Op-Amps

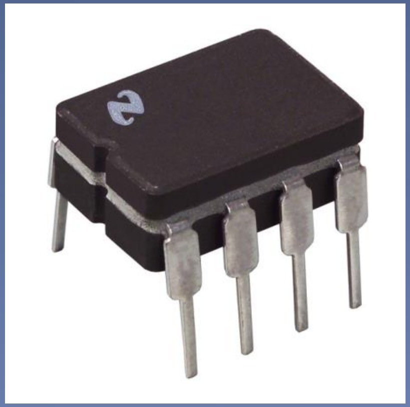
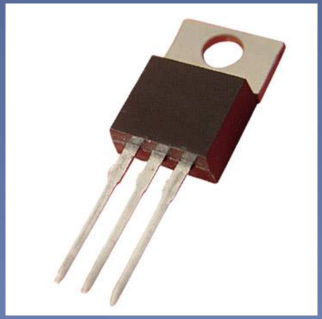
…and why they are useful to us

Outline of Presentation

- What is an Op-Amp?
- Characteristics of Ideal and Real Op-Amps
- Common Op-Amp Circuits
- Applications of Op-Amps
- References

What is an Op-Amp?

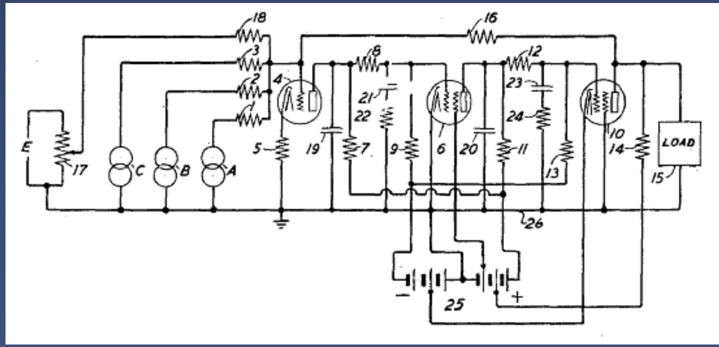
- An *Operational Amplifier* (known as an "Op-Amp") is a device that is used to amplify a signal using an external power source
- Op-Amps are generally composed of:
  - Transistors, Resistors, Capacitors


=

+

+

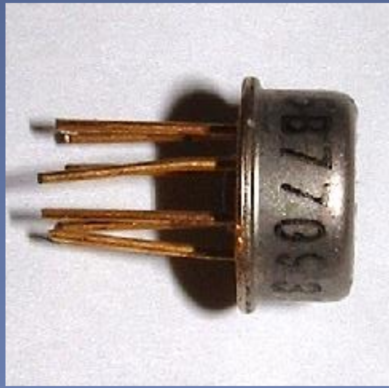

Brief History

- First patent for Vacuum Tube Op-Amp (1946)



- First Commercial Op-Amp available (1953)

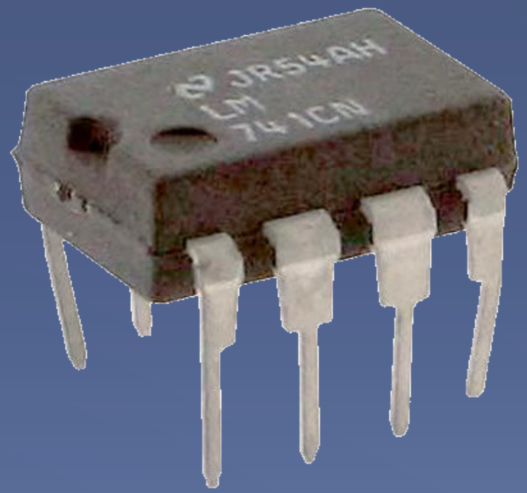
- First discrete IC Op-Amps (1961)



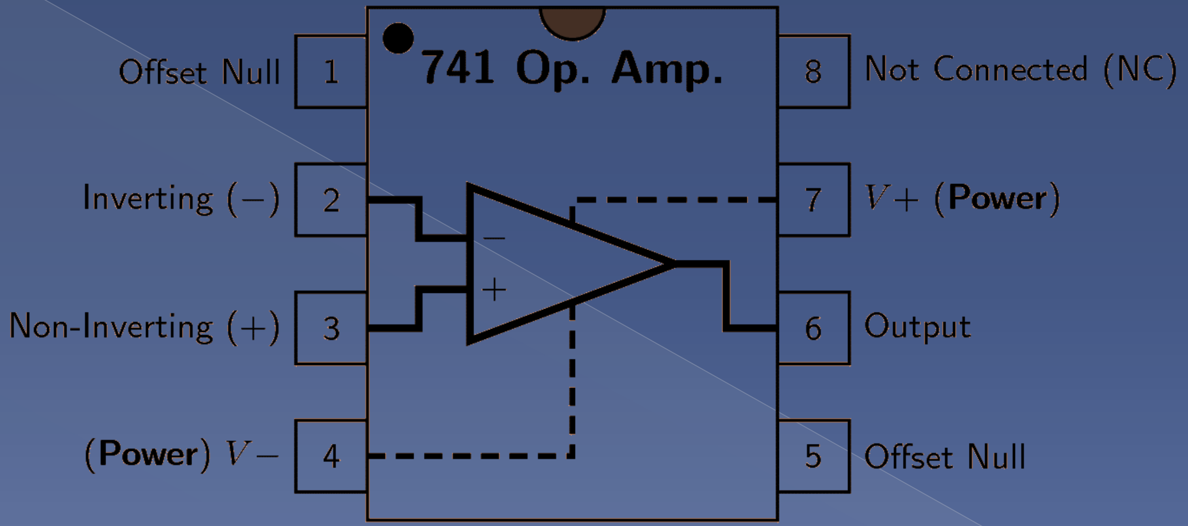
- First commercially successful Monolithic Op-Amps (1965)

Design

• Leading to the advent of the modern IC which is still used even today (1967 – present)



Fairchild μA741



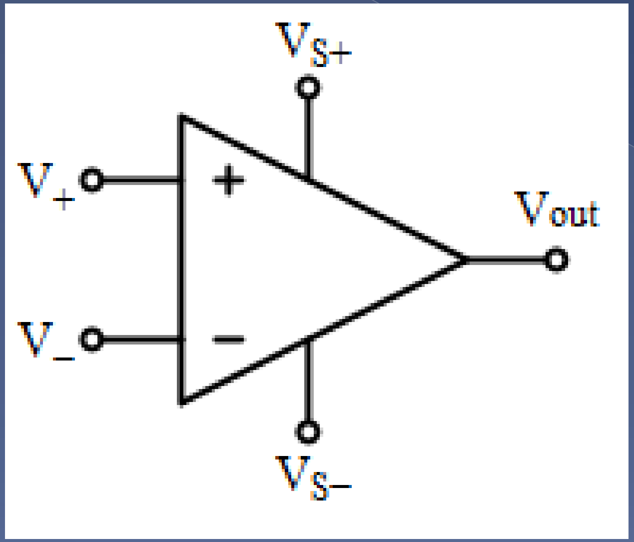
Electrical Schematic of μA741

BLOCK DIAGRAM OF OPAMP

- **The Input Stage**
- The input stage consisting of "Dual Input Balanced Output Differential Amplifier"
  This stage Determines the Input Impedence of Operational Amplifier, having two inputs Inverting and Non-Inverting. In this stage Differential amplifiers with a constant current source is used inorder to Increase the CMRR (common mode rejection ratio).
  The Intermediate Stage
- This stage also posses Two inputs but having only One Output. It is usually another Differential amplifier, which is driven by the preceding Output.
  This stage is commonly used to Increase the gain of amplifier. In the quiescent condition some dc error voltage may appears on the Output of This stage.
  The Level Shifting stage
- This stage is usually an Emitter Follower circuit in order to shift the error dc Level of preceding stage.This stage eliminate the chance of signal distortions.
  The Output Stage
- It is final Stage of an Operational amplifier, it is usually a complementary symmetry push pull Amplifier.
  This Stage Increases the Output voltage swing and the current delivering capabilities.
  It also essential for providing low output Impedence.

