BLM1612 - Circuit Theory

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Op-Amps

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

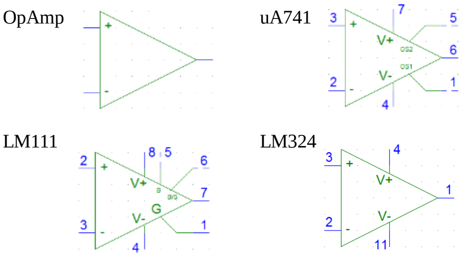
The Operational Amplifier

- 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.

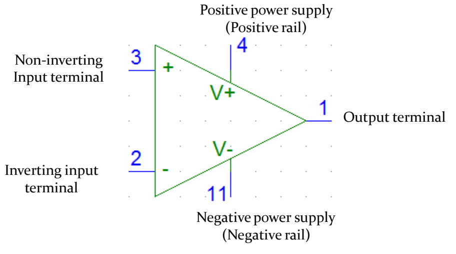
Op Amps Applications

- 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

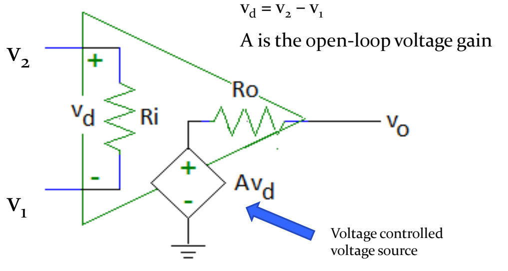
Symbols for Ideal and Real Op Amps



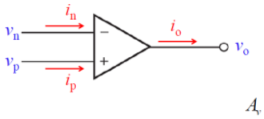
Terminals on an Op Amp



Op Amp Equivalent Circuit



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

$v_n \approx v_p$ $\quad$ $i_n = i_p \approx 0$

Ideal Op-Amp Rules
– No current ever flows into either input terminal.
–There is no voltage difference between the two input terminals.

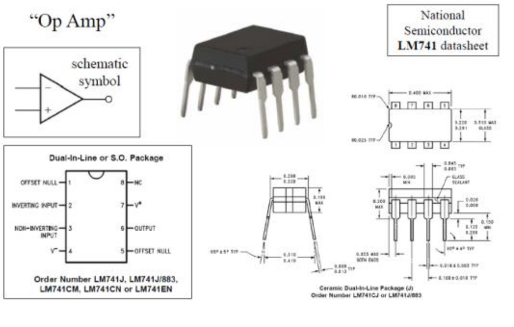
Typical Op-Amp Parameters

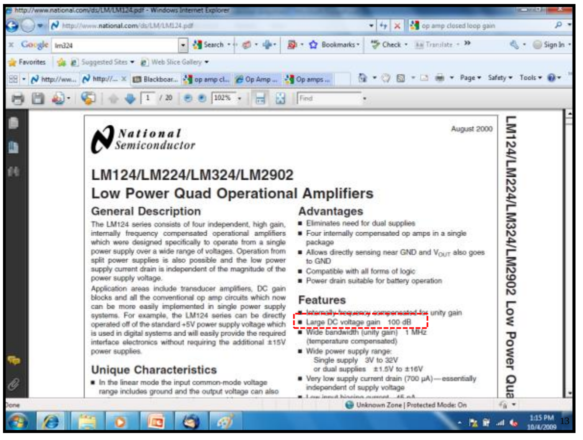
Parameter	Variable	Typical Ranges	Ideal Values
Open-Loop Voltage Gain	A	10^5 to 10^8	∞
Input Resistance	Ri	10^5 to 10^{13} Ω	∞ Ω
Output Resistance	Ro	10 to 100 Ω	0 Ω
Supply Voltage	Vcc/V+ -Vcc/V-	5 to 30 V -30V to 0V	N/A N/A

