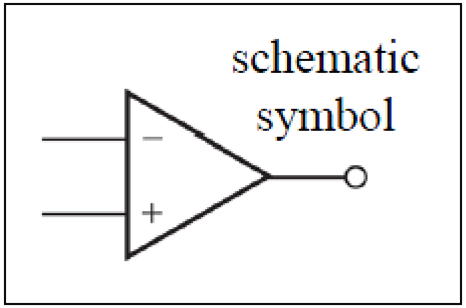
# How to Find These Values

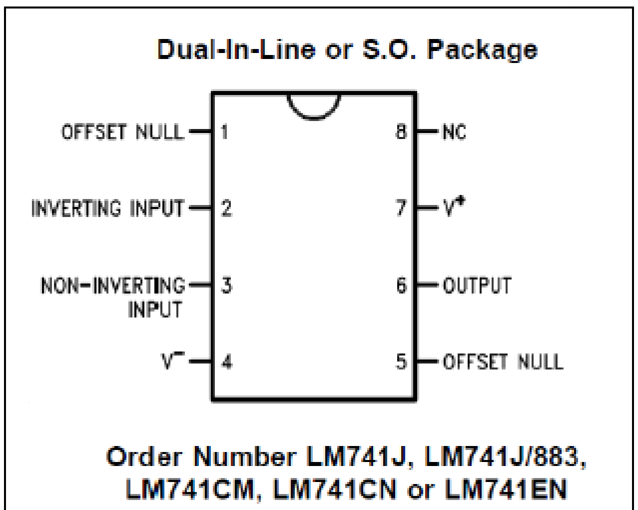
- Component Datasheets
  - Many manufacturers have made these freely available on the internet
    - Example:  LM741, LM 324, etc.

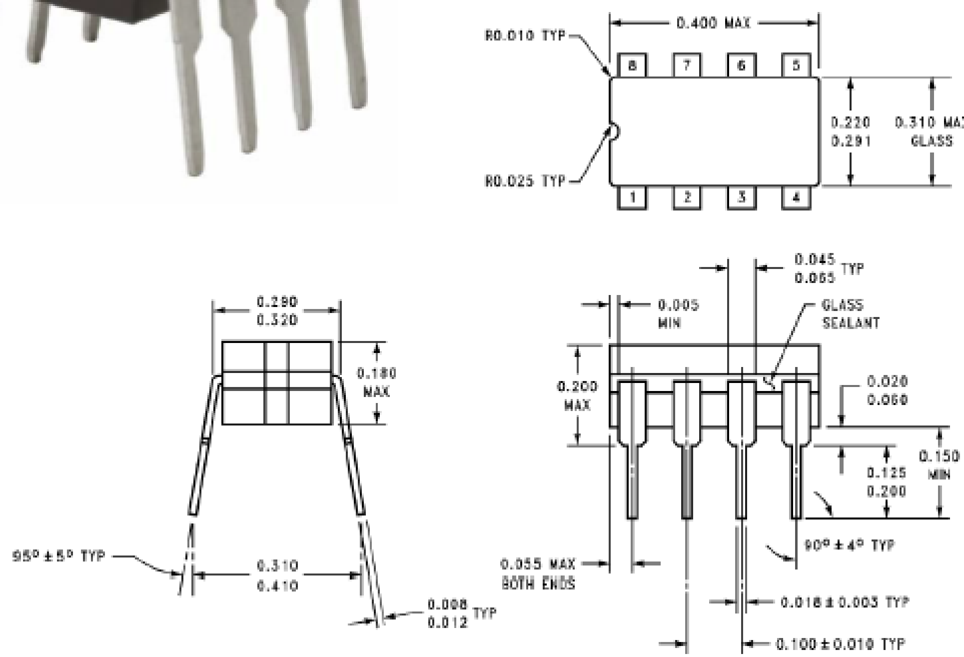
# The Operational Amplifier

"Op Amp"

National Semiconductor **LM741** datasheet



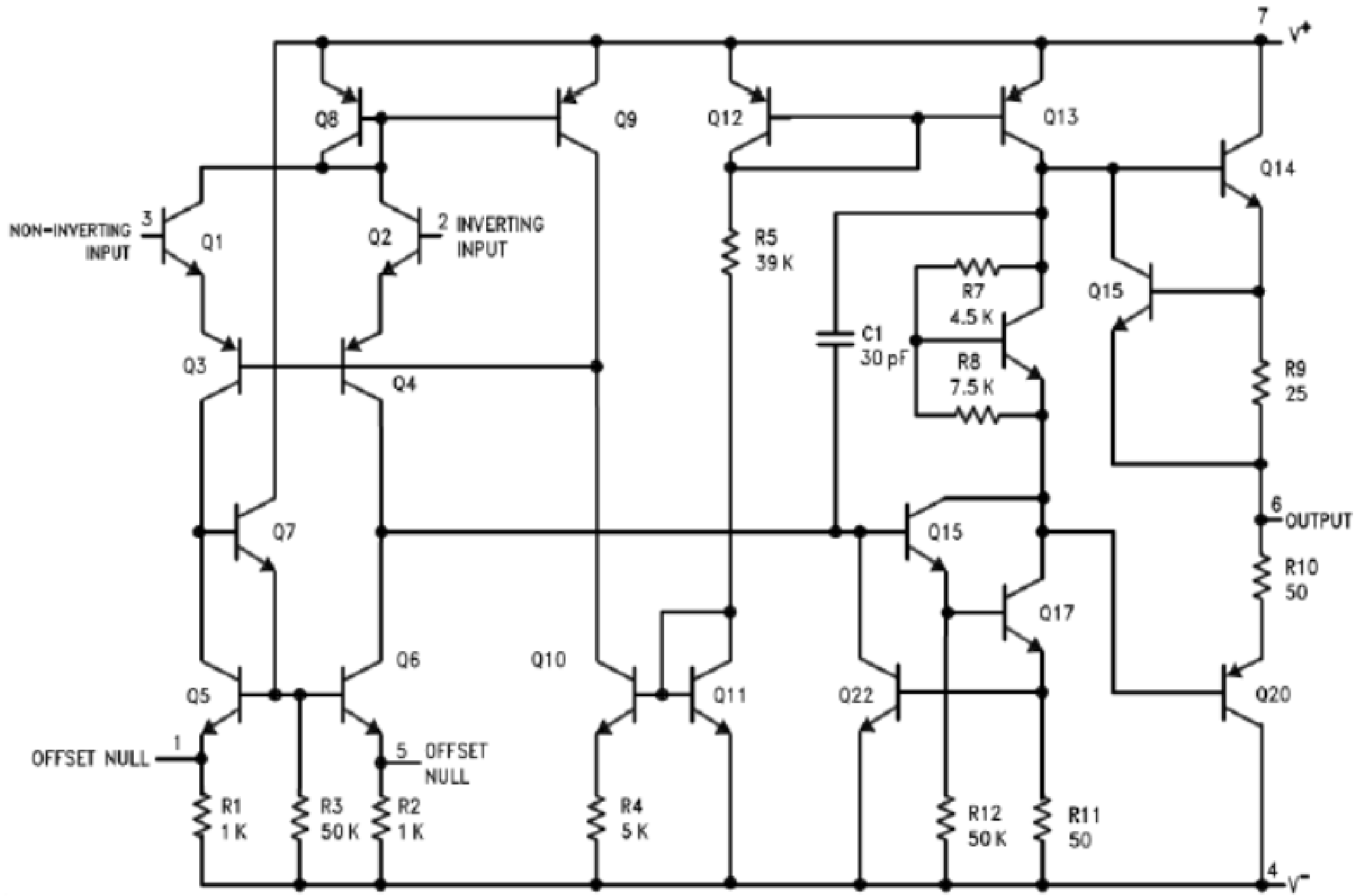




Ceramic Dual-In-Line Package (J)
Order Number LM741CJ or LM741J/883

# Inside of LM741

National Semiconductor LM741 datasheet



# Op-Amp Parameters

TABLE 6.3 Typical Parameter Values for Several Types of Op Amps

| **Part Number** | **$\mu$A741** | **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* | $2 \times 10^5$ V/V | $10^5$ V/V | $2 \times 10^5$ V/V | $10^6$ V/V | 2800 V/V |
| Input resistance | 2 MΩ | * | 1 TΩ | 10 TΩ | 190 kΩ |
| Output resistance | 75 Ω | * | ~1 Ω | ~15 Ω | * |
| Input bias current | 80 nA | 45 nA | 50 pA | 75 fA | 3 $\mu$A |
| Input offset voltage | 1.0 mV | 2.0 mV | 0.8 mV | 0.150 mV | ±1.0 mV |
| CMRR | 90 dB | 85 dB | 100 dB | 100 dB | 65 dB |
| Slew rate | 0.5 V/$\mu$s | * | 15 V/$\mu$s | 3 V/$\mu$s | 1800 V/$\mu$s |
| PSpice Model | ✓ | ✓ | ✓ | | |

http://www.national.com/ds/LM/LM124.pdf - Windows Internet Explorer

National Semiconductor

August 2000

# LM124/LM224/LM324/LM2902
# Low Power Quad Operational Amplifiers

## General Description

The LM124 series consists of four independent, high gain, internally frequency compensated operational amplifiers which were designed specifically to operate from a single power supply over a wide range of voltages. Operation from split power supplies is also possible and the low power supply current drain is independent of the magnitude of the power supply voltage.

Application areas include transducer amplifiers, DC gain blocks and all the conventional op amp circuits which now can be more easily implemented in single power supply systems. For example, the LM124 series can be directly operated off of the standard +5V power supply voltage which is used in digital systems and will easily provide the required interface electronics without requiring the additional ±15V power supplies.

## Unique Characteristics

- In the linear mode the input common-mode voltage range includes ground and the output voltage can also

## Advantages

- Eliminates need for dual supplies
- Four internally compensated op amps in a single package
- Allows directly sensing near GND and $V_{OUT}$ also goes to GND
- Compatible with all forms of logic
- Power drain suitable for battery operation

## Features

- Internally frequency compensated for unity gain
- Large DC voltage gain 100 dB
- Wide bandwidth (unity gain) 1 MHz (temperature compensated)
- Wide power supply range:
  - Single supply 3V to 32V
  - or dual supplies ±1.5V to ±16V
- Very low supply current drain (700 µA)—essentially independent of supply voltage
- Low input biasing current 45 nA

LM124/LM224/LM324/LM2902 Low Power Qua

# dB

- Decibels

  Since $P = V^2/R$

  $10 \log (P/P_{ref})$ or $20 \log (V/V_{ref})$

  In this case:

  $20 \log (V_o/V_{in}) = 20 \log (A) = 100$

  $A = 10^5 = 100{,}000$

## Electrical Characteristics

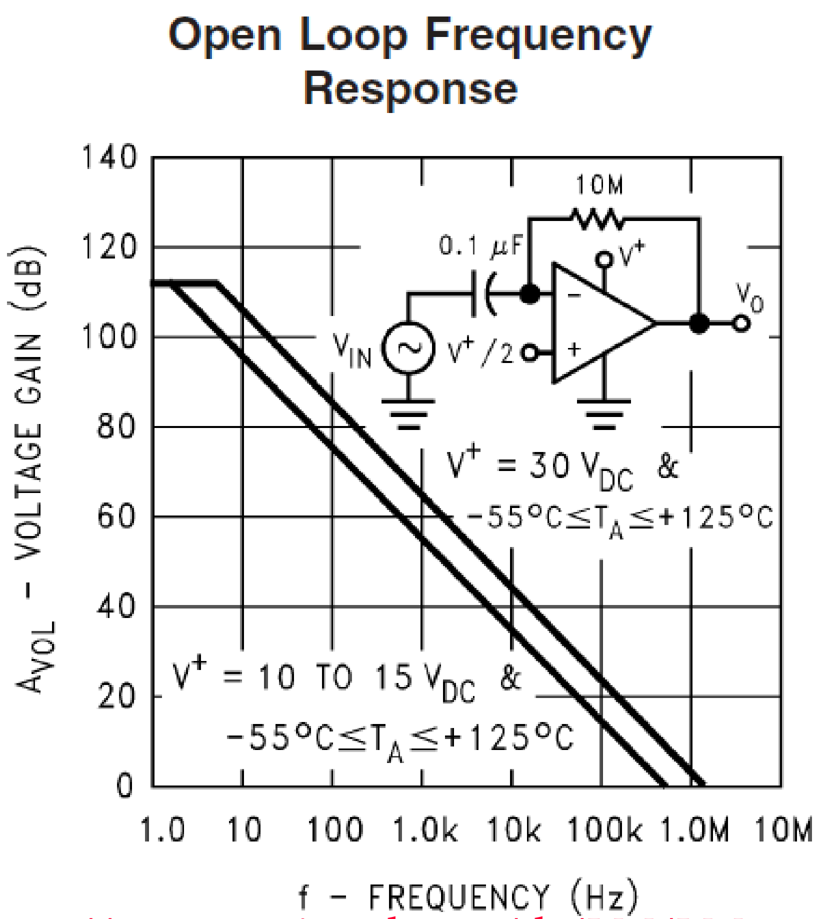
$V^+ = +5.0V$, (Note 7), unless otherwise stated

| Parameter | Conditions | LM124A | | | LM224A | | | LM324A | | | Units |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Min | Typ | Max | Min | Typ | Max | Min | Typ | Max | |
| Input Offset Voltage | (Note 8) $T_A = 25°C$ | | 1 | 2 | | 1 | 3 | | 2 | 3 | mV |
| Input Bias Current (Note 9) | $I_{IN(+)}$ or $I_{IN(-)}$, $V_{CM} = 0V$, $T_A = 25°C$ | | 20 | 50 | | 40 | 80 | | 45 | 100 | nA |
| Input Offset Current | $I_{IN(+)}$ or $I_{IN(-)}$, $V_{CM} = 0V$, $T_A = 25°C$ | | 2 | 10 | | 2 | 15 | | 5 | 30 | nA |
| Input Common-Mode Voltage Range (Note 10) | $V^+ = 30V$, (LM2902, $V^+ = 26V$), $T_A = 25°C$ | 0 | | $V^+-1.5$ | 0 | | $V^+-1.5$ | 0 | | $V^+-1.5$ | V |
| Supply Current | Over Full Temperature Range<br>$R_L = \infty$ On All Op Amps<br>$V^+ = 30V$ (LM2902 $V^+ = 26V$)<br>$V^+ = 5V$ | | 1.5<br>0.7 | 3<br>1.2 | | 1.5<br>0.7 | 3<br>1.2 | | 1.5<br>0.7 | 3<br>1.2 | mA |
| Large Signal Voltage Gain | $V^+ = 15V$, $R_L \geq 2k\Omega$, ($V_O = 1V$ to $11V$), $T_A = 25°C$ | 50 | 100 | | 50 | 100 | | 25 | 100 | | V/mV |
| Common-Mode | DC, $V_{CM} = 0V$ to $V^+ - 1.5V$, | 70 | 85 | | 70 | 85 | | 65 | 85 | | dB |