Op-Amps and their Math

A traditional Op-Amp:



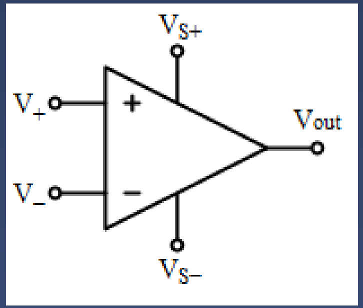
V_+ : non-inverting input
V_- : inverting input
V_{out} : output
V_{S+} : positive power supply
V_{S-} : negative power supply

$$\boxed{V_{out} = K\,(V_+ - V_-)}$$

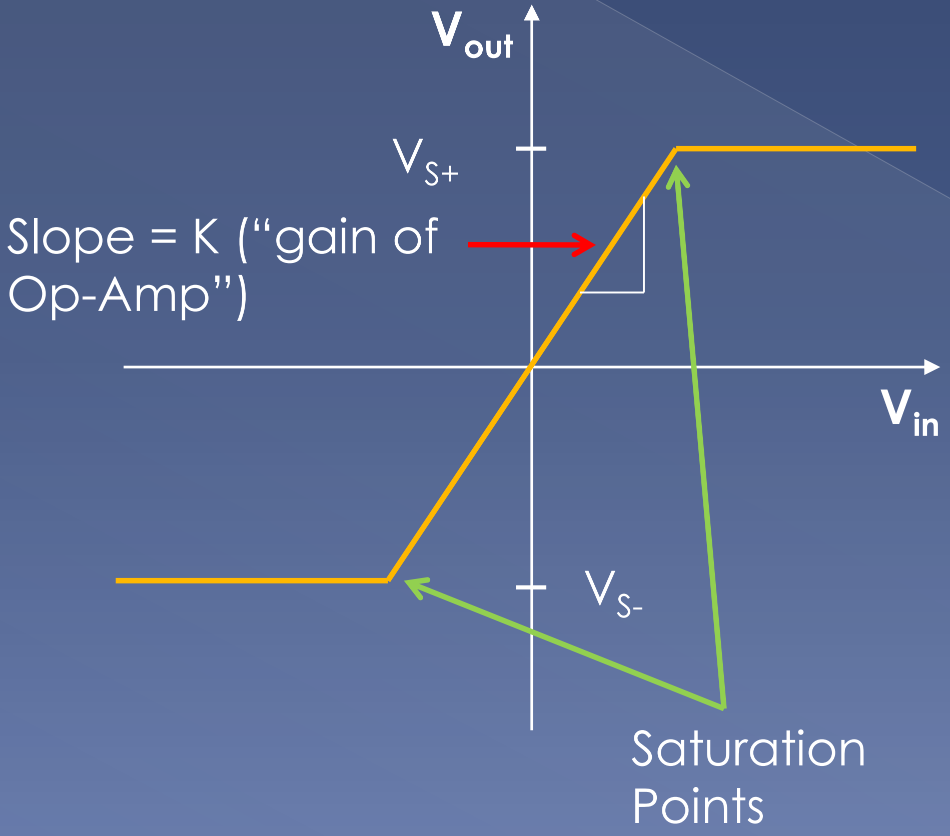
- The difference between the two inputs voltages (V_+ and V_-) multiplied by the gain (K, "amplification factor") of the Op-Amp gives you the output voltage

- The output voltage can only be as high as the <u>difference</u> between the power supply (V_{S+} / V_{S-})and ground (0 Volts)

Saturation



Saturation is caused by increasing/decreasing the input voltage to cause the output voltage to equal the power supply's voltage*



The slope is normally much steeper than it is shown here. Potentially just a few milli-volts (mV) of change in the difference between V_+ and V_- could cause the op-amp to reach the saturation level

* Note that saturation level of traditional Op-Amp is 80% of supply voltage with exception of CMOS op-amp which has a saturation at the power supply's voltage

Outline of Presentation

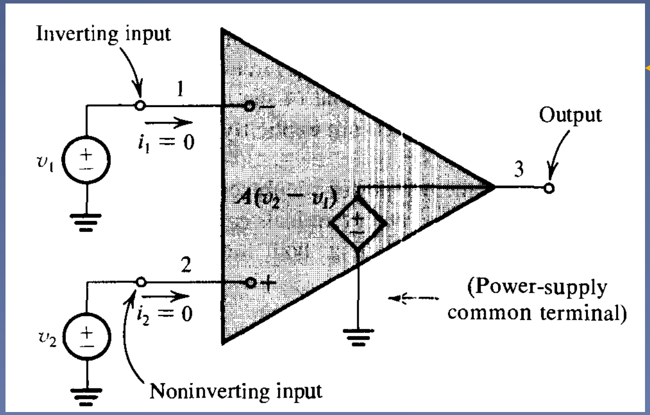
- What is an Op-Amp?
- Characteristics of Ideal and Real Op-Amps
- Common Op-Amp Circuits
- Applications of Op-Amps
- References

An Ideal Op-Amp Characteristics:

- Infinite voltage gain
- Infinite input impedance
- Zero output impedance
- Infinite bandwidth
- Zero input offset voltage (i.e., exactly zero out if zero in).
- Infinite CMRR(common mode rejection ratio=Ad/Ac)
- Infinite slew rate
- Zero Noise

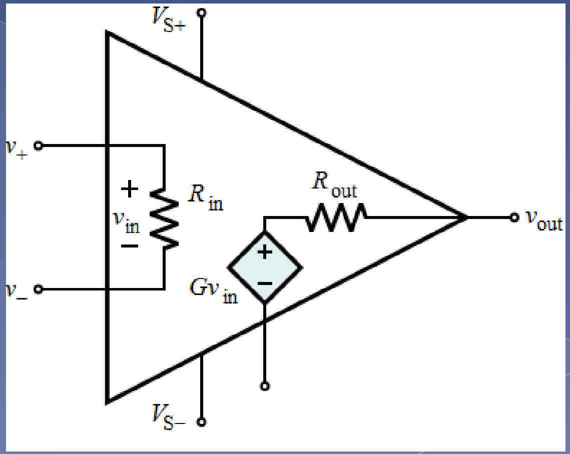
Ideal versus Real Op-Amps

Parameter	Ideal Op-Amp	Real Op-Amp
Differential Voltage Gain	∞	10^5 - 10^9
Gain Bandwidth Product (Hz)	∞	1-20 MHz
Input Resistance (R)	∞	10^6 - 10^{12} Ω
Output Resistance (R)	0	100 - 1000 Ω