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





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

LM124/LM224/LM324/LM2902 Low Power Qua

dB

- Decibels

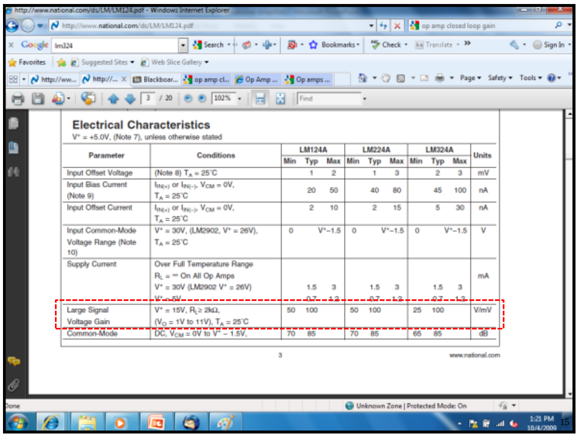
  Since $P = V^2/R$

  $10 \log (P/P_{ref})$ 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

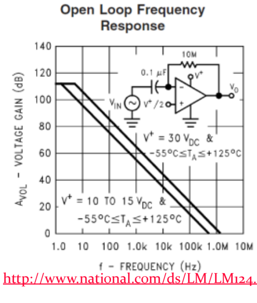
Parameter	Conditions	LM124A Min	LM124A Typ	LM124A Max	LM224A Min	LM224A Typ	LM224A Max	LM324A Min	LM324A Typ	LM324A Max	Units
Input Offset Voltage	(Note 8) $T_A = 25°C$		1	2		1	3		2	3	mV
Input Bias Current (Note 9)	$I_{IN(+)}$ or $I_{IN(-)}$, $V_{CM} = 0V$, $T_A = 25°C$		20	50		40	80		45	100	nA
Input 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 $R_L = \infty$ On All Op Amps $V^+ = 30V$ (LM2902 $V^+ = 26V$) $V^+ = 5V$		1.5 0.7	3 1.2		1.5 0.7	3 1.2		1.5 0.7	3 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

3 www.national.com

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

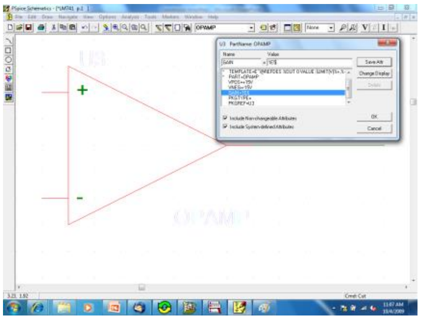


http://www.national.com/ds/LM/LM124.pdf

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

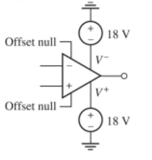
- Open Circuit Output Voltage

  $v_o = A\ v_d$

- 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^-

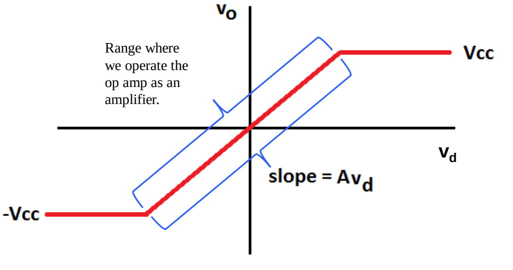
Open Circuit Output Voltage

- 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	$Av_d < V^-$	$v_o \sim V^-$

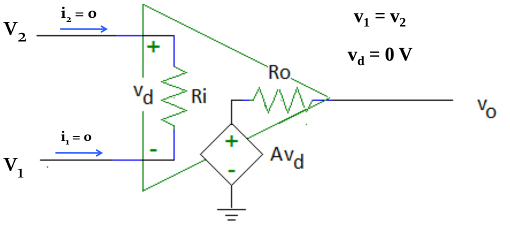
The voltage produced by the dependent voltage source inside the op amp is limited by the voltage applied to the positive and negative rails.

Voltage Transfer Characteristic



Ideal Op-Amp

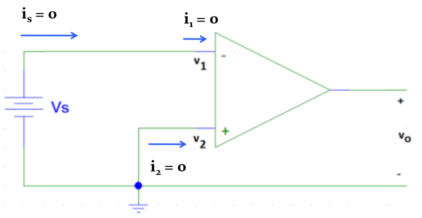
Because Ri is equal to ∞Ω, the voltage across Ri is 0V.



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.

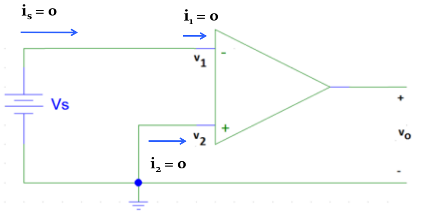
25

…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.

26

…Example 01: Voltage Comparator

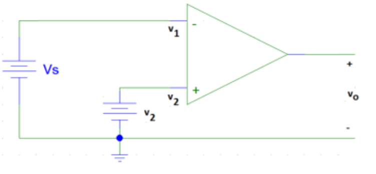


When Vs is equal to 0V, Vo = 0V.
When Vs is smaller than 0V, Vo = V^+.
When Vs is larger than 0V, Vo = V^-.