# Large Signal Voltage Gain = A

- Typical
  - A = 100 V/mV = 100V/0.001V = 100,000
- Minimum
  - A = 25 V/mV = 25 V/0.001V = 25,000

# Caution – A is Frequency Dependent

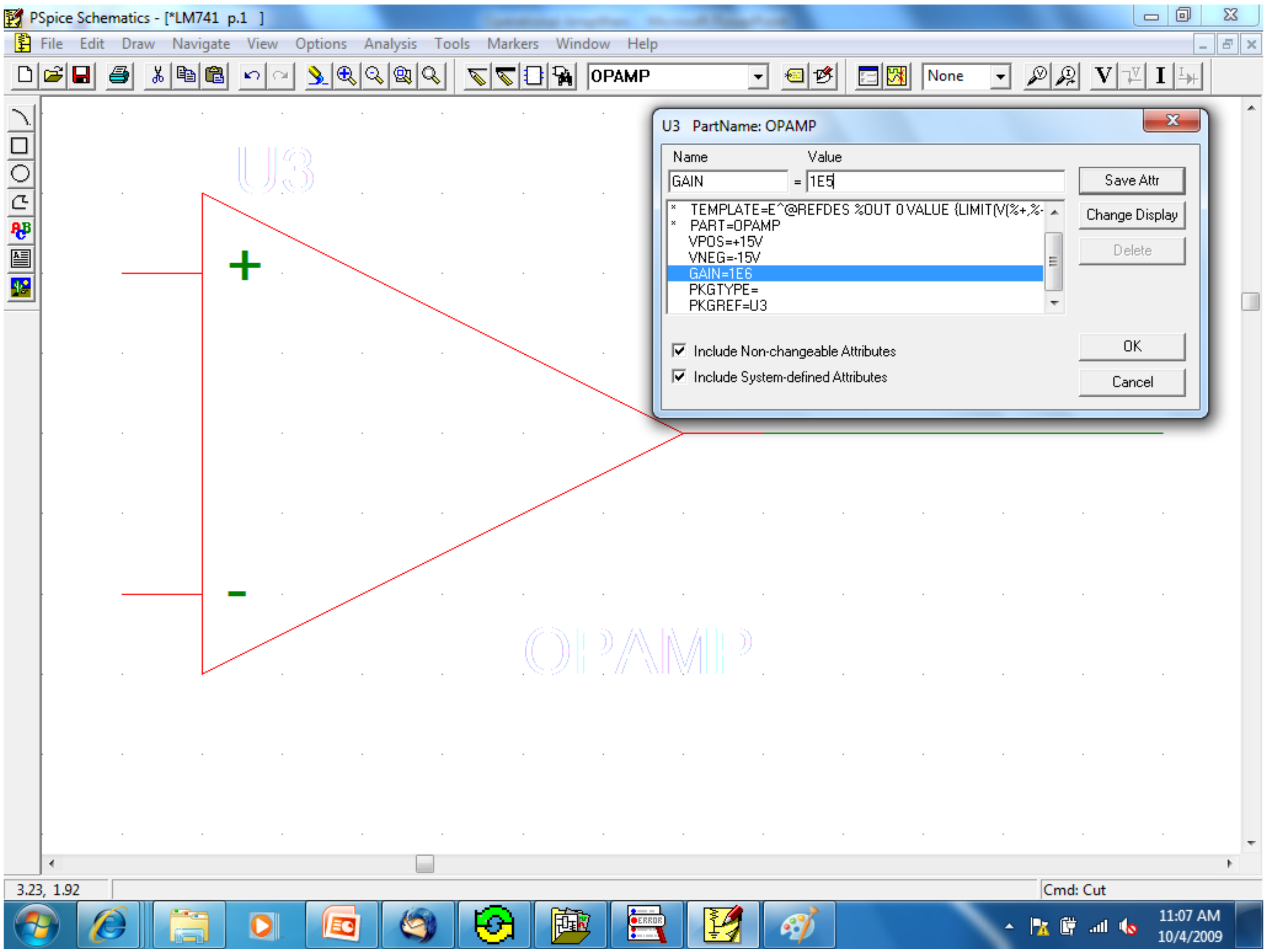



http://www.national.com/ds/LM/LM124.pdf

# Modifying Gain in Pspice OpAmp

- Place part in a circuit
- Double click on component
- Enter a new value for the part attribute called GAIN

# OrCAD Schematics



# Open Circuit Output Voltage

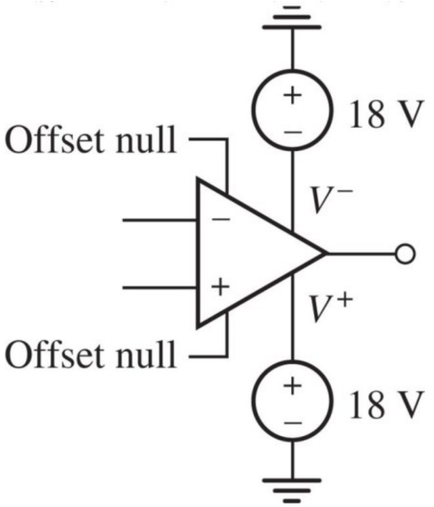
- Open Circuit Output Voltage

$$v_o = A\ v_d$$

- Ideal Op-Amp

$$v_o = \infty\ (v_d)$$

- Saturation in real Op-Amp




  - 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.

- Above, +18V is connected to $V^+$ and -18 V is connected to $V^-$

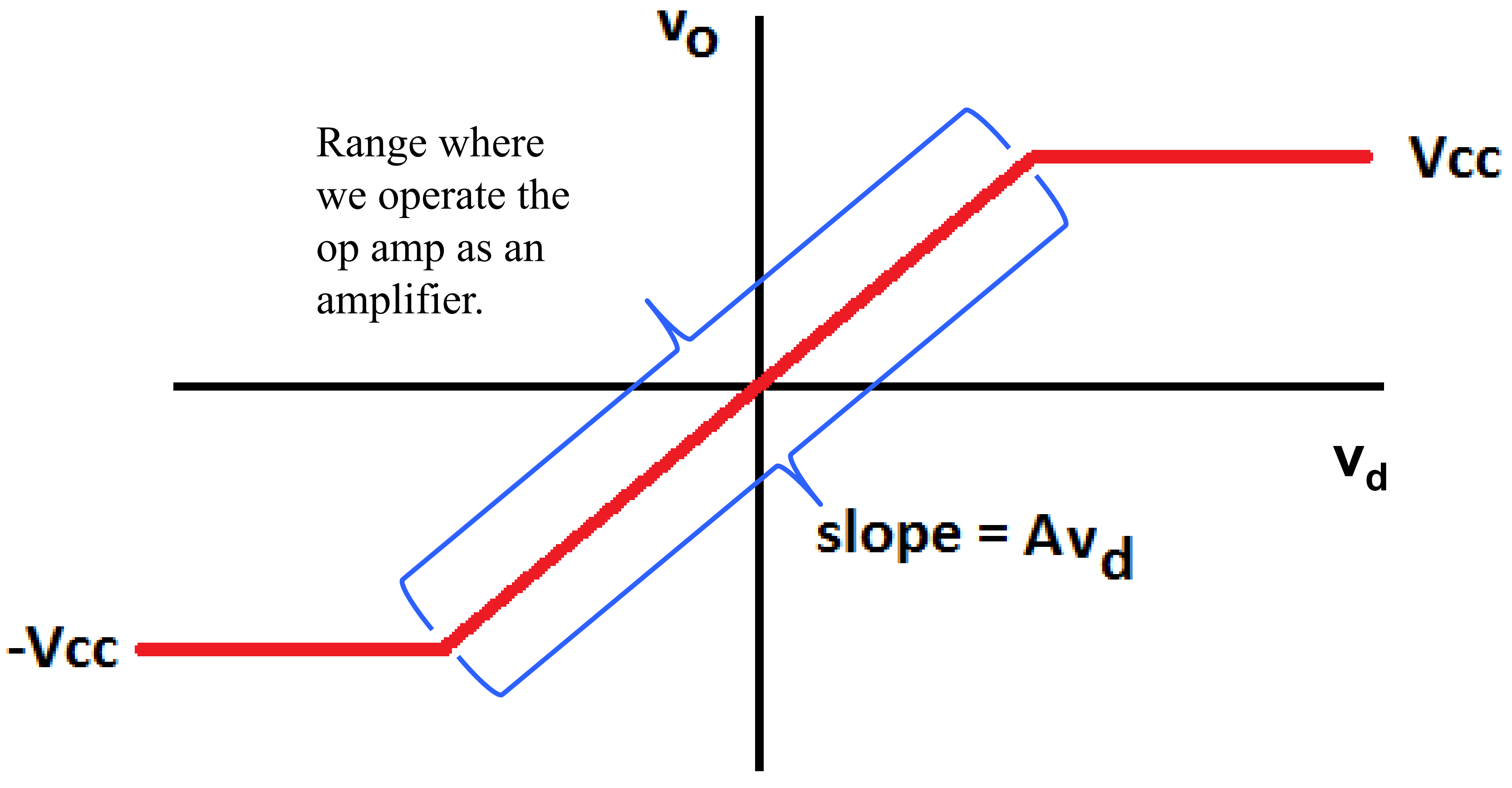
# Open Circuit Output Voltage

- Real Op Amp

| | Voltage Range | Output Voltage |
|---|---|---|
| **Positive Saturation** | $Av_d > V^+$ | $v_o \sim V^+$ |
| **Linear Region** | $V^- < Av_d < V^+$ | $v_o = A\,v_d$ |
| **Negative Saturation** | $Av_d < V^-$ | $v_o \sim V^-$ |

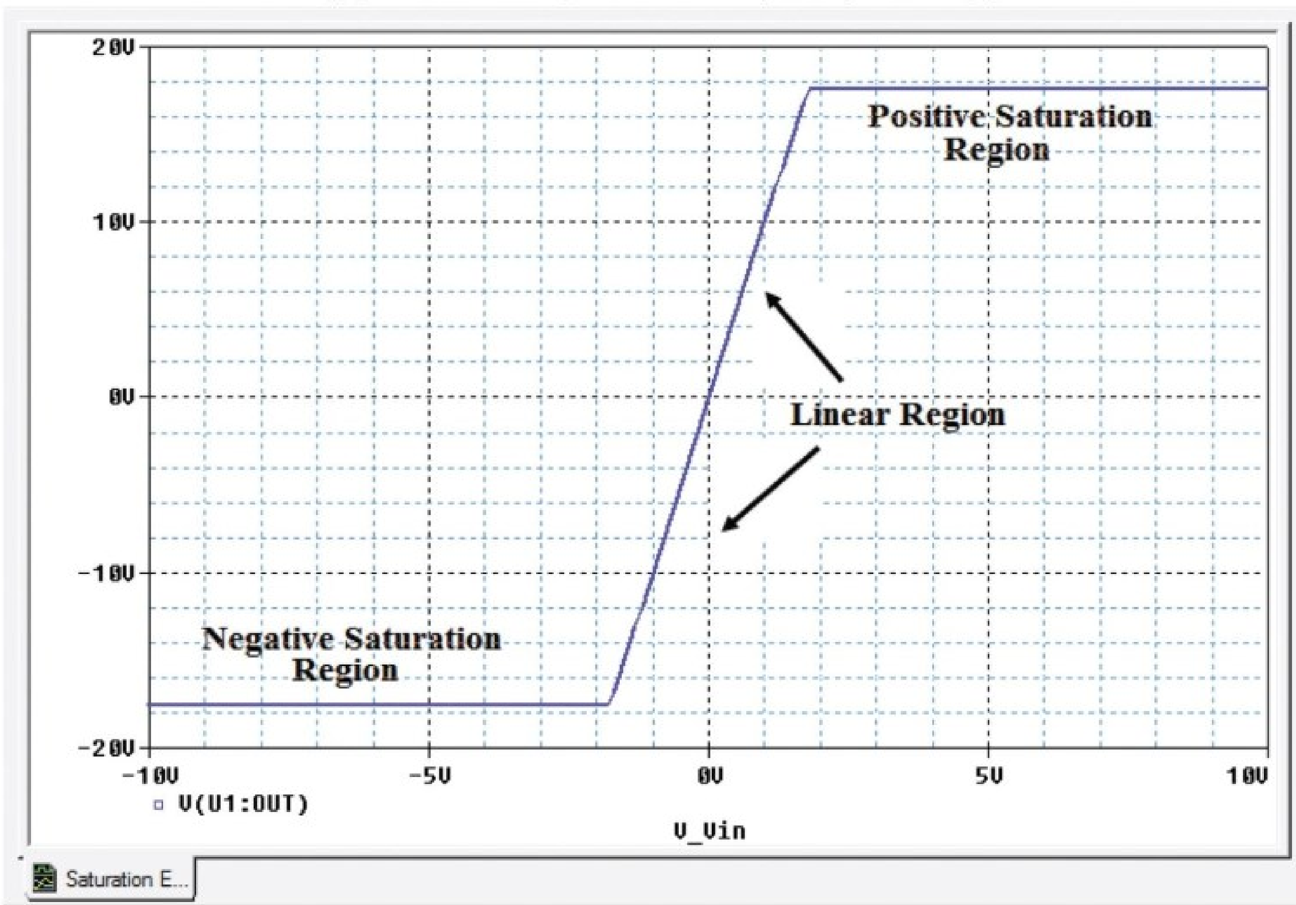
The voltage produced by the dependent voltage source inside the op amp is limited by the voltage applied to the positive and negative rails.