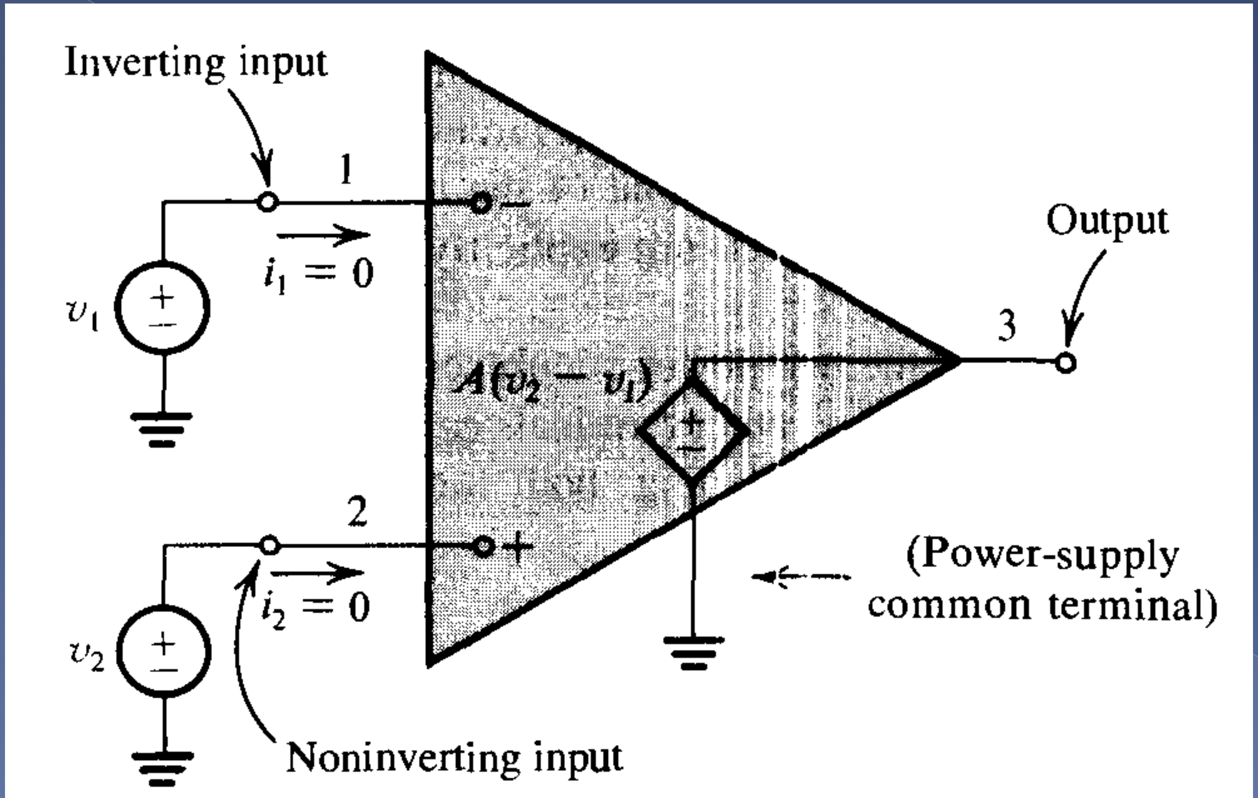
Ideal

Real



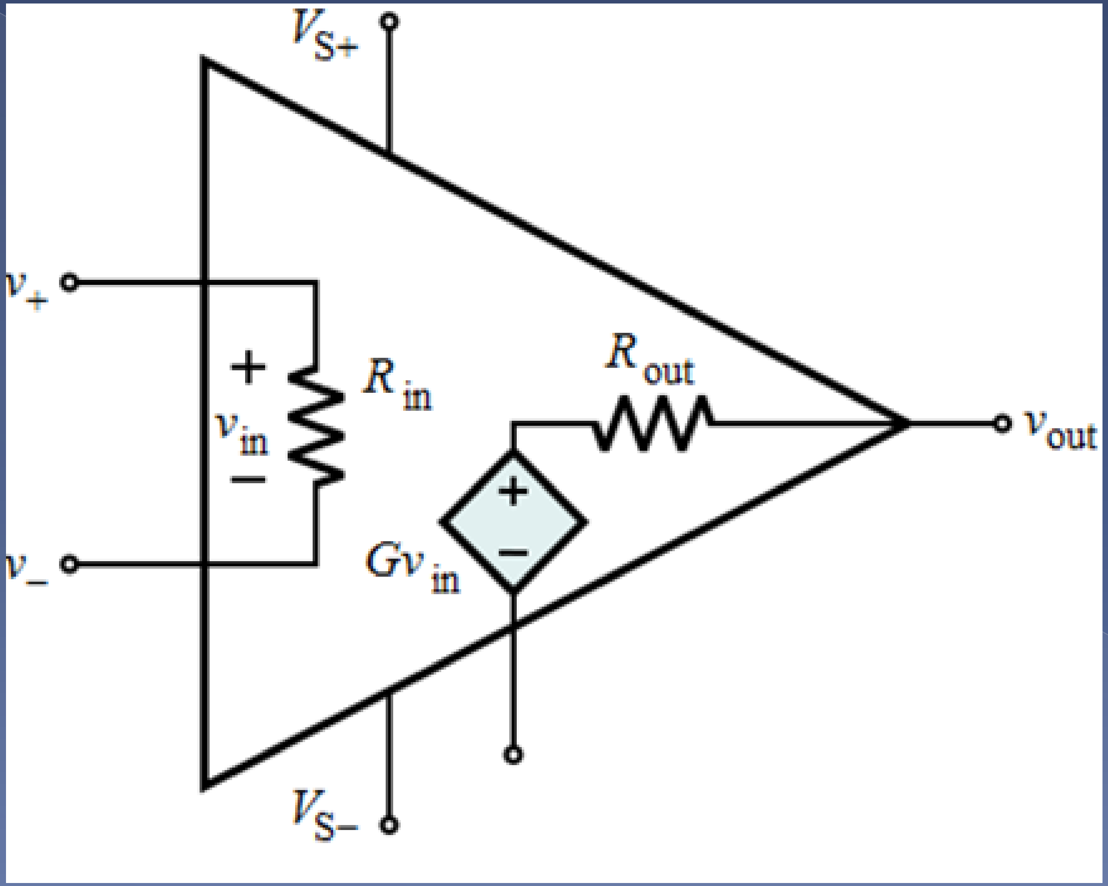
http://hyperphysics.phy-astr.gsu.edu/hbase/electronic/opamp.html#c4