27

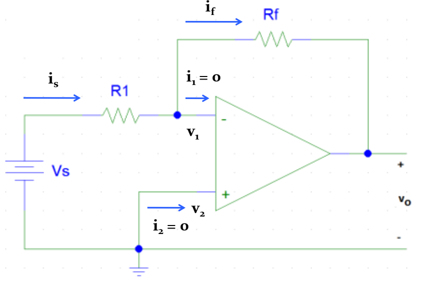
Electronic Response

- 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?



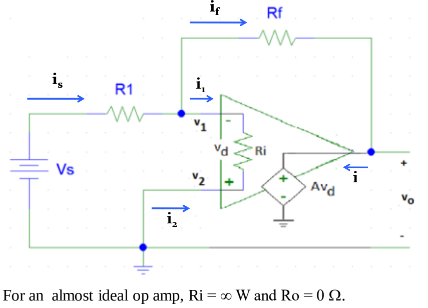
28

Example 02: Closed Loop Gain…



29

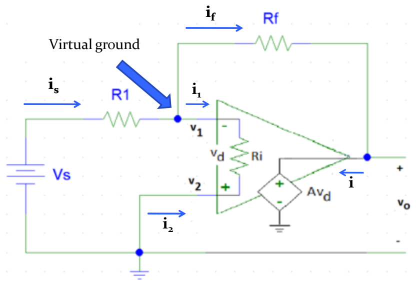
…Example 02…



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

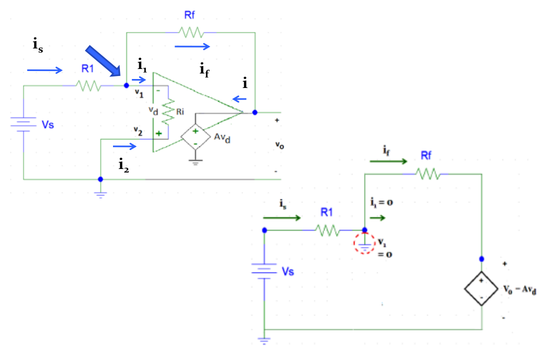
30

…Example 02…



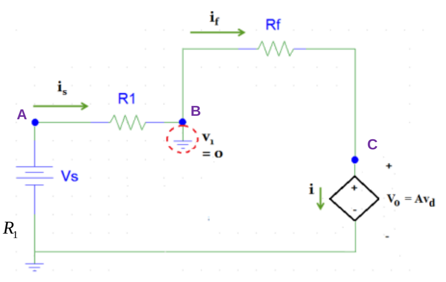
The op amp outputs a voltage Vo such that V1 = V2.

…Example 02…



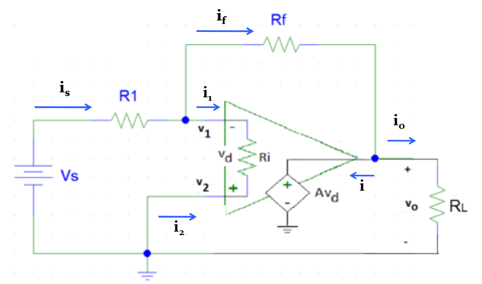
…Example 02: Closed Loop Gain

$v_1 = 0V$
$V_S = R_1 i_s$
$v_o = -R_f i_f$
$i_s = i_f = i$
$v_o / V_s = -R_f / R_1$
$A_V = -R_f / R_1$



This circuit is known as an inverting amplifier.

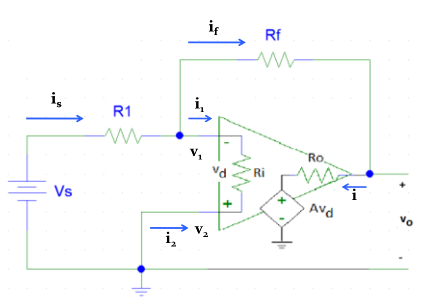
Types of Gain



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 Ω
Transconductance Gain	A_G	i_o/v_s	A/V or Ω^{-1}

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



…Example 03

$$i_s = i_1 + i_f$$
$$i = i_f$$
$$-i_1 = i_2$$
$$v_d = v_2 - v_1 = Ri(-i_1) = Ri(i_2)$$
$$V_o = Av_d - Ro(-i)$$
$$V_s = R1(i_s) - v_d$$
$$V_s = R1(i_s) + Rf(i_f) + V_o$$