# Voltage Transfer Characteristic



# Saturation

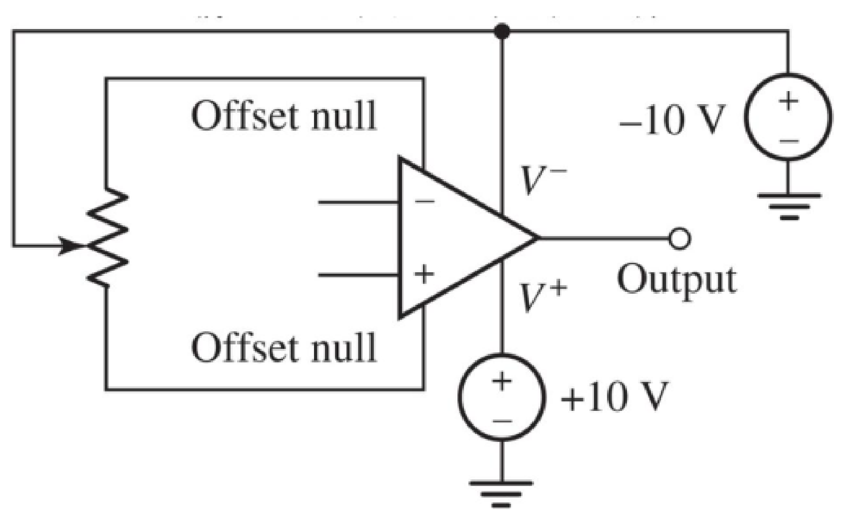
$v_{out}=10v_{in}$, but only up to the ±18 V supplies

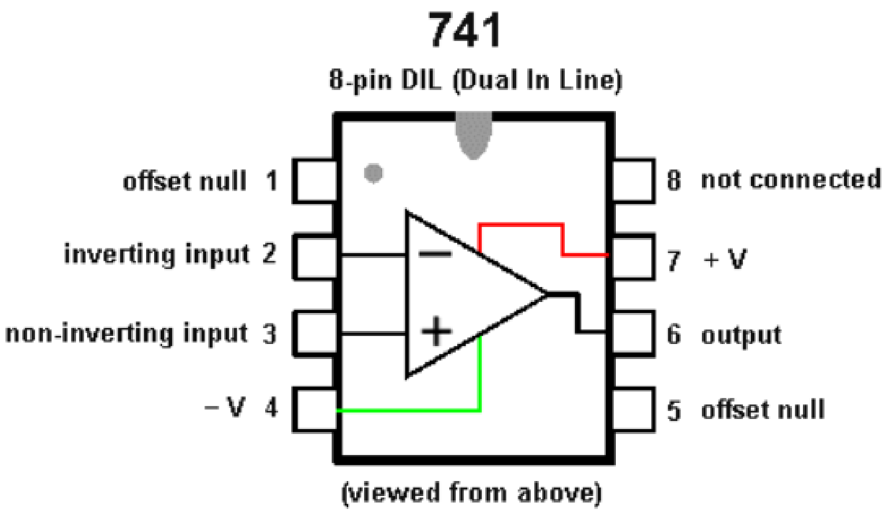


# Input Bias Current and Input Offset Voltage

• 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

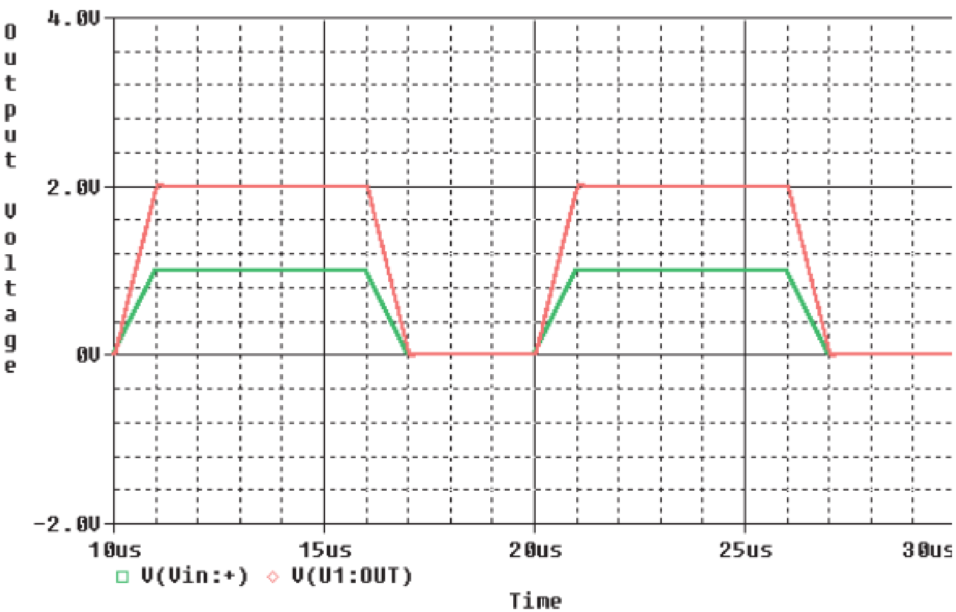
• An ideal op-amp amplifies the differential input; if this input is 0 volts (i.e. both inputs are at the same voltage with respect to ground), the output should be zero. However, due to manufacturing process, the differential input transistors of real op-amps may not be exactly matched. This causes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



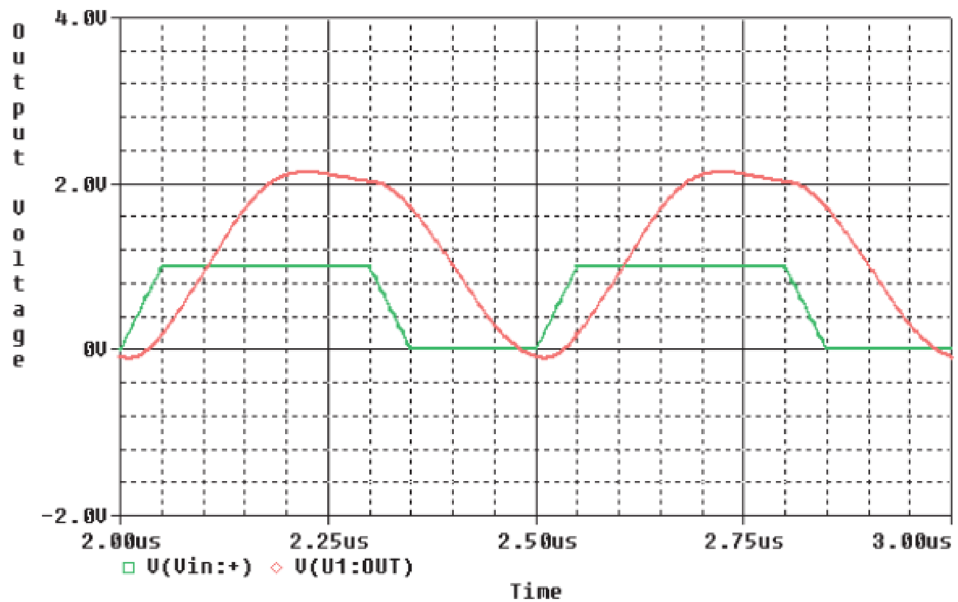



# Slew Rate

- 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



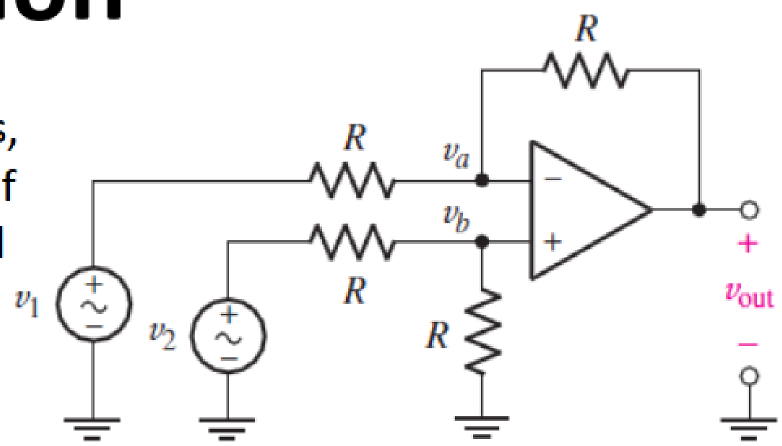

rise and fall times 50 ns, pulse width 250 ns

examples: input (green) and output (red)

# 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

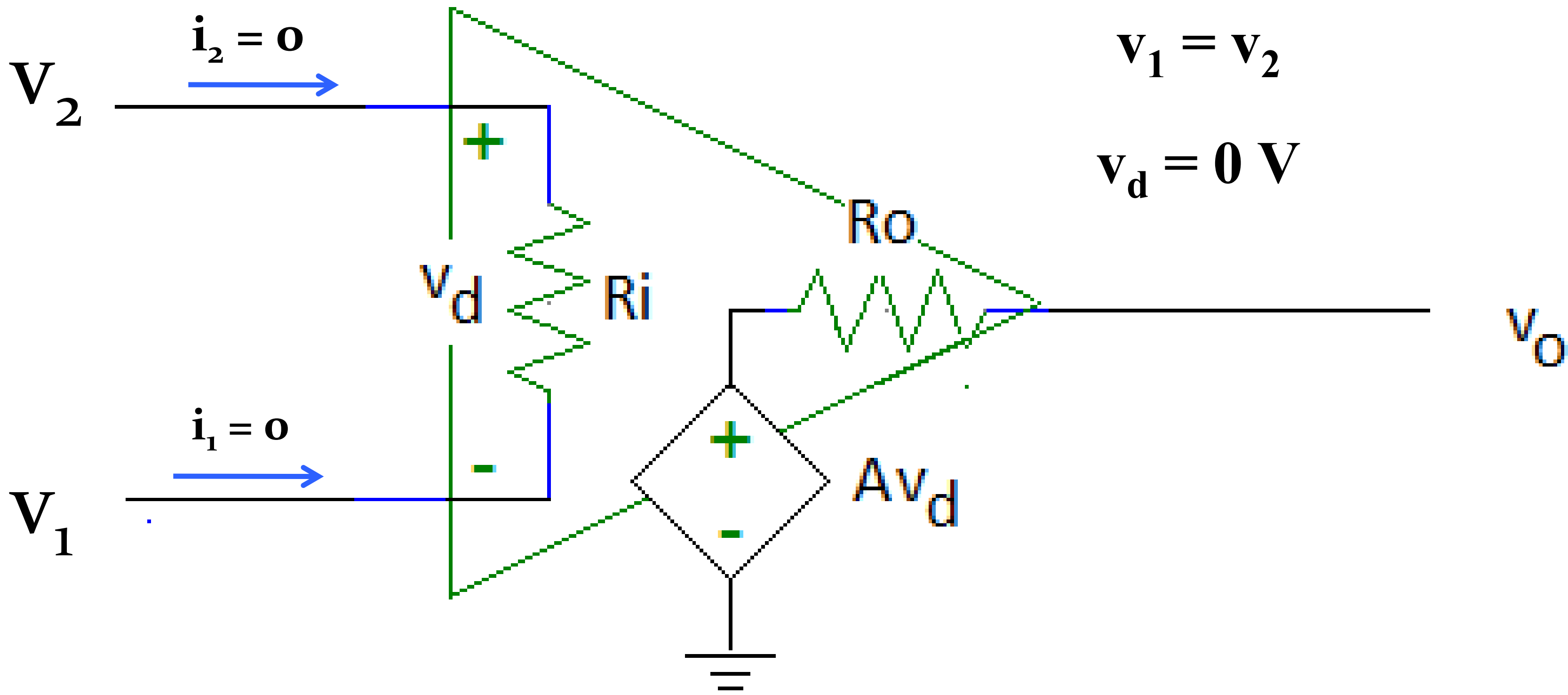
$$A_{CM} = \left|\frac{v_{o_{CM}}}{v_{CM}}\right| \qquad \text{CMRR} \equiv \left|\frac{A}{A_{CM}}\right| \qquad \text{CMRR}_{(\text{dB})} \equiv 20 \log_{10}\left|\frac{A}{A_{CM}}\right| \quad \text{dB}$$

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.

# Ideal Op-Amp

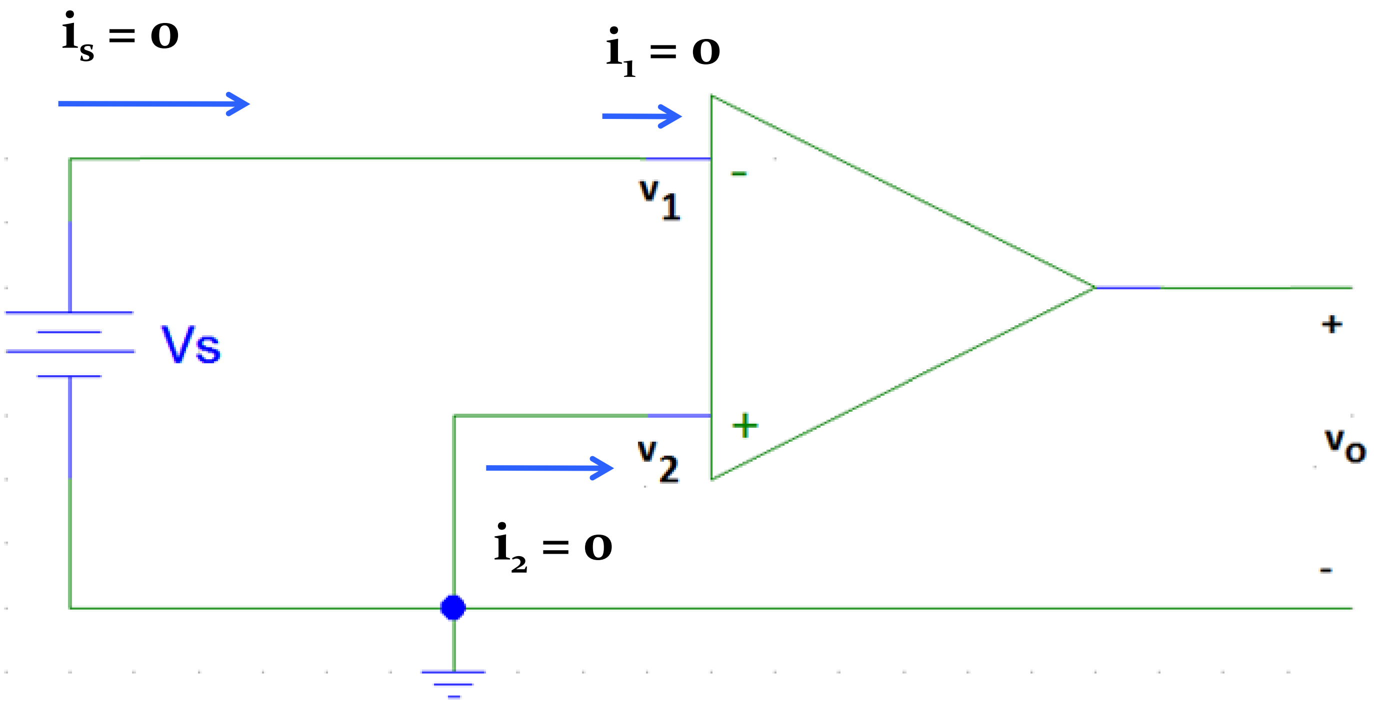
**Because Ri is equal to ∞Ω, the voltage across Ri is 0V.**



# Almost Ideal Op Amp

- $Ri = \infty\ \Omega$
  - Therefore, $i_1 = i_2 = 0A$
- $Ro = 0\ \Omega$
- Usually, $v_d = 0V$ so $v_1 = v_2$
  - The op-amp forces the voltage at the inverting input terminal to be equal to the voltage at the noninverting input terminal if there is some component connecting the output terminal to the inverting input terminal.
- Rarely is the op-amp limited to $V^- < v_o < V^+$.
  - The output voltage is allowed to be as positive or as negative as needed to force $v_d = 0V$.