Ideal Op-Amp



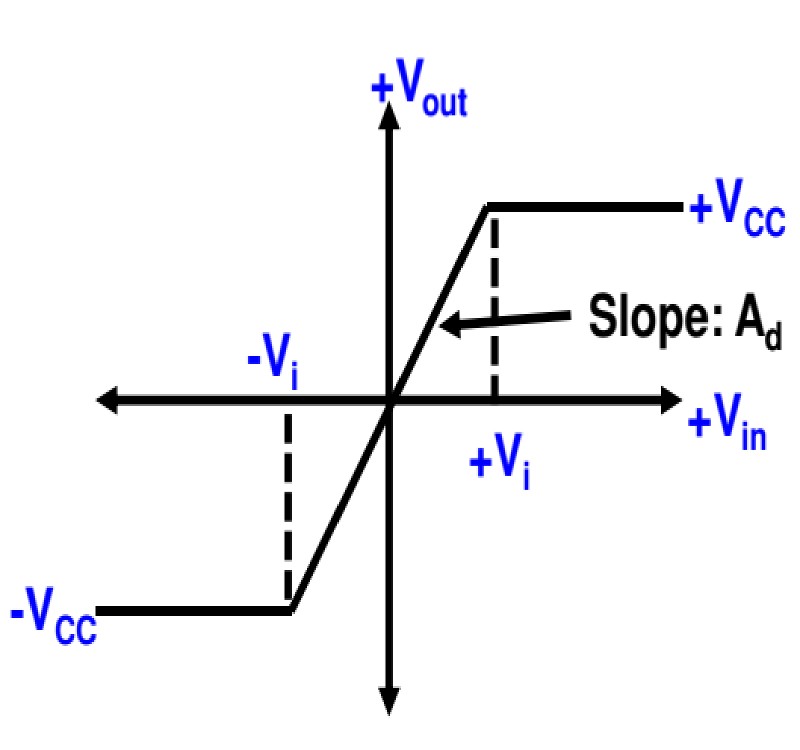
Inverting input
1
$i_1 = 0$
v_1
+
−
$A(v_2 - v_1)$
+
−
Output
3
2
+
$i_2 = 0$
v_2
(Power-supply
common terminal)
Noninverting input

Practical Op-Amp



Virtual Ground Concept

- An Op-Amp has a very high gain typically order of 10^5.
- If power supply voltage V_{CC} =15V
- Then maximum input voltage which can be applied

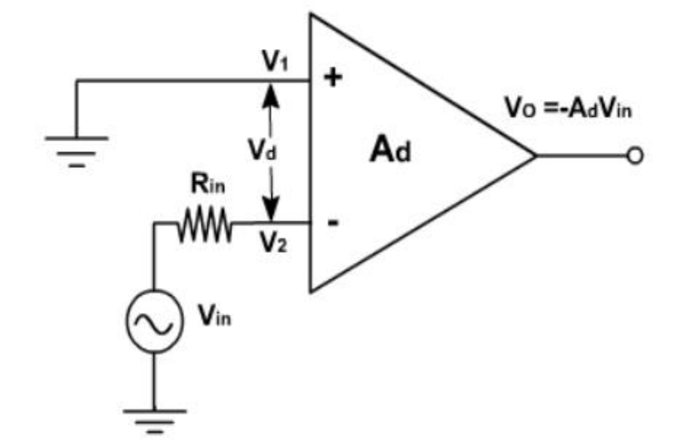


$V_d = V_{CC} / A_d = 15/10^5 = 150\mu V$

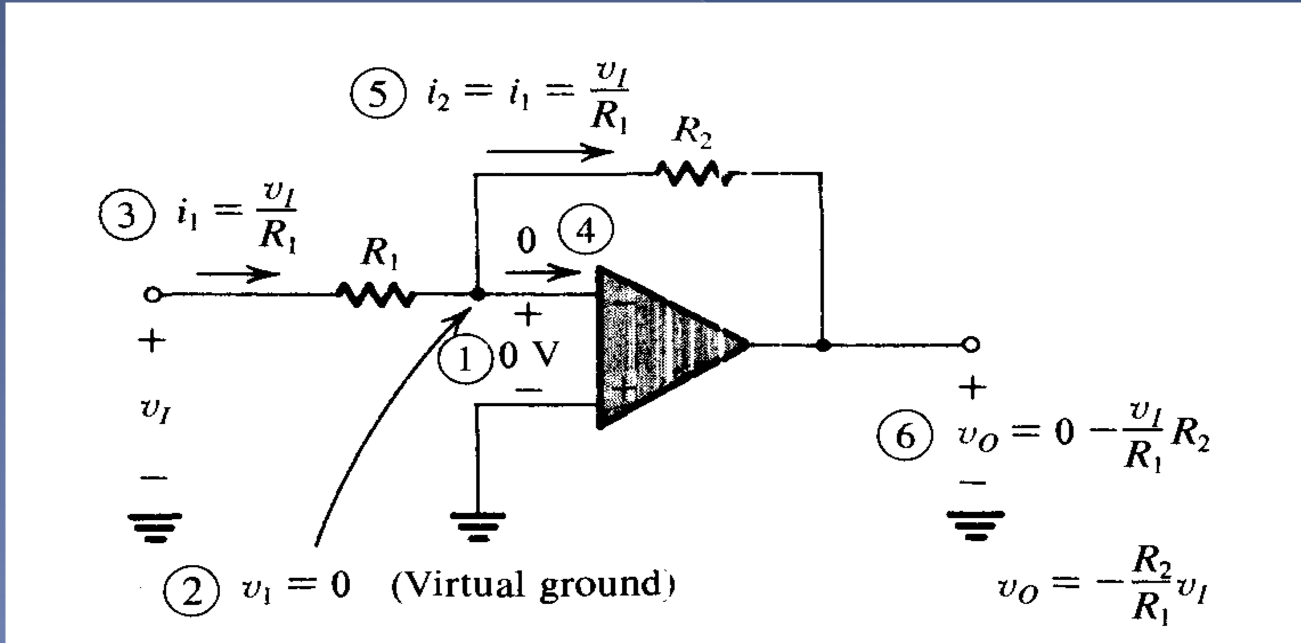
i.e. Op-Amp can work as a linear amplifier (from +Vi to –Vi), if input voltage is less than 150μV.
Above that Op-Amp saturates.

- if V1 is grounded then V2 can not be more than 150 μV which is very very small and close to ground.

- Therefore V2 can also be considered at ground if V1 is at ground. Physically V2 is not connected to the ground yet we considered V2 at ground that is called virtual ground.

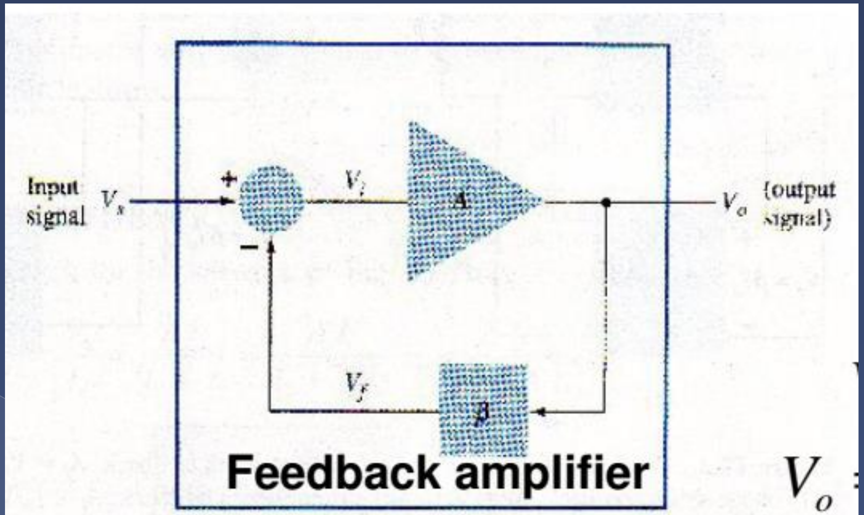


- We also speak of a "virtual short circuit" that exists between the two input terminals.
- Here the word virtual should be emphasized, and one should not make the mistake of physically shorting terminals 1 and 2 together while analyzing a circuit.
- A virtual short circuit means that whatever voltage is at 2 will automatically appear at 1 because of the infinite gain A.