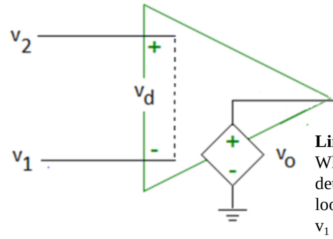
$$V_o/V_s = (-R_f/R1)\{Ab/[1 + Ab]\}, \text{ where } b = R1/(R1+R_f)$$

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

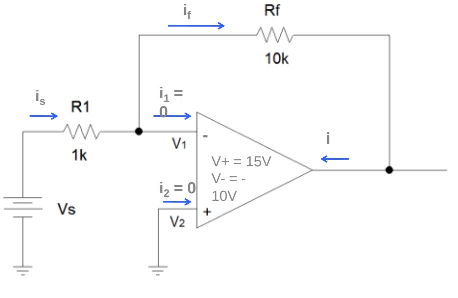


Ri = ∞ Ω and Ro = 0 Ω

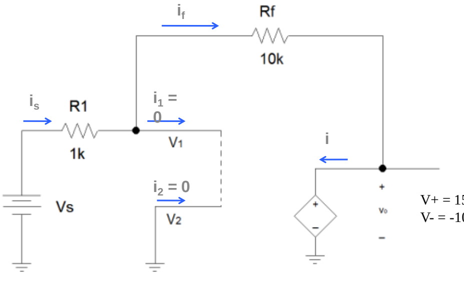
Linear Region:
When $V^+ < v_o < V^-$, v_o is determined from the closed loop gain A_v times v_2 as $v_1 = v_2$ ($v_d = 0$ V).

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…



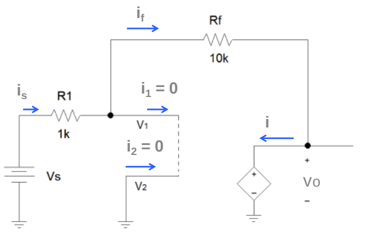
…Example 04…



…Example 04…

- Closed loop gains are dependent on the values of R1 and Rf.
  - Therefore, you have to calculate the closed loop gain for each new problem.

…Example 04…



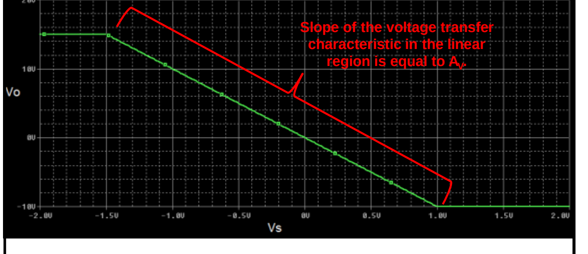
$$i_s = i_f + i_1 + i_2 = i_f$$
$$i_s = V_S / R_1$$
$$i_f = -V_o / R_f$$
$$A_v = V_o / V_s = -R_f / R_1$$
$$R_f = 10k\Omega$$
$$R_1 = 1k\Omega$$
$$A_v = -10$$

…Example 04…

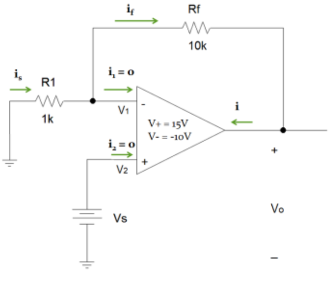
- Since A_V = -10
  - If Vs = 0V, V0 = -10(0V) = 0V
  - If Vs = 0.5V, Vo = -10(0.5V) = -5V
  - If Vs = 1V, Vo = -10(1V) = -10V
  - If Vs = 1.1V, Vo = -10(1.1V) < V^-, Vo = -10V
  - If Vs = -1.2V, V0 = -10(-1.2V) = +12V
  - If Vs = -1.51V, Vo = -10(-1.51V) > V^+, Vo = +15V