# Example 01: Voltage Comparator…

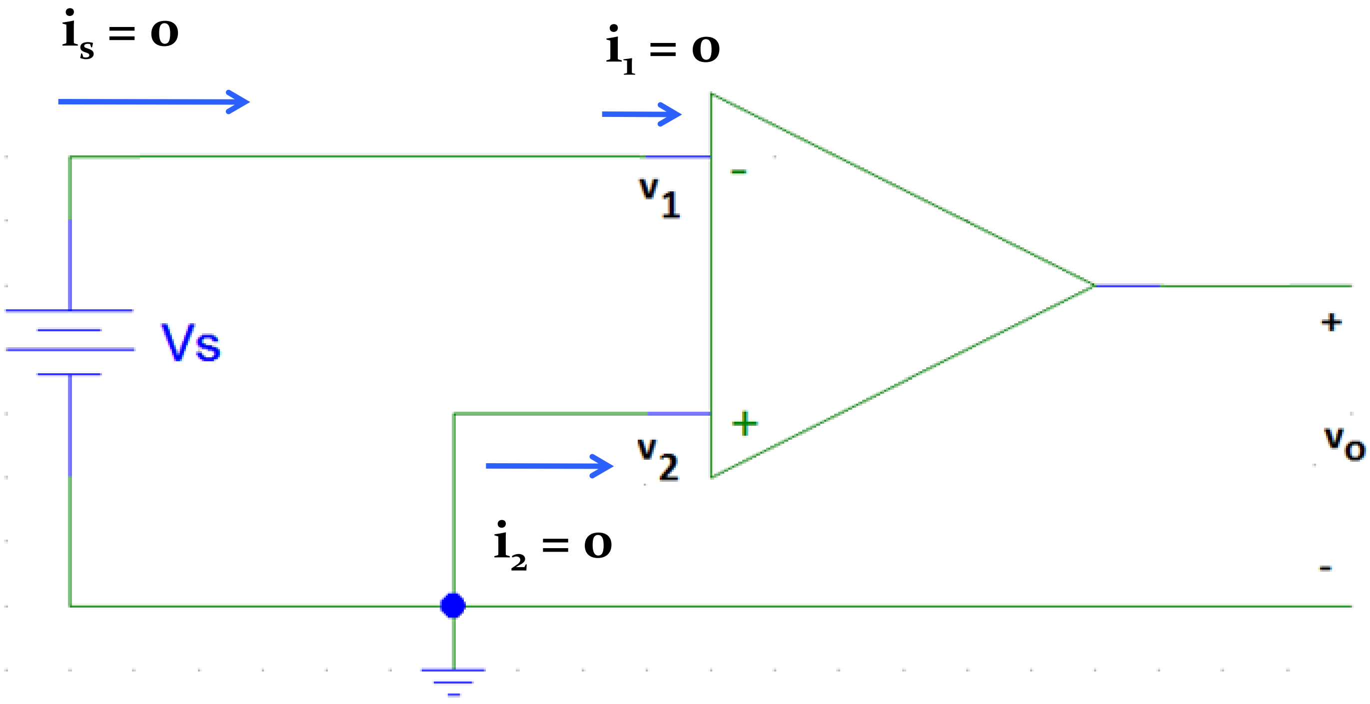



Note that the inverting input and non-inverting input terminals have rotated in this schematic.

# …Example 01…

- The internal circuitry in the op-amp tries to force the voltage at the inverting input to be equal to the non-inverting input.
  – As we will see shortly, a number of op-amp circuits have a resistor between the output terminal and the inverting input terminals to allow the output voltage to influence the value of the voltage at the inverting input terminal.

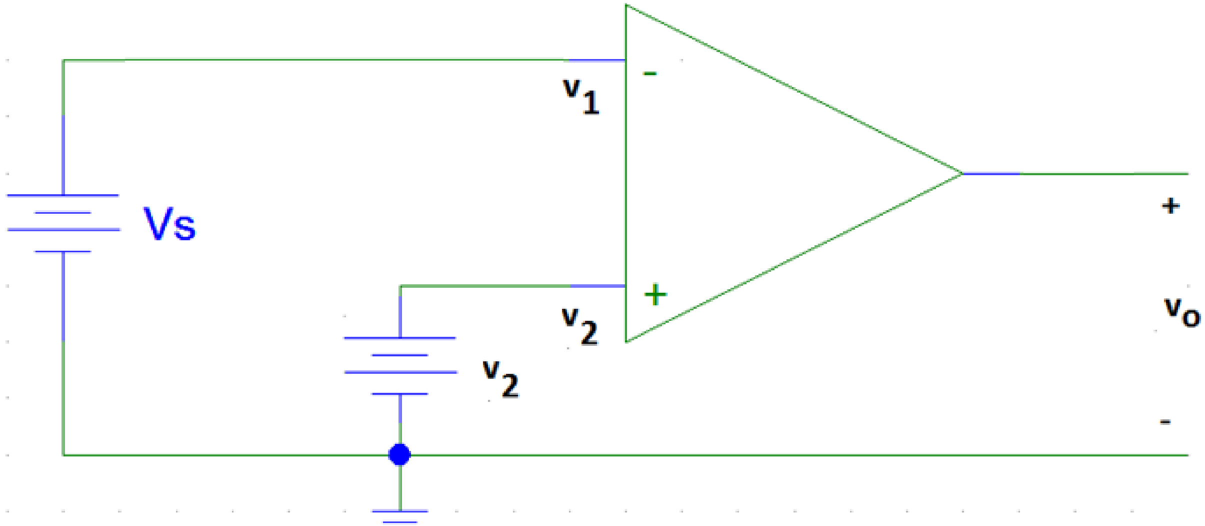
# …Example 01: Voltage Comparator



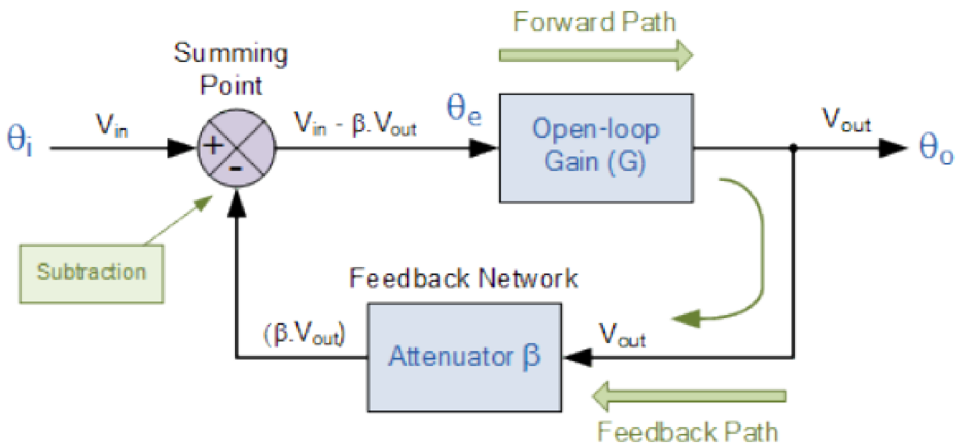

When Vs is equal to 0V, Vo = 0V.
When Vs is smaller than 0V, Vo = $V^+$.
When Vs is larger than 0V, Vo = $V^-$.

# Electronic Response

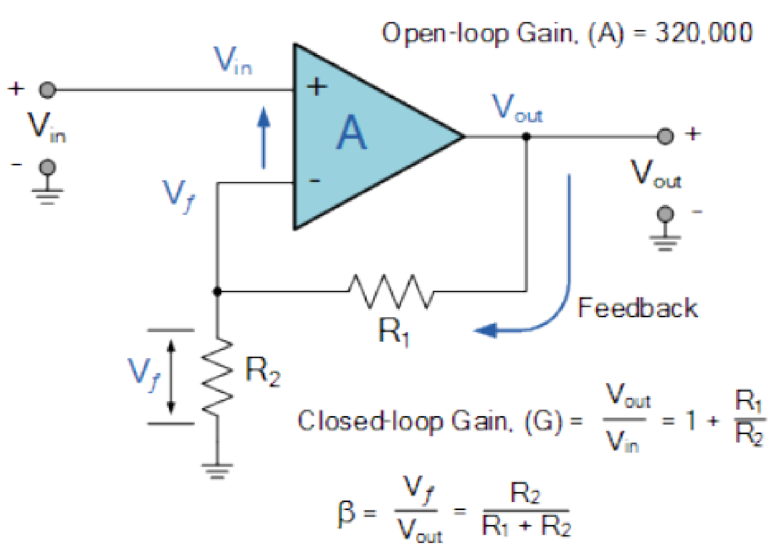
- Given how an op-amp functions, what do you expect Vo to be if $v_2$ = 5V when:
  1. Vs = 0V?
  2. Vs = 5V?
  3. Vs = 6V?



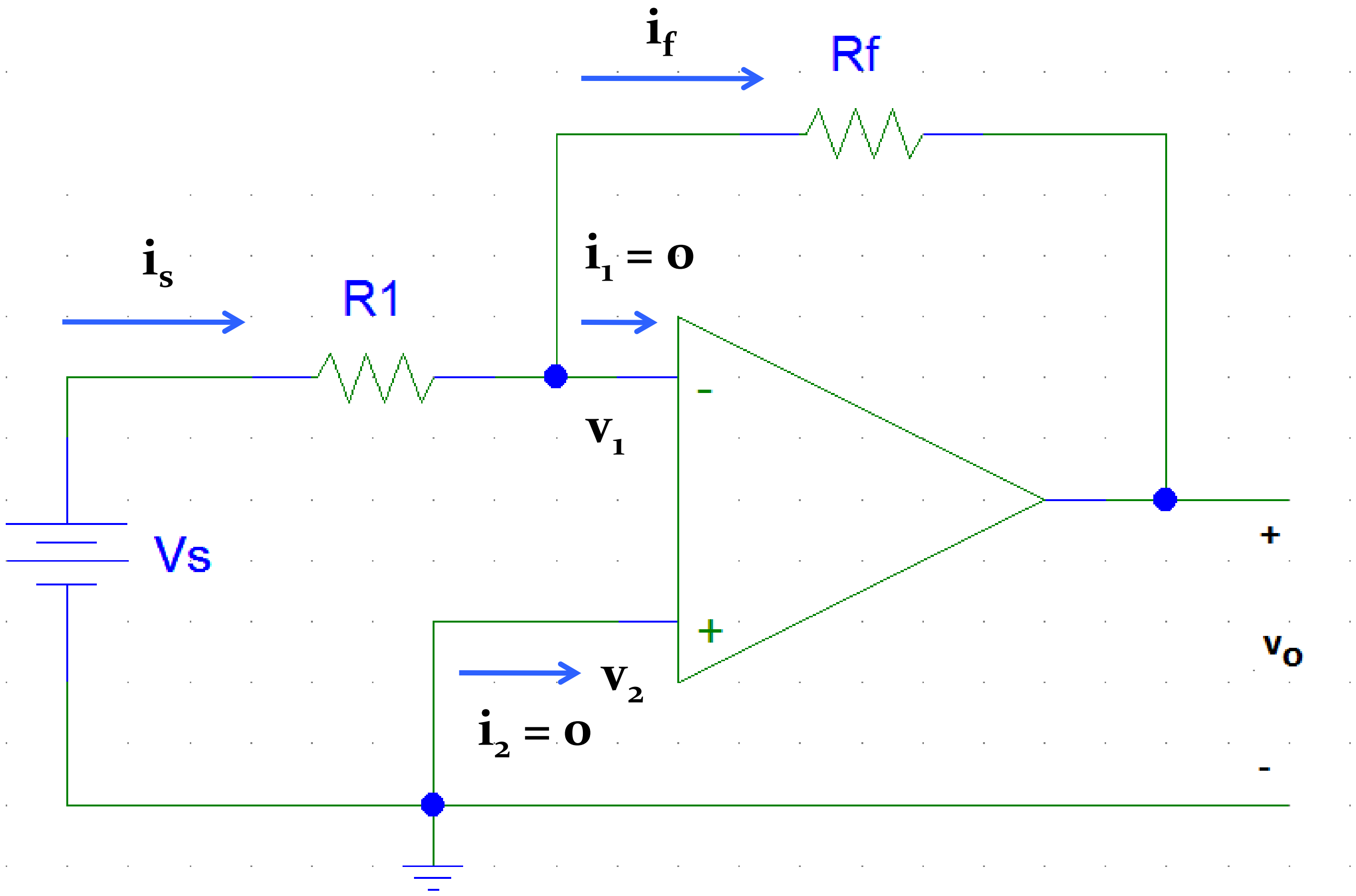
# Negative Feedback



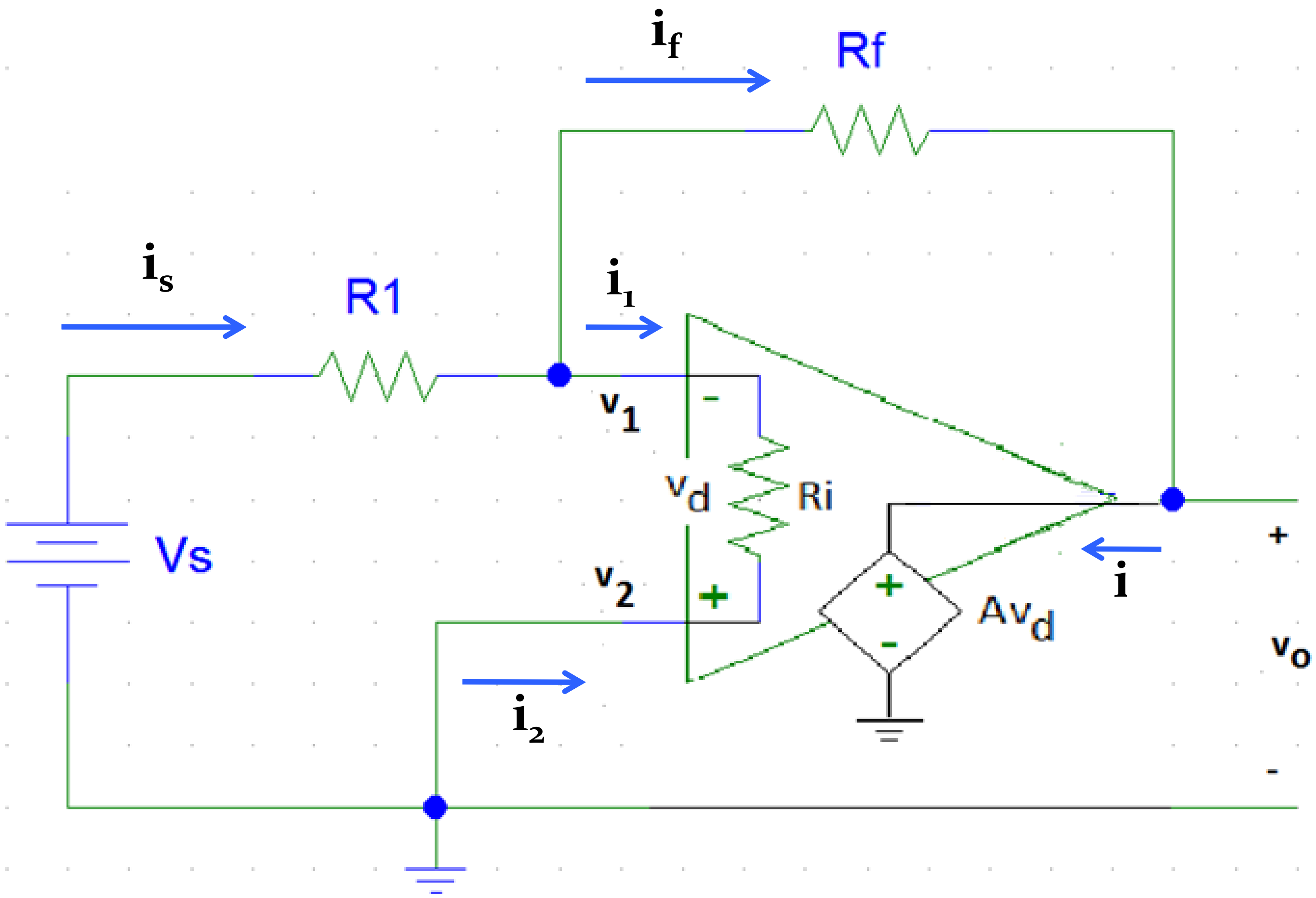

- the main advantages of using **Negative Feedback** in amplifier circuits is to greatly improve their stability, better tolerance to component variations, stabilization against DC drift as well as increasing the amplifiers bandwidth.