Need of negative feedback in op-amp

- Any input signal slightly greater than zero drive the output to saturation level because of very high gain.
- Thus when operated in open-loop, the output of the OPAMP is either negative or positive saturation or switches between positive and negative saturation levels (comparator). Therefore open loop op-amp is not used in linear applications.
- With negative feedback, the voltage gain (A_{cl}) can be reduced and controlled so that op-amp can function as a linear amplifier.
- In addition to provide a control and stable voltage gain, negative feedback provides control of input & output impedance and amplifier bandwidth



Feedback amplifier

- If feedback signal Vf is connected in series with the input, then Vi = Vs- Vf

$$V_o = AV_i = A(V_s - V_f) \quad \text{But} \quad V_f = \beta V_o$$

$$V_o = A(V_s - \beta V_o) \qquad \boxed{V_o(1+\beta A) = AV_s}$$

A_f : closed-loop gain of the amplifier
A: Open-loop gain of the amplifier gain

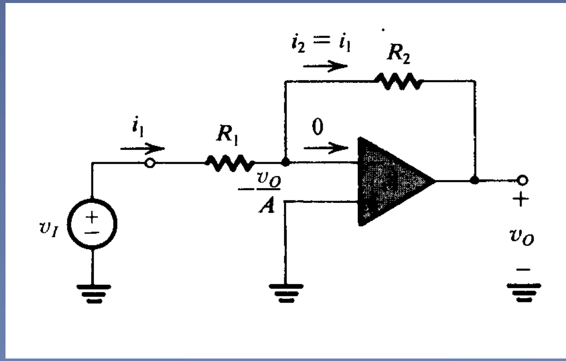
$$\boxed{A_f = \frac{V_o}{V_s} = \frac{A}{(1+\beta A)}}$$

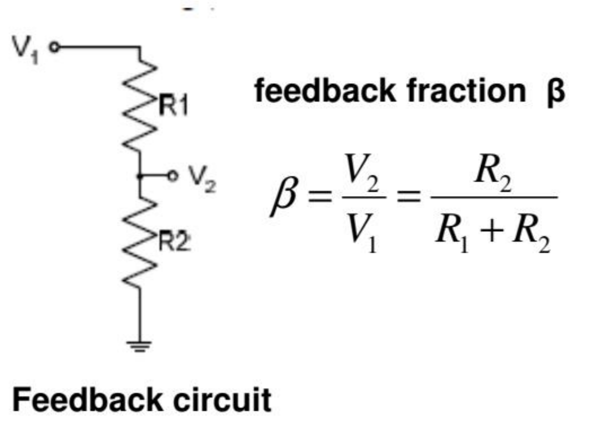
- Feedback amplifier contains two component namely feedback circuit and amplifier circuit.

- Feedback circuit is essentially a potential divider consisting of resistances R1 & R2

- The purpose of feedback circuit is to return a fraction of the output voltage to the input of the amplifier circuit.

- Feedback am





Outline of Presentation

- What is an Op-Amp?
- Characteristics of Ideal and Real Op-Amps
- Common Op-Amp Circuits
- Applications of Op-Amps
- References

Basics of an Op-Amp Circuit

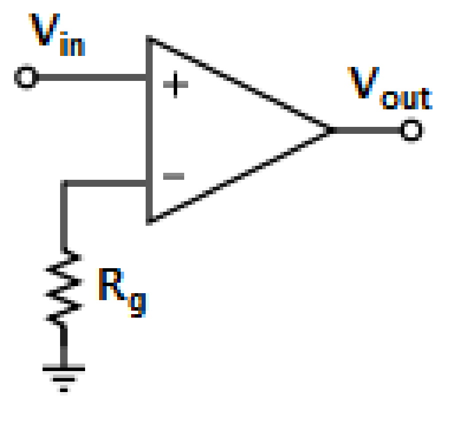
- An op-amp amplifies the difference of the inputs V_+ and V_- (known as the differential input voltage)
- This is the equation for an *open loop* gain amplifier:

$$\boxed{V_{out} = K(V_+ - V_-)}$$

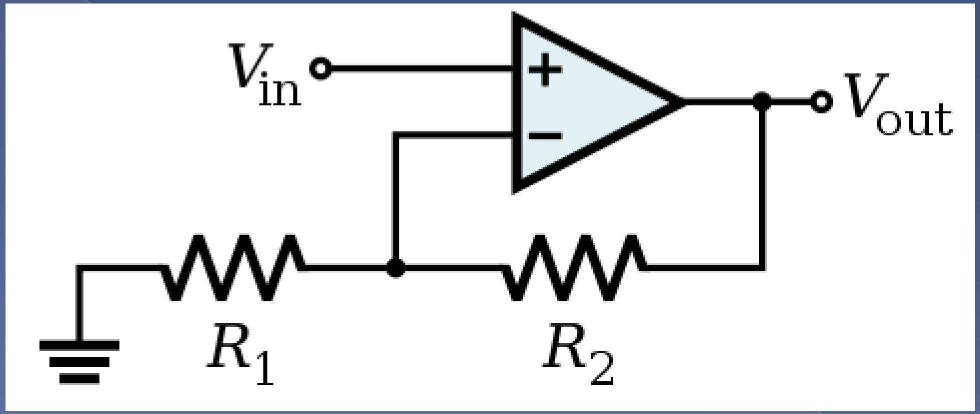
- K is typically very large – at around 10,000 or more for IC Op-Amps
- This equation is the basis for all the types of amps we will be discussing

Open Loop vs Closed Loop

- A closed loop op-amp has feedback from the output to the input, an open loop op-amp does not



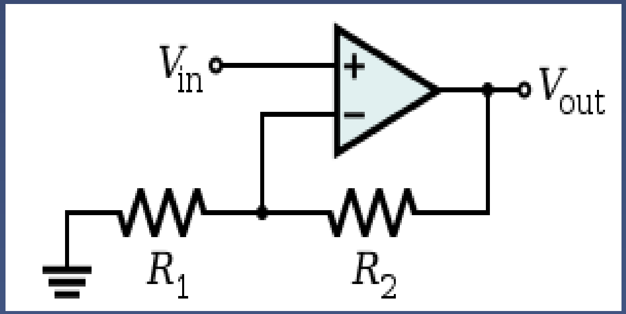
Open Loop



Closed Loop

Non-Inverting Op-Amp

- Amplifies the input voltage by a constant
- Closed loop op-amp
- Voltage input connected to non-inverting input
- Voltage output connected to inverting input through a feedback resistor
- Inverting input is also connected to ground
- Non-inverting input is only determined by voltage output