…Example 04

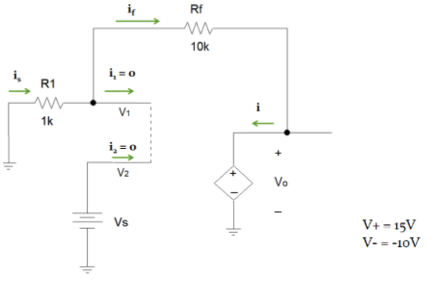
- Voltage transfer characteristic



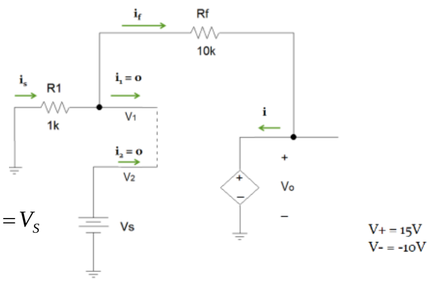
Example 05: Noninverting Amplifier…



…Example 05…



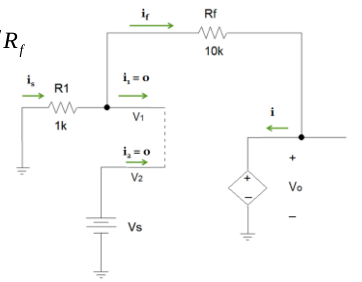
…Example 05…



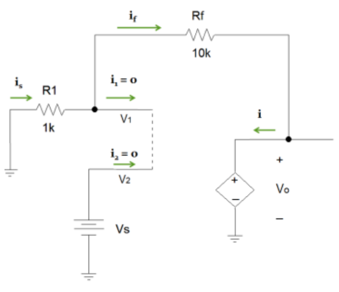
$$V_2 = V_1 = V_S$$

…Example 05…

$$i_s = -V_S / R_1$$
$$i_f = (V_S - V_o)/R_f$$
$$V_o = V_S - R_f i_f$$



…Example 05: Noninverting Amplifier…



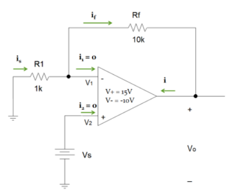
$$i_f = i_s$$

$$V_o = V_S - R_f i_s$$

$$V_o = R_f \frac{V_S}{R_1} + V_S$$

$$A_v = \frac{V_o}{V_S} = 1 + \frac{R_f}{R_1}$$

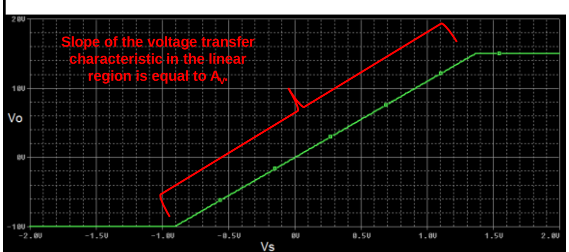
…Example 05…



- $A_V = +11$
  - If Vs = 0V, V0 = 11(0V) = 0V
  - If Vs = 0.5V, Vo = 11(0.5V) = +5.5V
  - If Vs = 1.6V, Vo = 11(1.6V) > V^+, Vo = +15V
  - If Vs = -0.9V, V0 = 11(-0.9V) = -9.9V
  - If Vs = -1.01V, Vo = 11(-1.01V) > V^+ Vo = +15V

…Example 05

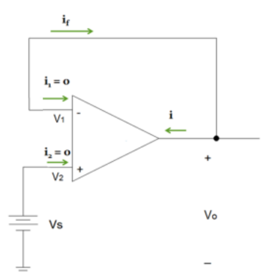
- Voltage transfer characteristic



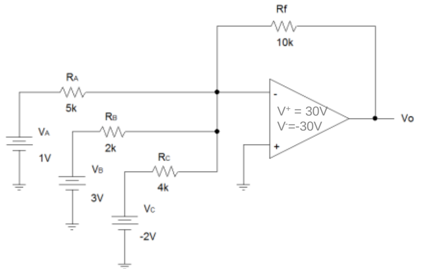
Example 06: Voltage Follower

A voltage follower is a noninverting amplifier where $R_f = 0\Omega$ and $R_1 = \infty\Omega$.

$V_o/V_s = 1 + R_f/R_1 = 1 + 0 = 1$

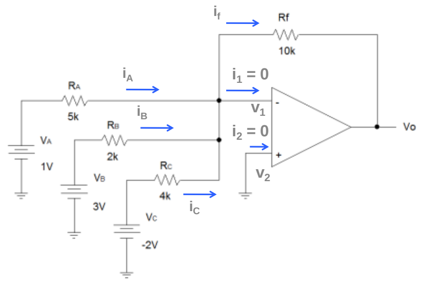


Example 07: Summing Amplifier…



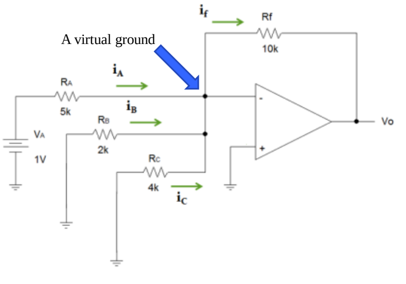
A summing amplifier is an inverting amplifier with multiple inputs.