# Example 02: Closed Loop Gain…

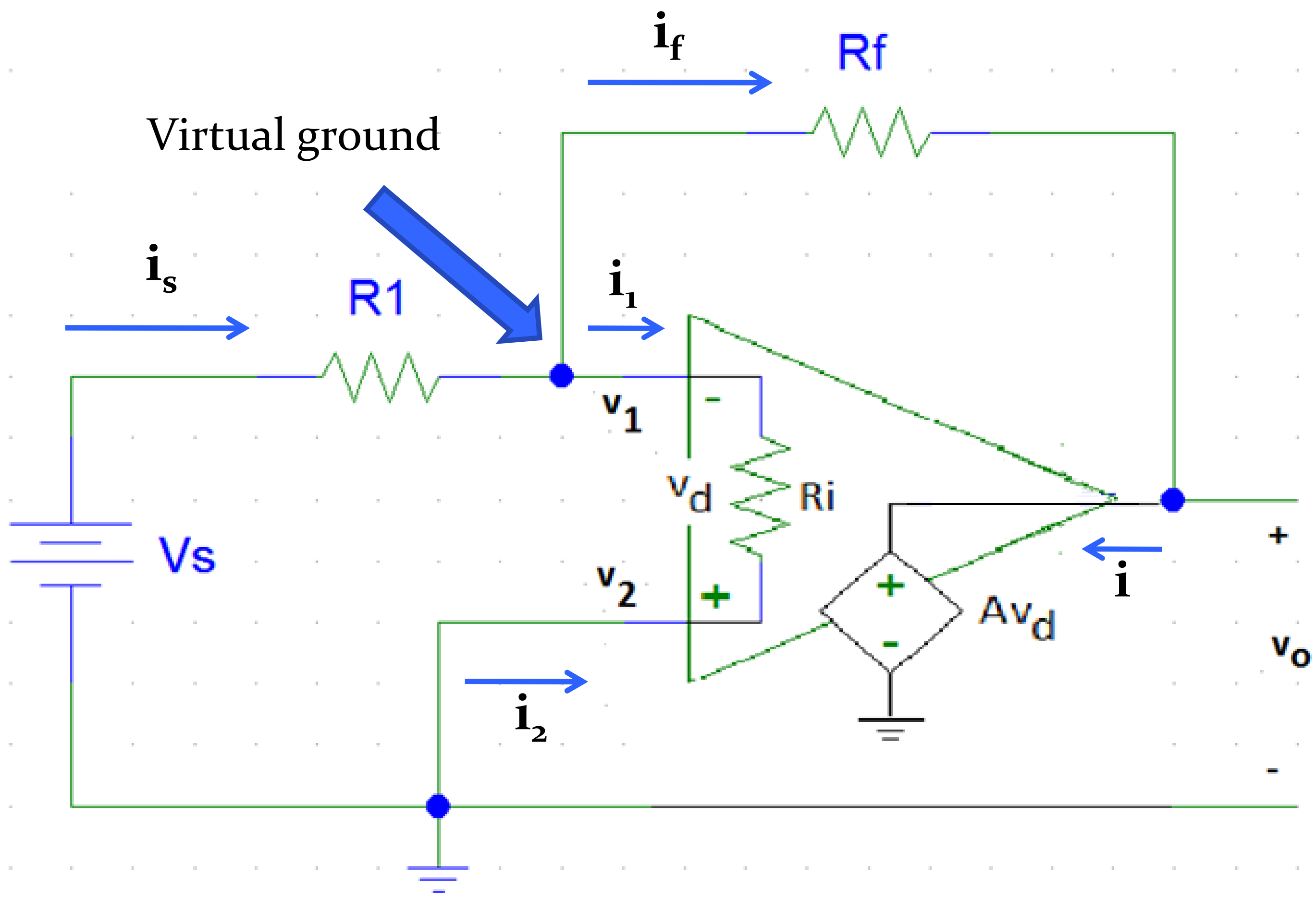


# …Example 02…



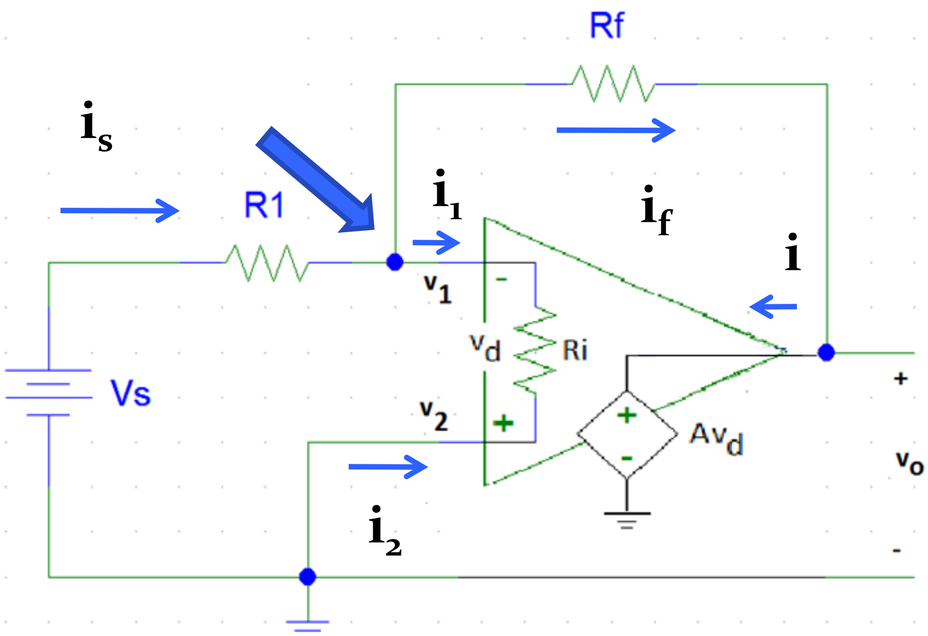

For an almost ideal op amp, Ri = ∞ Ω and Ro = 0 Ω.
The output voltage will never reach $V^+$ or $V^-$.

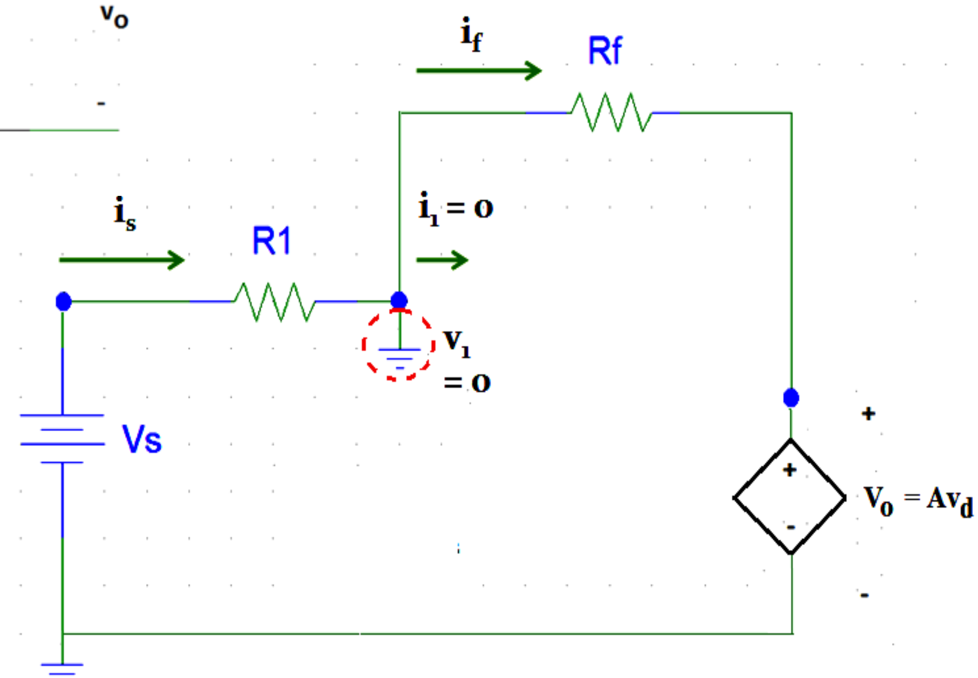
# …Example 02…




The op amp outputs a voltage Vo such that $V_1 = V_2$.

# …Example 02…



# …Example 02: Closed Loop Gain

$v_1 = 0V$

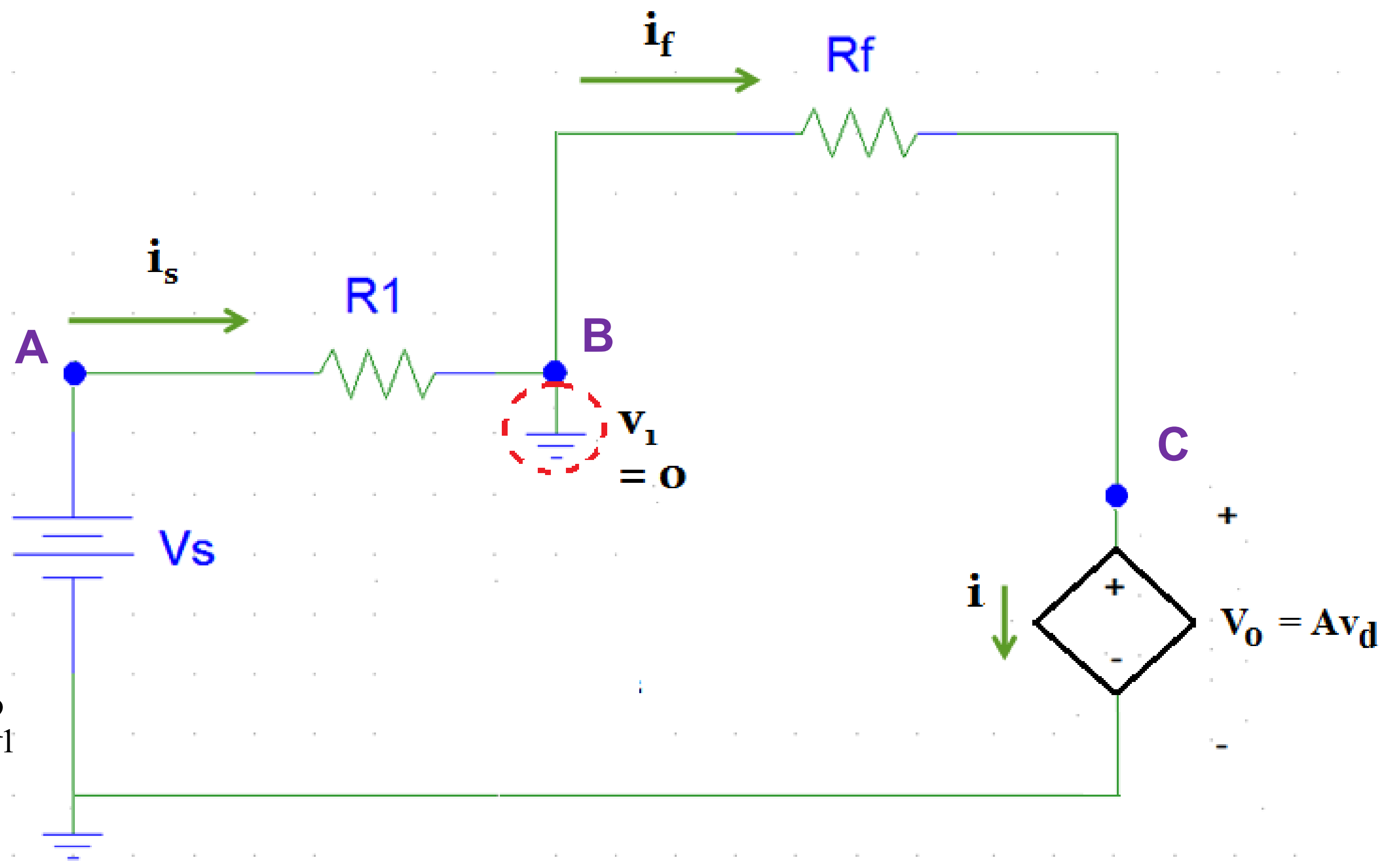
$V_S = R_1 i_s$

$v_o = -R_f i_f$

$i_s = i_f = i$

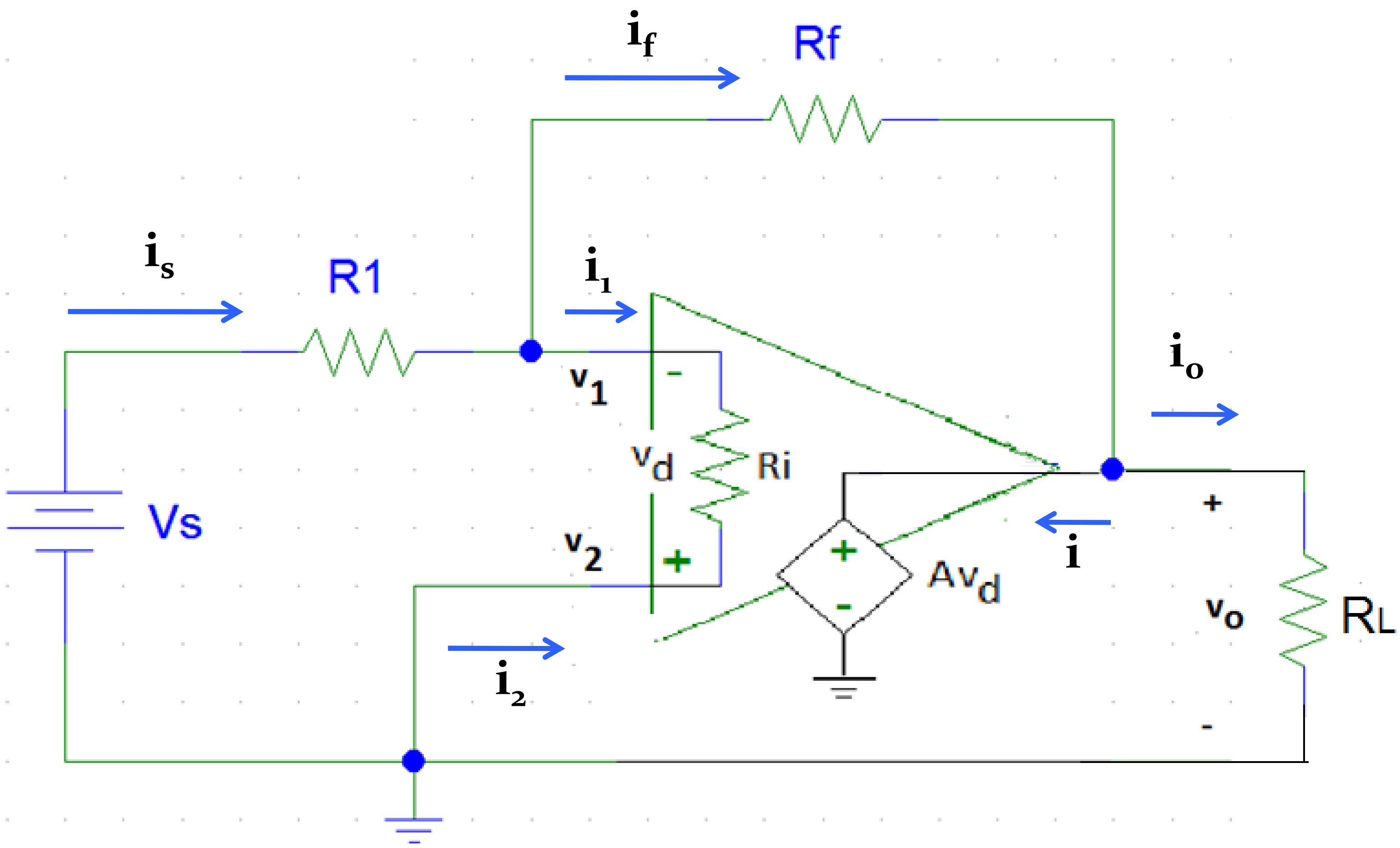
$v_o / V_s = -R_f / R_1$

$A_V = -R_f / R_1$




This circuit is known as an inverting amplifier.