Non-Inverting Op-Amp

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

$R_1/(R_1+R_2)$ ← Voltage Divider

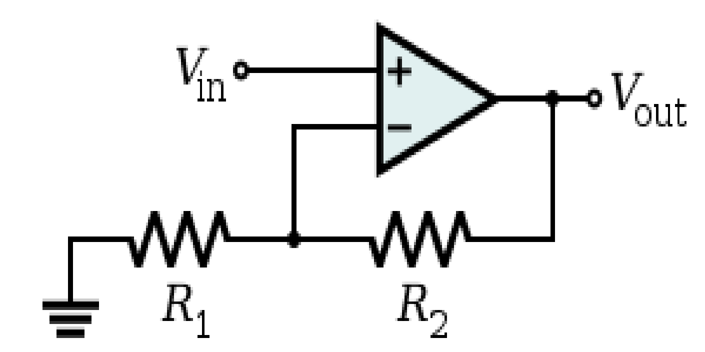
$$V_{-}=V_{out}\ (R_1/(R_1+R_2)\ )$$

$$V_{out}=[V_{in}-V_{out}\ (R_1/(R_1+R_2))]\ K$$

$$V_{out}=V_{in}/[(1/K)+\ (R_1/(R_1+R_2))]$$

As discussed previously assuming, K is very large, we have:

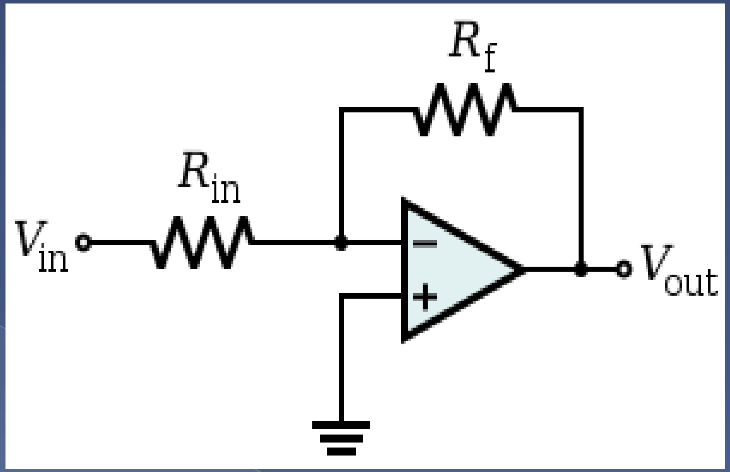
$$V_{out}=V_{in}/(R_1/(R_1+R_2))$$



$$V_{out}=V_{in}\ (1+(R_2/R_1))$$

Inverting Op-Amp

- Amplifies and inverts the input voltage
- Closed loop op-amp
- Non-inverting input is determined by *both* voltage input and output
- The polarity of the output voltage is opposite to that of the input voltage
- Voltage input is connected to inverting input
- Voltage output is connected to inverting input through a feedback resistor
- Non-inverting input is grounded



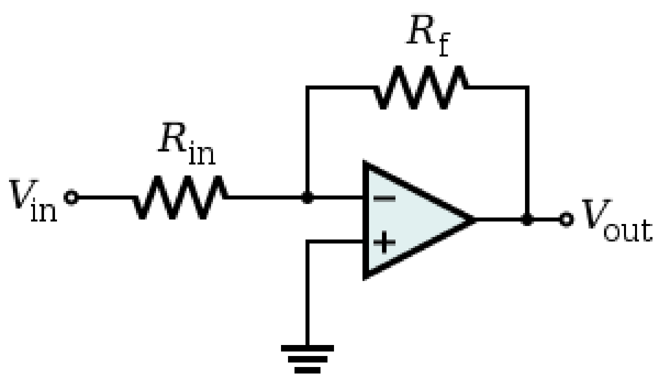
Inverting Op-Amp

$$\boxed{V_{out}=K(V_{+}-V_{-})}$$

$$V_{-}=V_{out}(R_{in}/(R_{in}+R_{f}))+V_{in}(R_{f}/(R_{in}+R_{f}))$$

Using Superposition Theorem

$$V_{-}=(V_{out}R_{in}+V_{in}R_{f})/(R_{in}+R_{f})$$



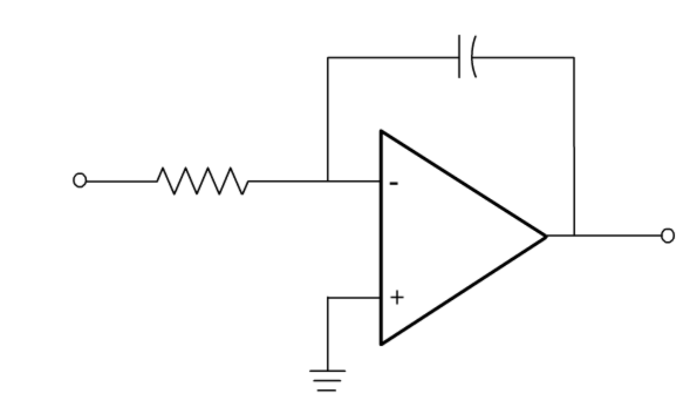
$$V_{out}=K(0-V_{-})$$

$$V_{out}=-V_{in}R_{f}/[(R_{in}+R_{f})/K+(R_{in})]$$

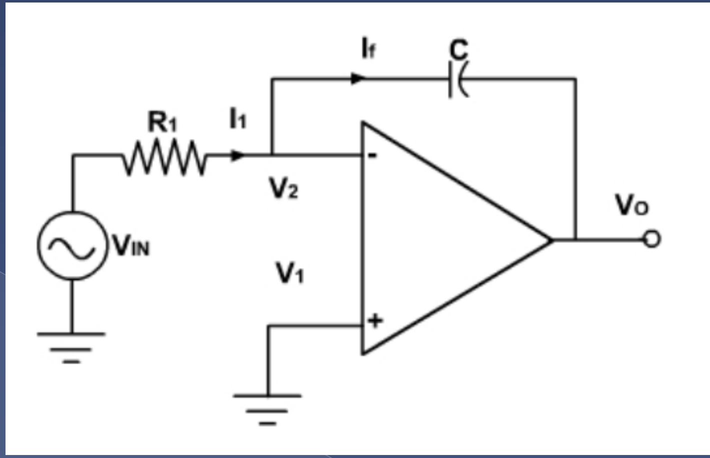
$$\boxed{V_{out}=-V_{in}R_{f}/R_{in}}$$

Integrating Op-Amp

- Integrates the inverted input signal over time
- Closed loop op-amp
- Voltage output is connected to inverting input through a *capacitor*
- The resistor and capacitor form an RC circuit
- Magnitude of the output is determined by length of time voltage is present at input
- The longer the input voltage is present, the greater the output