…Example 07…

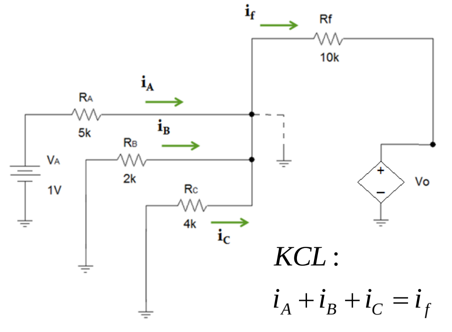


We apply superposition to obtain a relationship between Vo and the input voltages.

…Example 07…



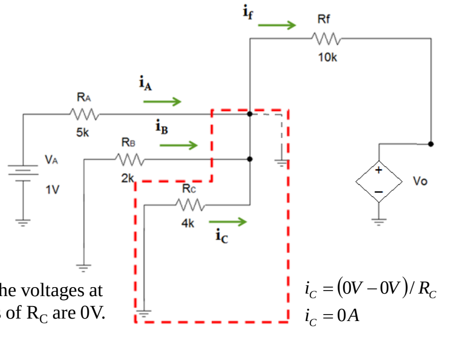
…Example 07…



$KCL:$

$$i_A + i_B + i_C = i_f$$

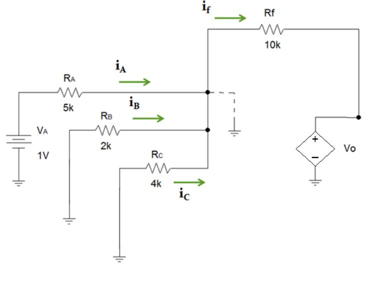
…Example 07…



Note that the voltages at both nodes of R_C are 0V.

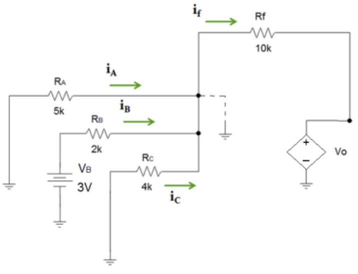
$$i_C = (0V - 0V)/R_C$$
$$i_C = 0A$$

…Example 07…



$$i_A + i_B + i_C = i_f$$
$$i_A = i_f$$
$$i_A = (V_A - 0V)/R_A$$
$$i_f = (0V - V_o)/R_f$$
$$V_o = -\frac{R_f}{R_A} V_A$$

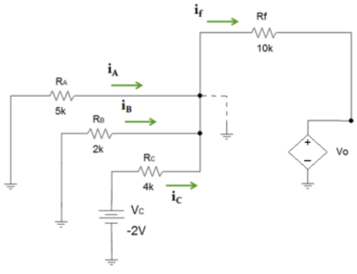
…Example 07…



$$i_A = i_C = 0$$
$$i_B = i_f$$
$$i_B = (V_B - 0V)/R_B$$
$$i_f = (0V - V_o)/R_f$$
$$V_o = -\frac{R_f}{R_B} V_B$$

61

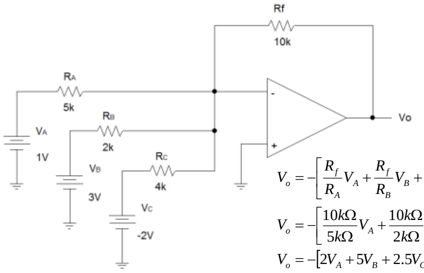
…Example 07…



$$i_A = i_B = 0$$
$$i_C = i_f$$
$$i_C = (V_C - 0V)/R_C$$
$$i_f = (0V - V_o)/R_f$$
$$V_o = -\frac{R_f}{R_C} V_C$$