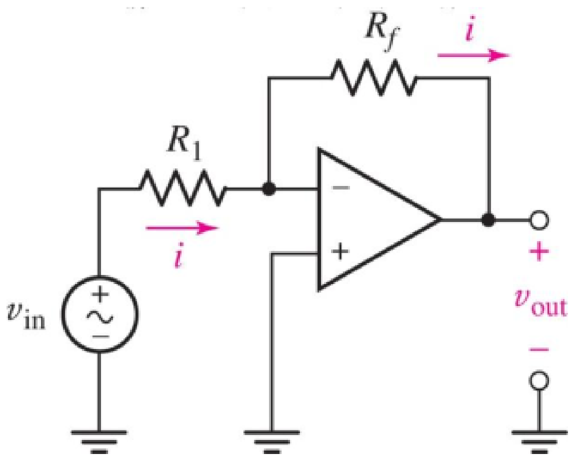
# Types of Gain



# Types of Closed Loop Gain

| Gain | Variable Name | Equation | Units |
|---|---|---|---|
| Voltage Gain | $A_V$ | $v_o/v_s$ | None or V/V |
| Current Gain | $A_I$ | $i_o/i_s$ | None or A/A |
| Transresistance Gain | $A_R$ | $v_o/i_s$ | V/A or $\Omega$ |
| Transconductance Gain | $A_G$ | $i_o/v_s$ | A/V or $\Omega^{-1}$ |

# Example 03: Closed Loop Gain with Real Op-Amp…




- For a 741 Op-Amp (A=200,000, $R_i$=2MΩ, $R_o$=75Ω)
- $v_{out}(t)$ = -49.997 sin 3t mV.

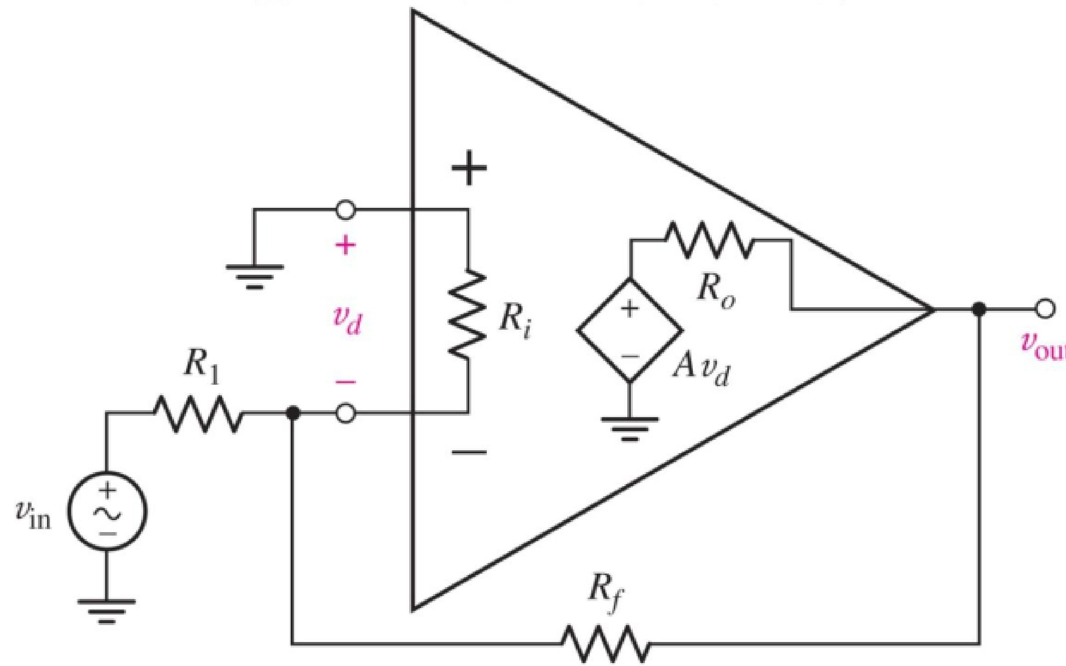
An ideal op amp produces $v_{out}(t)$ = -50 sin 3t mV. [Analyze the detailed op amp model using nodal analysis.]

Example:

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

$R_f$=47 kΩ,

$R_1$=4.7 kΩ

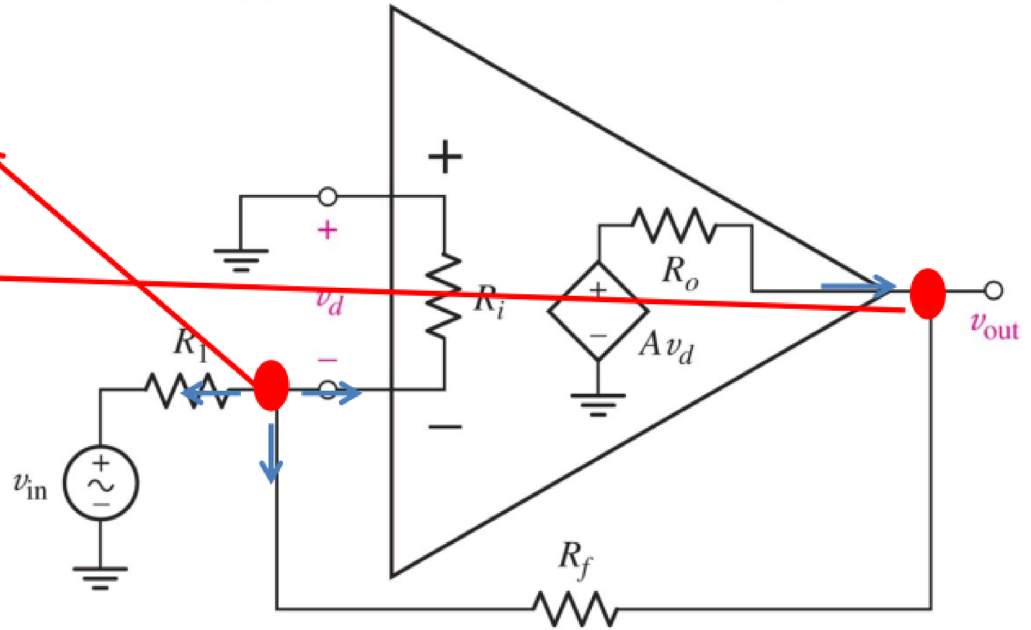


# …Example 03

- 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.

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

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




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

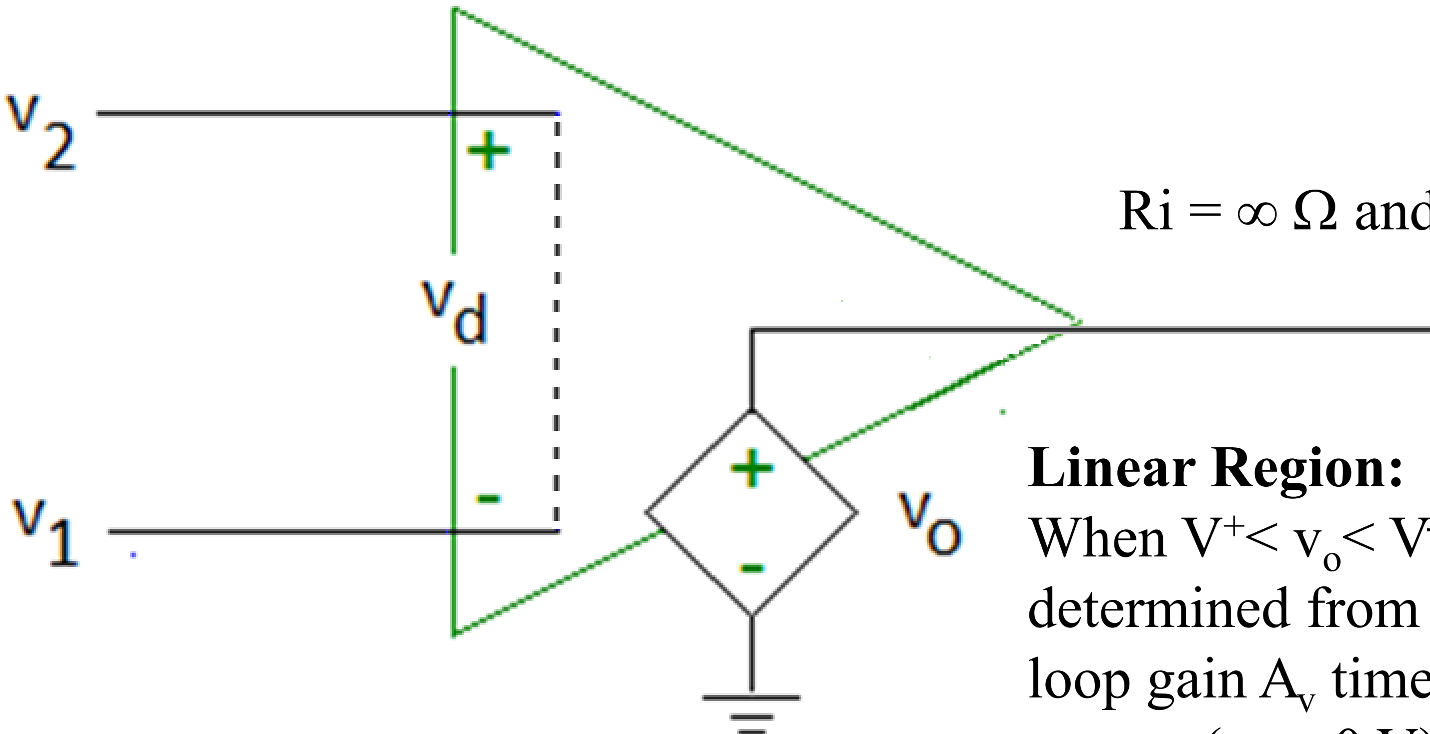
$$v_{out} = -9.999448 v_{in} = -49.99724 \sin 3t \quad \text{mV}$$

# Summary

- The output of an ideal op-amp is a voltage from a dependent voltage source that attempts to force the voltage at the inverting input terminal to equal the voltage at the non-inverting input terminal.
  - Almost ideal op-amp: Output voltage limited to the range between $V^+$ and $V^-$.
- Ideal op amp is assumed to have Ri = ∞ Ω and Ro = 0 Ω.
  - Almost ideal op-amp: $v_d = 0$ V and the current flowing into the output terminal of the op-amp is as much as required to force $v_1 = v_2$ when $V^+ < v_o < V^-$.
- Operation of an op-amp was used in the analysis of voltage comparator and inverting amplifier circuits.
  - Effect of Ri < ∞ Ω and Ro > 0 Ω was shown.

# Op-Amp Circuits

# Almost Ideal Op-Amp Model



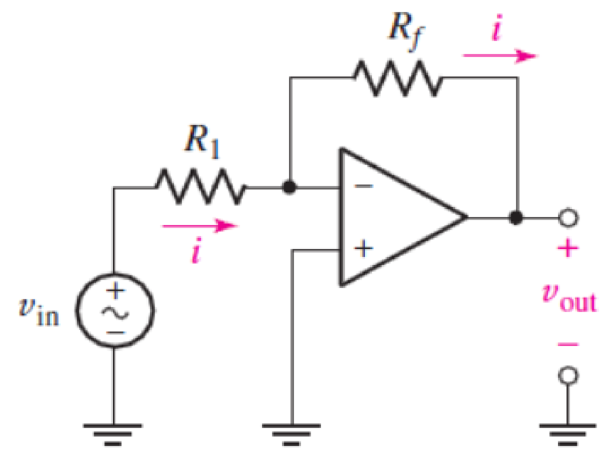

Ri = ∞ Ω and Ro = 0 Ω

**Linear Region:**
When $V^+ < v_o < V^-$ , $v_o$ is determined from the closed loop gain $A_v$ times $v_2$ as $v_1 = v_2$ ($v_d = 0$ V).