Integrator

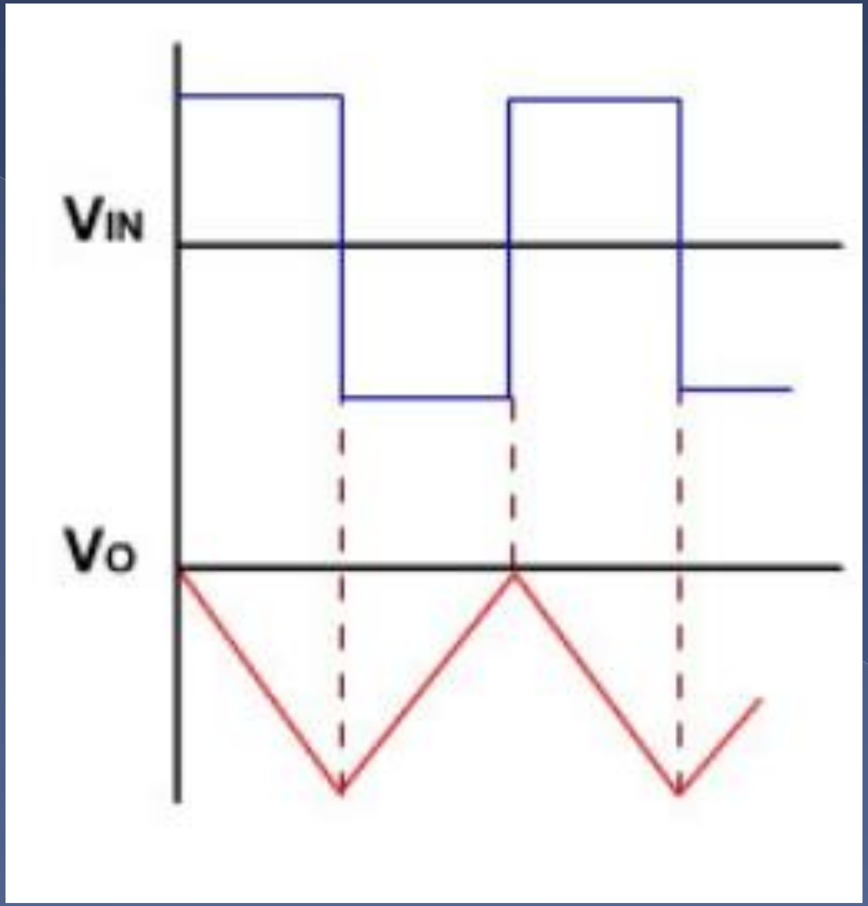


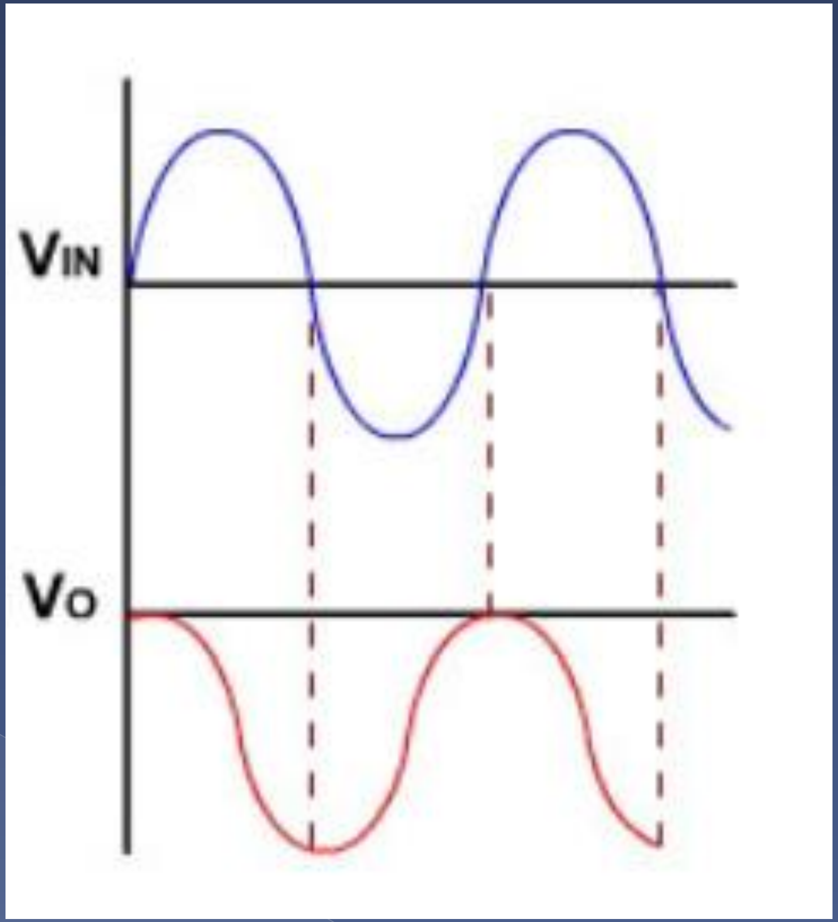
- Here, the feedback element is a capacitor. The current drawn by OPAMP is zero and V2 is virtually grounded

$$i_1 = i_f \qquad \frac{V_{in} - 0}{R_1} = C\frac{d}{dt}(0 - V_o)$$

Integrating both sides with respect to time from 0 to t, we get

$$\int_0^t \frac{V_{in}}{R_1} dt = -\int_0^t C\frac{dV_o}{dt} \qquad \boxed{V_o = \frac{-1}{R_1 C}\int_0^t V_{in} dt}$$





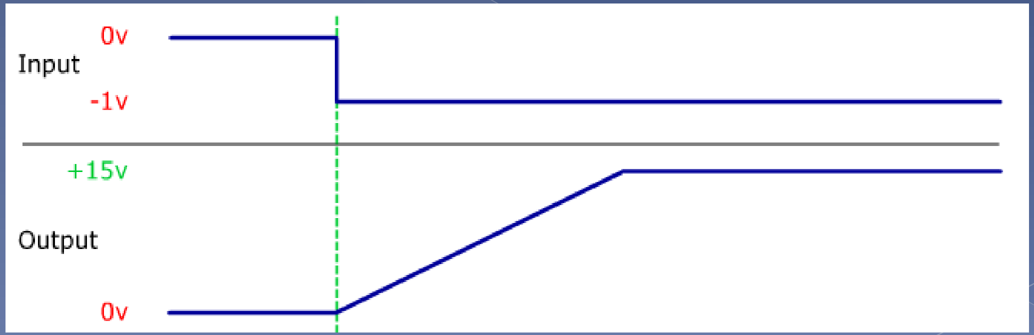
For accurate integration, the time period of the input signal T must be longer than or equal to R1C.

Integrating Op-Amp

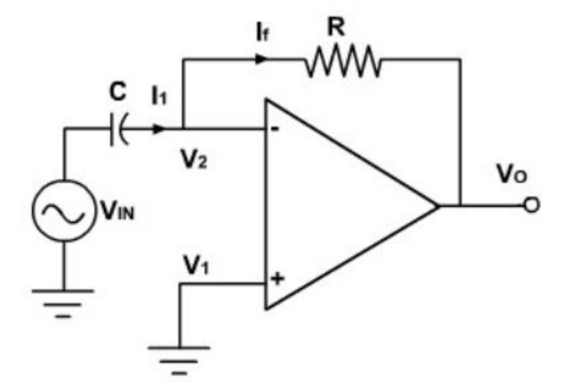
- When the circuit is first connected the capacitor acts as a short. Gain is less than 1, V_{out} is 0
- As time progresses, and the capacitor charges, it's effective resistance increases. Now V_{out} is increasing as well
- When the capacitor is fully charged it acts as an open circuit with infinite resistance. Now V_{out} goes into saturation (~80% power supply voltage)
- The rate of voltage output increase depends on the RC time constant