62

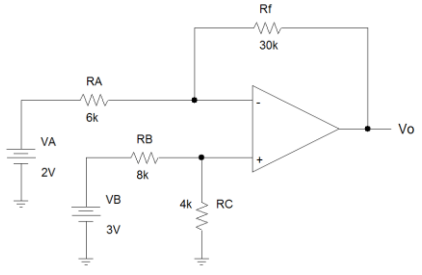
…Example 07



$$V_o = -\left[\frac{R_f}{R_A} V_A + \frac{R_f}{R_B} V_B + \frac{R_f}{R_C} V_C\right]$$
$$V_o = -\left[\frac{10k\Omega}{5k\Omega} V_A + \frac{10k\Omega}{2k\Omega} V_B + \frac{10k\Omega}{4k\Omega} V_C\right]$$
$$V_o = -[2V_A + 5V_B + 2.5V_C]$$
$$V_o = -[2(1V) + 5(3V) + 2.5(-2V)]$$
$$V_o = -12V$$

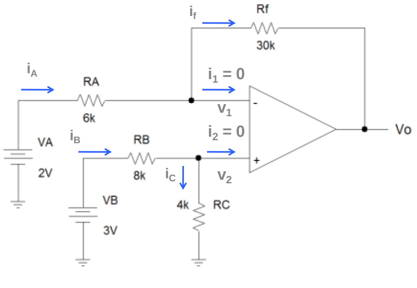
63

Example 08: Difference Amplifier…



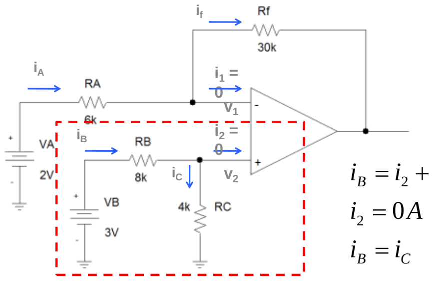
64

…Example 08…



65

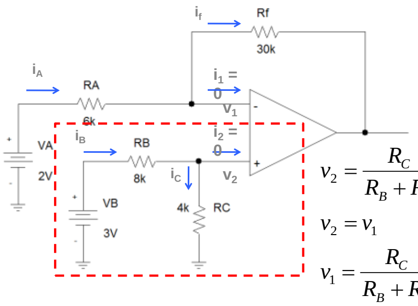
…Example 08…



$$i_B = i_2 + i_C$$
$$i_2 = 0A$$
$$i_B = i_C$$

66

…Example 08…

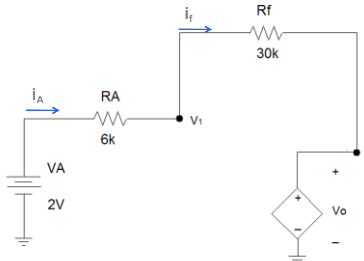


$$v_2 = \frac{R_C}{R_B + R_C} V_B$$

$$v_2 = v_1$$

$$v_1 = \frac{R_C}{R_B + R_C} V_B$$

…Example 08…



$$v_1 = \frac{R_C}{R_B + R_C} V_B$$

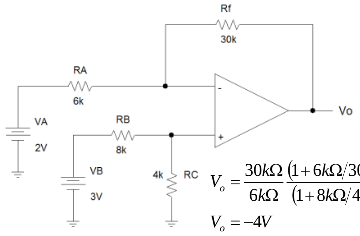
$$i_A = (V_A - v_1)/R_A$$

$$i_A = i_f$$

$$i_f = (v_1 - V_o)/R_f$$

…Example 08…

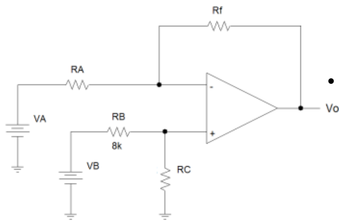
$$V_o = \frac{R_f}{R_A}\frac{(1+R_A/R_f)}{(1+R_B/R_C)}V_B - \frac{R_f}{R_A}V_A$$



$$V_o = \frac{30k\Omega}{6k\Omega}\frac{(1+6k\Omega/30k\Omega)}{(1+8k\Omega/4k\Omega)}(3V) - \frac{30k\Omega}{6k\Omega}(2V)$$