**Saturation:**
When $A_v\ v_2 \geq V^+$, $v_o = V^+$.
When $A_v\ v_2 \leq V^-$, $v_o = V^-$.

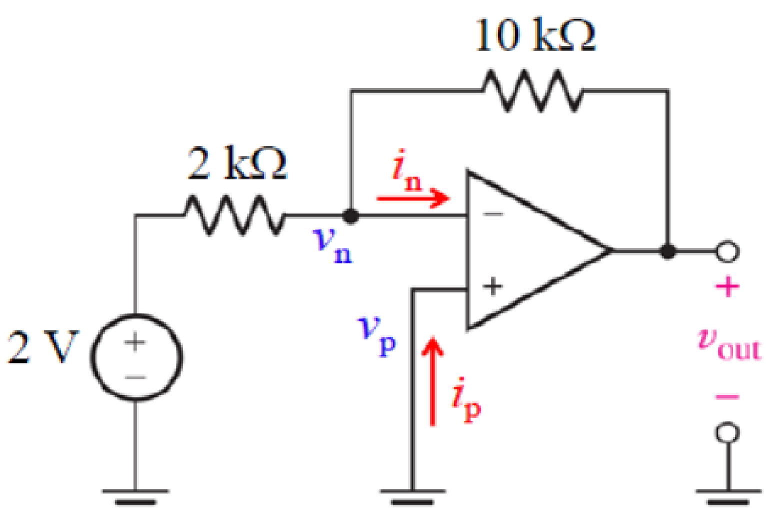
# Example 04: Inverting Amplifier…

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




$$v_n = v_p$$

$$i_n = i_p = 0$$




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

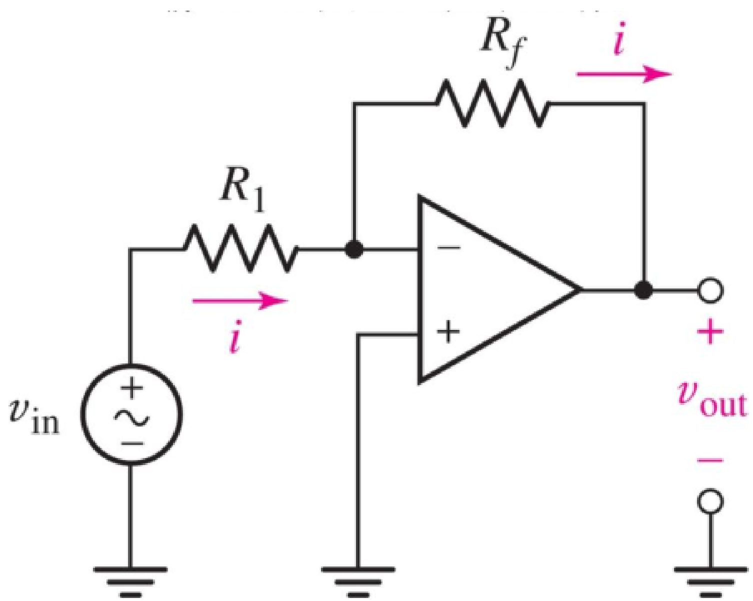
$$v_p = 0$$

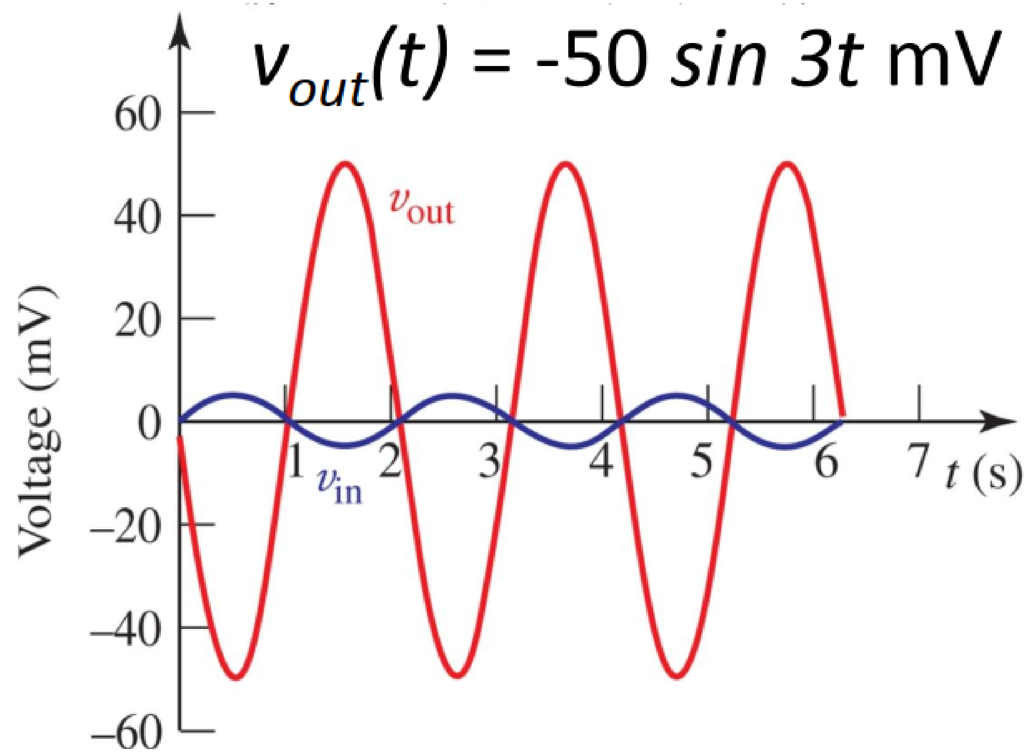
$$v_{out} = -10 \text{ V}$$

(inverting amplifier)

# …Example 04…

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



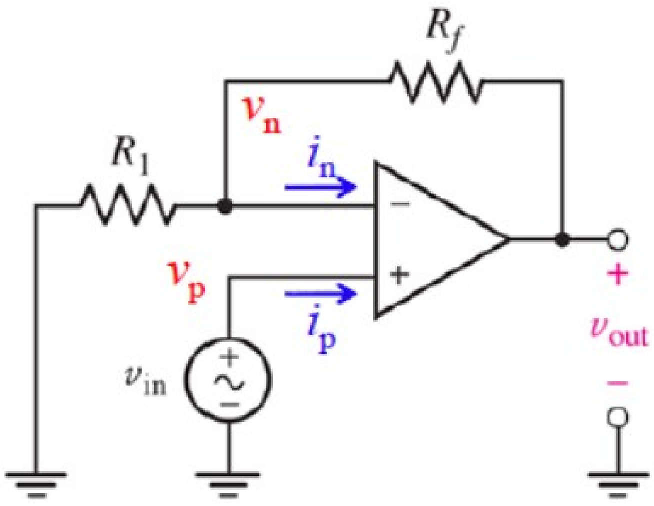




$v_{out}(t)$ = -50 *sin 3t* mV

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

# Example 05: Noninverting Amplifier…

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




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

$$v_p = v_{in}$$

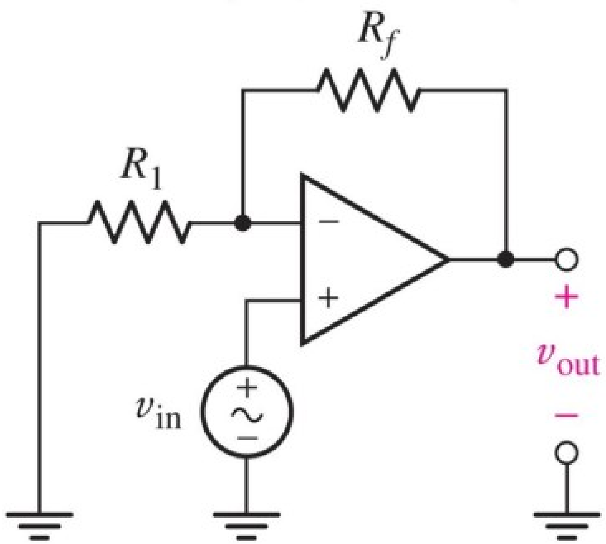
$$\frac{-v_{in}}{R_1} + \frac{v_{out} - v_{in}}{R_f} = 0 \qquad \frac{v_{in}}{R_1} + \frac{v_{in}}{R_f} = \frac{v_{out}}{R_f}$$

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

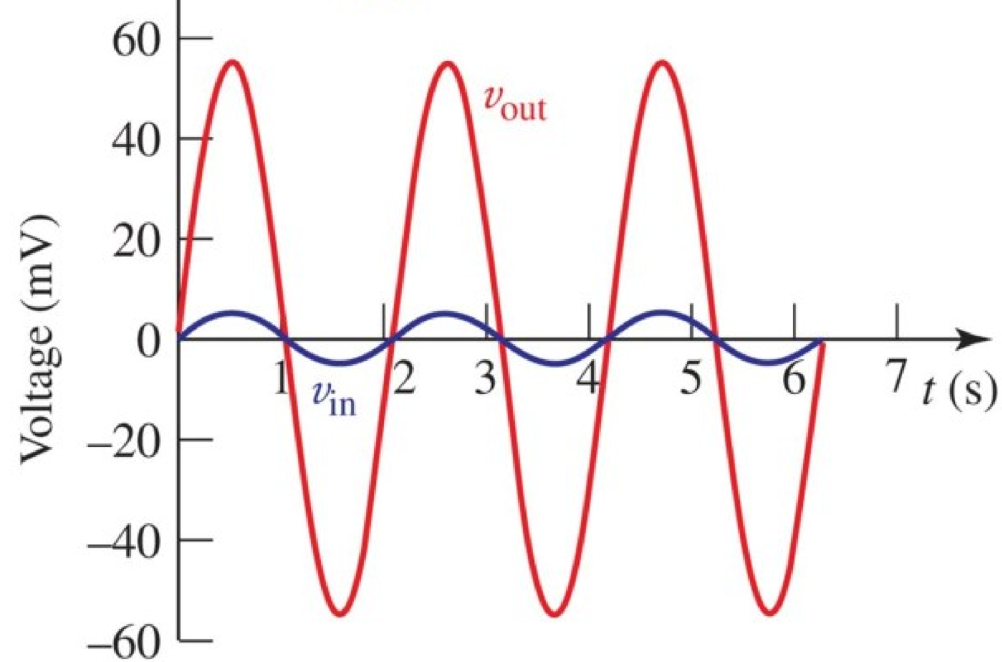
non-inverting amplifier

# …Example 05…

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




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

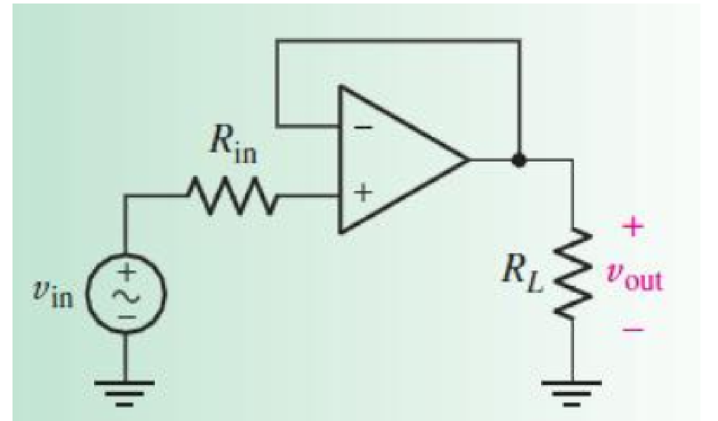


# Example 06:  Voltage Follower

• 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.

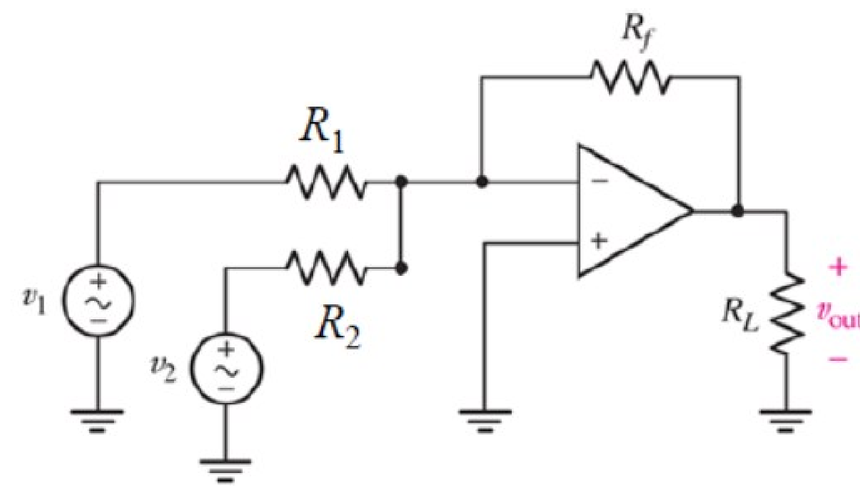



$$v_{out} = v_{in}$$

# Example 07: Summing Amplifier…

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

$$v_n = v_p \qquad i_n = i_p = 0$$




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

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

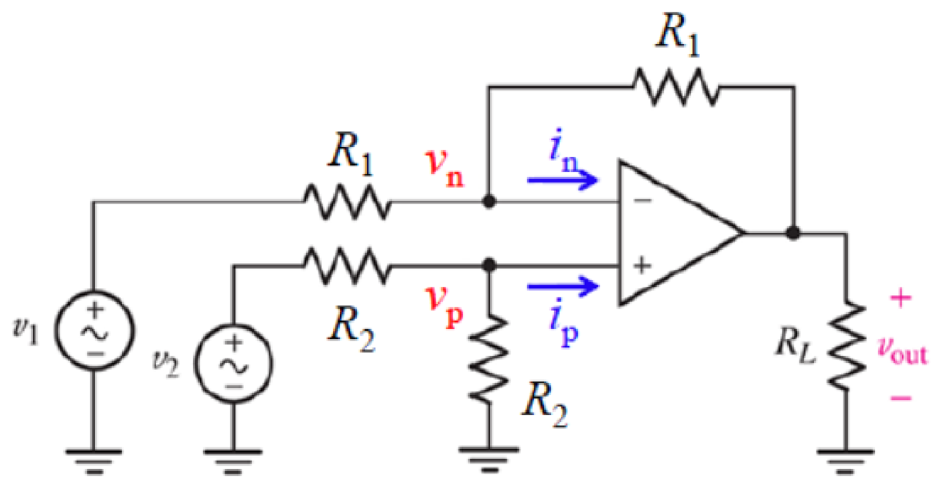
(inverting) summing amplifier

# Example 08: Difference Amplifier…

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

$$v_n = v_p$$

$$i_n = i_p = 0$$

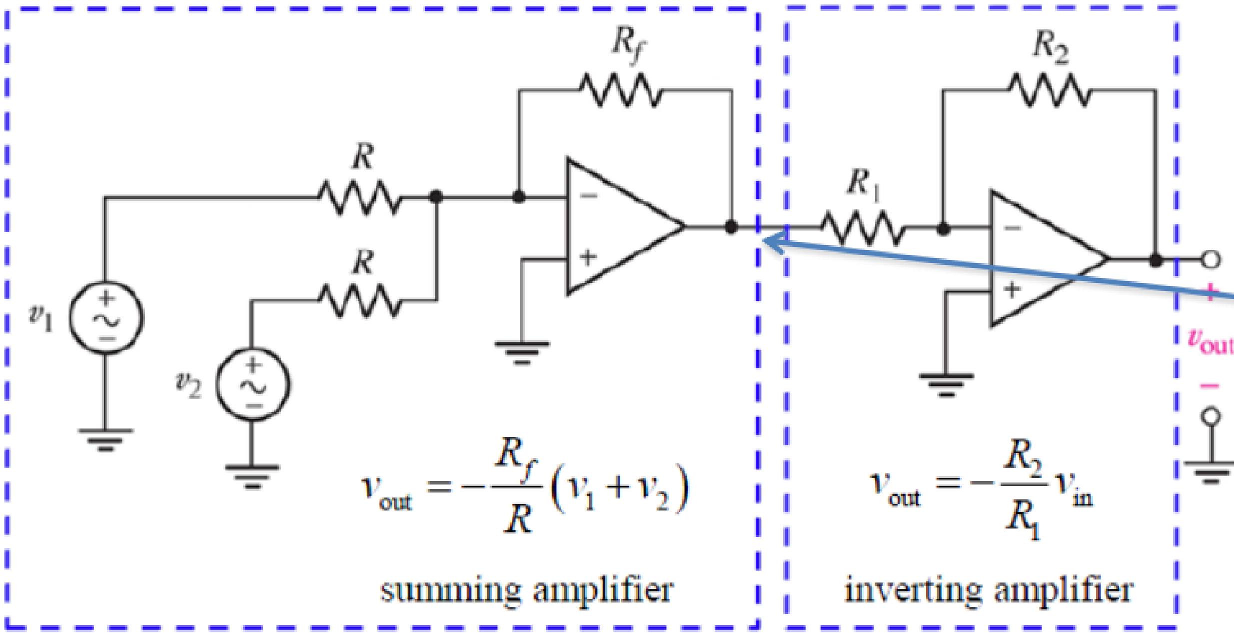



$$v_{out} = v_2 - v_1$$

difference amplifier

# Example 09: Cascading Op Amps…

• 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.

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

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

# …Example 09…

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

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

**non-inverting amp**

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

**inverting amp**

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

**inverting sum**

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

**difference**

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

inverting sum

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

# …Example 09…

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

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

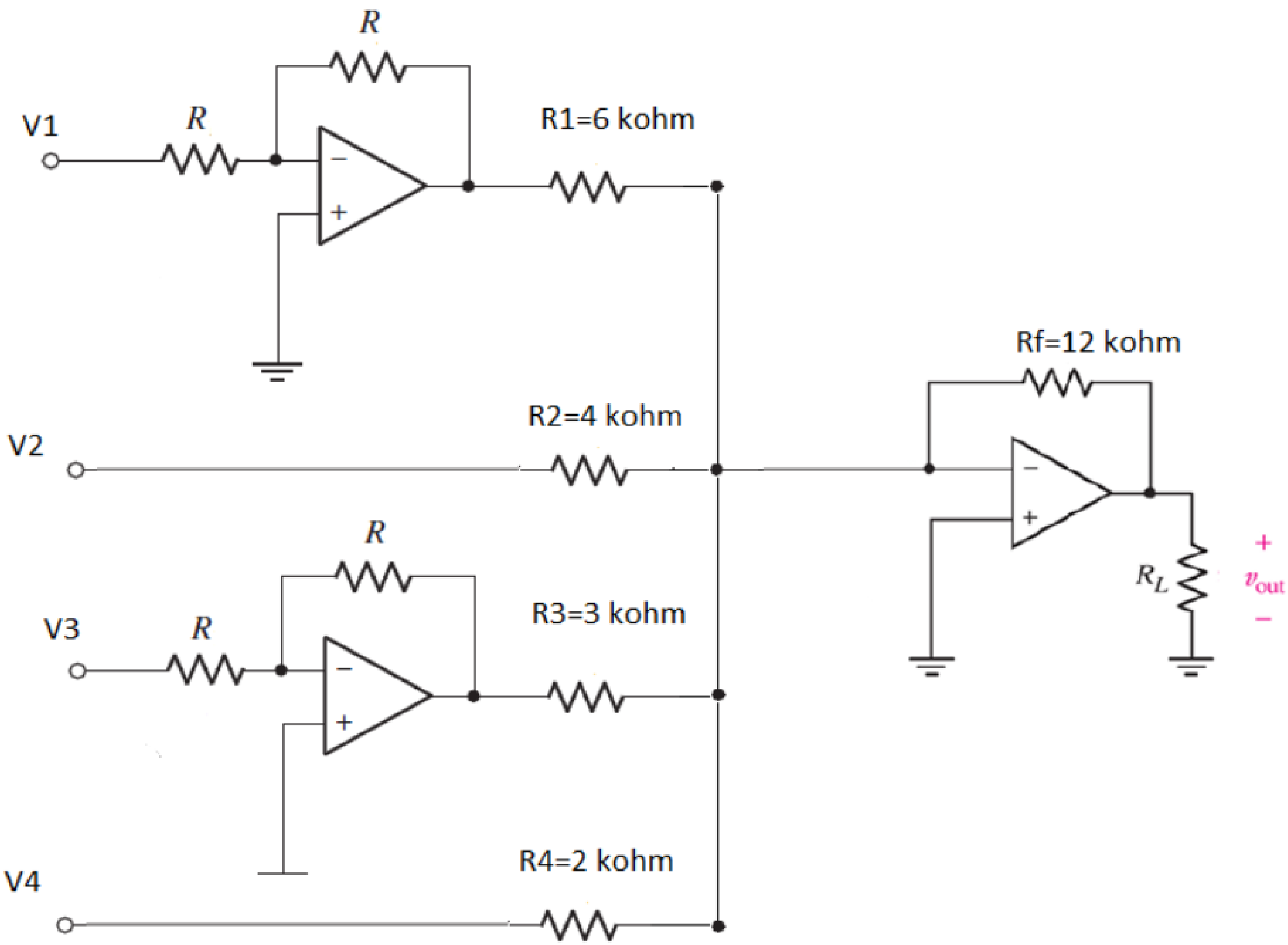
Choose $R_{\text{a}} = R_{\text{b}} = R_{\text{c}} = R_{\text{d}} = 2\ \text{k}\Omega$ …

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

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

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

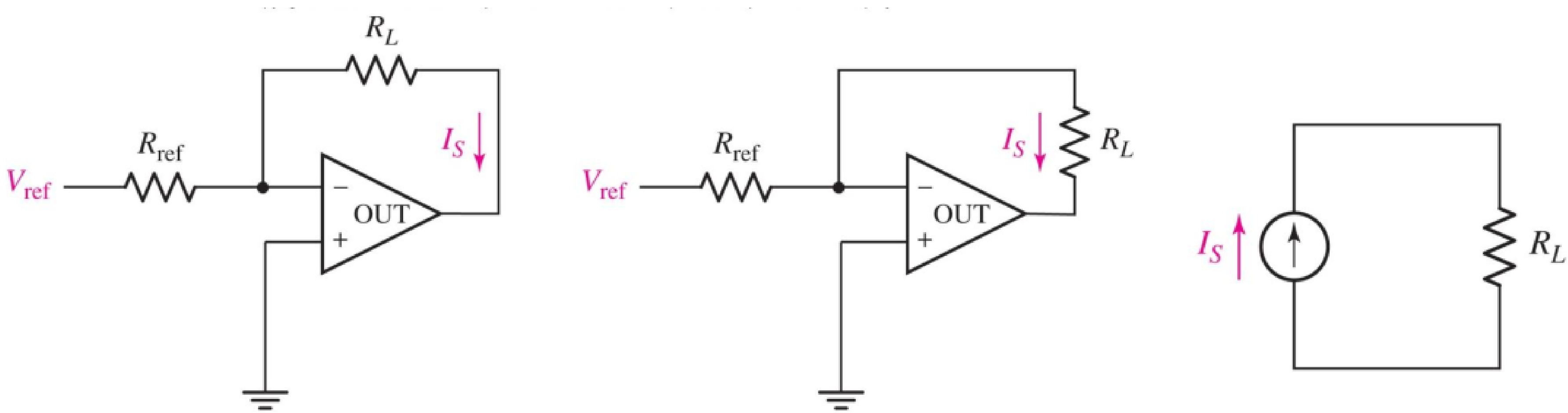
# …Example 09…




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

# Example 10 – A Current Source

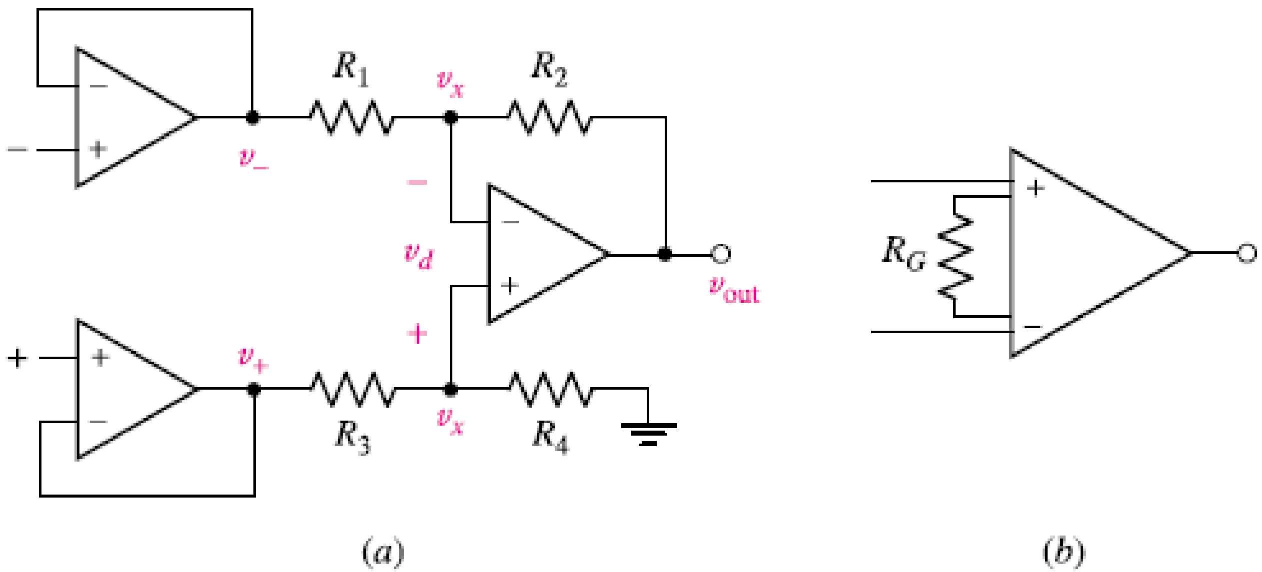
- With a reference voltage source $V_{ref}$, we can drive a constant current $I_s = V_{ref} / R_{ref}$ through any load $R_L$.
- the current supplied to $R_L$ *does not depend on its* resistance—the primary attribute of an ideal current source.



# Instrumentation amplifier

- This device allows precise amplification of small voltage differences:

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



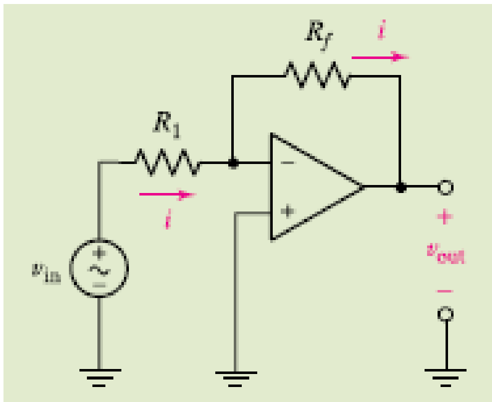

(a) The basic instrumentation amplifier. (b) Commonly used symbol.

# Summary

- The 'almost ideal' op amp model:
  - $Ri = \infty\Omega$.
    - $i_1 = i_2 = 0A$; $v_1 = v_2$
  - $Ro = 0\Omega$.
    - No power/voltage loss between the dependent voltage source and $v_o$.
  - The output voltage is limited by the voltages applied to the positive and negative rails.
    - $V^+ \geq v_o \geq V^-$
- This model can be used to determine the closed loop voltage gain for any op amp circuit.
  - Superposition can be used to solve for the output of a summing amplifier.
  - Cascaded op amp circuits can be separated into individual amplifiers and the overall gain is the multiplication of the gain of each amplifier.

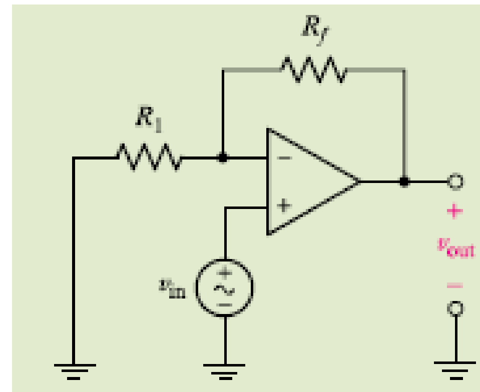
# Summary of Basic Op Amp Circuits

**Inverting Amplifier**



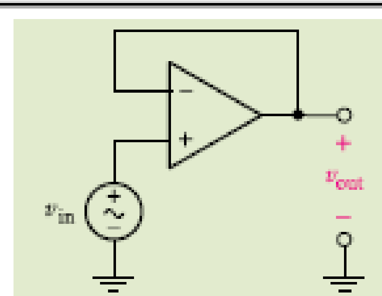

$$v_{out} = -\frac{R_f}{R_1} v_{in}$$

**Noninverting Amplifier**




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

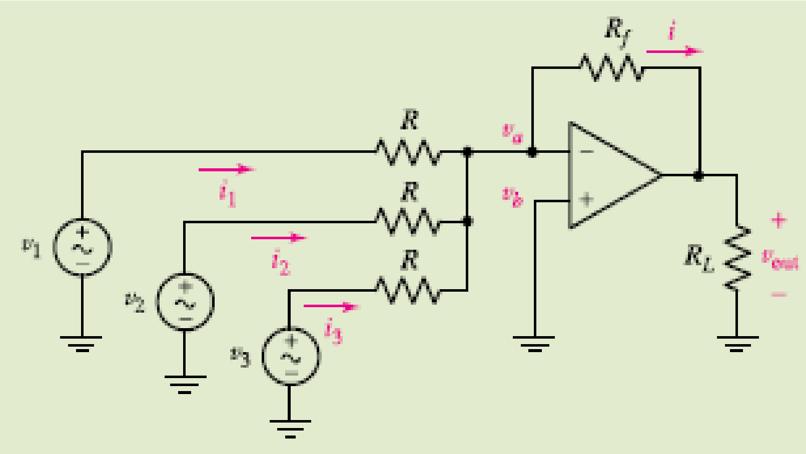
Voltage Follower (also known as a Unity Gain Amplifier)




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

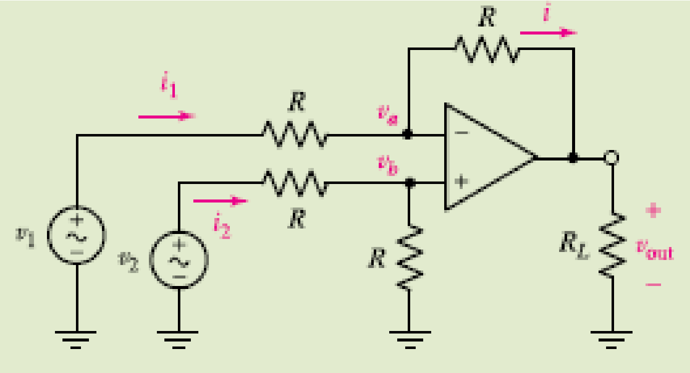
# Summary of Basic Op Amp Circuits

Summing Amplifier




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

Difference Amplifier




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