$$V_o = -4V$$

…Example 08



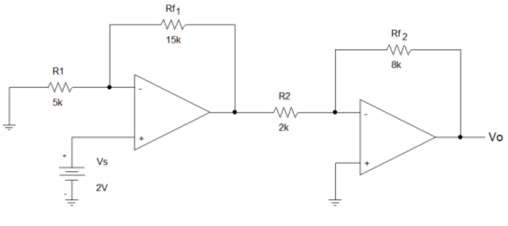
- If $R_A/R_f = R_B/R_C$

$$V_o = \frac{R_f}{R_A}(V_B - V_A)$$

- And if $R_A = R_f$

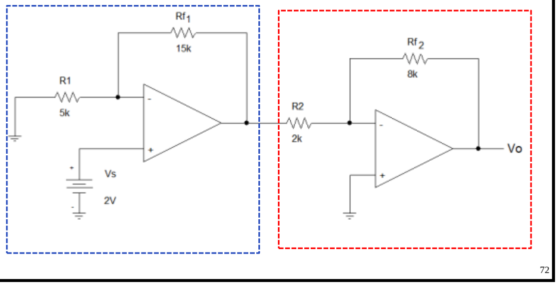
$$V_o = V_B - V_A$$

Example 09: Cascading Op Amps…



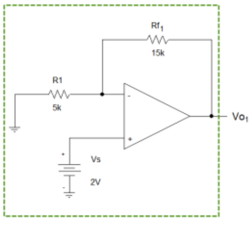
…Example 09…

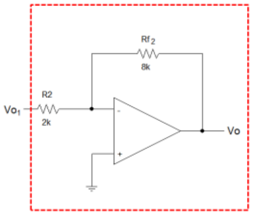
- Treat as two separate amplifier circuits



…Example 09…

1st Circuit **2nd Circuit**

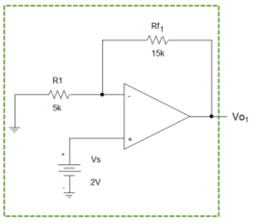




73

…Example 09…

- It is a noninverting amplifier.



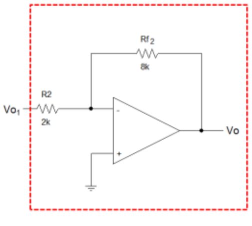
$$V_{o1} = \left(1 + \frac{R_{f1}}{R_1}\right) V_S$$

$$A_{V1} = \frac{V_{o1}}{V_S} = \left(1 + \frac{R_{f1}}{R_1}\right)$$

74

…Example 09…

- It is a inverting amplifier.



$$V_o = -\frac{R_{f2}}{R_2} V_{01}$$

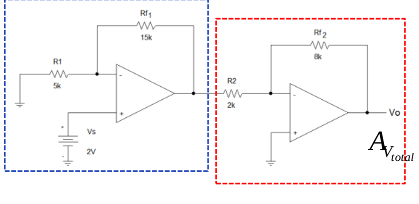
$$A_{V2} = \frac{V_o}{V_{01}} = -\frac{R_{f2}}{R_2}$$

75

…Example 09…

- The gain of the cascaded amplifiers is the multiplication of the two individual amplifiers

$$V_o = -\frac{R_{f2}}{R2} V_{01} = -\frac{R_{f2}}{R_2}\left(1 + \frac{R_{f2}}{R_1}\right) V_S$$



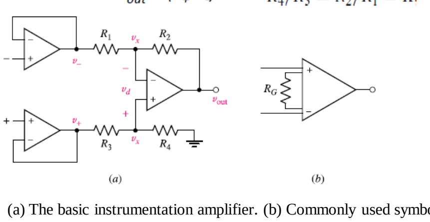
$$A_{V_{total}} = A_{V1} A_{V2}$$

76

Instrumentation amplifier

- This device allows precise amplification of small voltage differences:

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



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

77

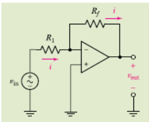
Summary

- The 'almost ideal' op amp model:
  - Ri = ∞Ω.
    - $i_1 = i_2 = 0A$; $v_1 = v_2$
  - Ro = 0Ω.
    - 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.

78

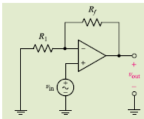
Summary of Basic Op Amp Circuits

Inverting Amplifier



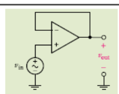
$v_{out} = -\frac{R_f}{R_1} v_{in}$

Noninverting Amplifier



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

Voltage Follower (also known as a Unity Gain Amplifier)

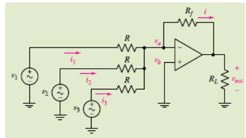


$v_{out} = v_{in}$

79

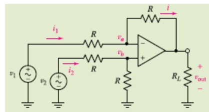
Summary of Basic Op Amp Circuits

Summing Amplifier



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

Difference Amplifier



$v_{out} = v_2 - v_1$

80