$$V_{out} = -V_{in} R_C / R_{in}$$

$$V_{out} = -\frac{1}{RC}\int_0^t V_{in}(\tau)\,d\tau$$



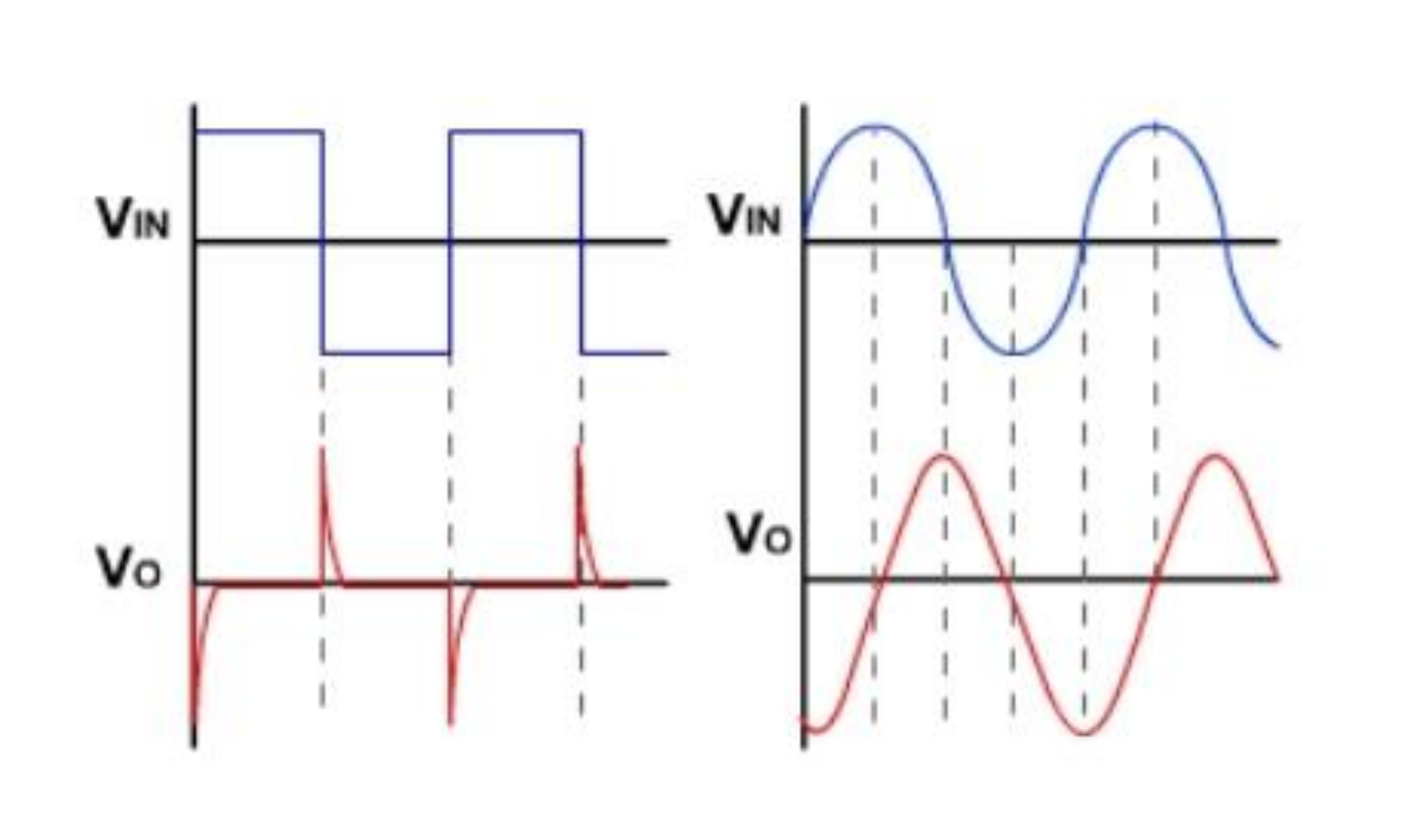
Differentiator



A circuit in which the output voltage waveform is the differentiation of input voltage is called differentiator

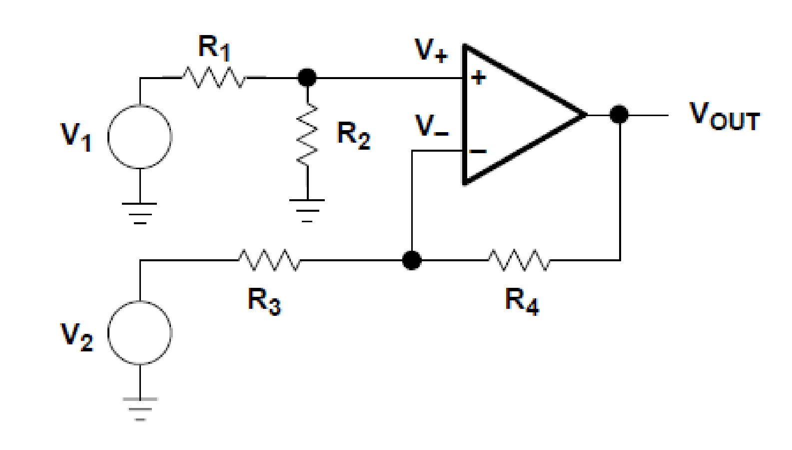
$$i_1 = i_f \quad \Rightarrow \quad C\frac{d}{dt}(V_{in} - 0) = \frac{0 - V_o}{R}$$

$$\boxed{V_o = -RC\frac{d(V_{in})}{dt}}$$



VIN
VO
VIN
VO

Differential Amplifier



Voltage relations

$$V_+ = V_1 \frac{R_2}{R_1 + R_2}$$

$$V_{OUT1} = V_+(G_+) = V_1 \frac{R_2}{R_1 + R_2}\left(\frac{R_3 + R_4}{R_3}\right)$$

- The purpose of the differential amplifier is to produce an output proportional to the difference of the input voltages
- V_+ is given by the voltage divider equation

Differential Amplifier continued

<u>Output voltage</u>

$$V_{OUT2} = V_2\left(-\frac{R_4}{R_3}\right)$$

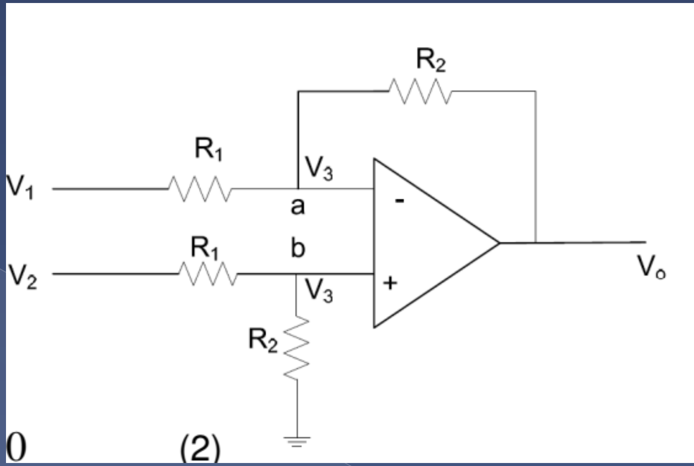
$$V_{OUT} = V_1 \frac{R_2}{R_1 + R_2}\left(\frac{R_3 + R_4}{R_3}\right) - V_2 \frac{R_4}{R_3}$$

$$V_{OUT} = \left(V_1 - V_2\right)\frac{R_4}{R_3}$$

When R2/R1=R4/R3

V_{out} as we see is the difference of voltage V1 & V2 multiplied by the resistance R4 & R3 which scales the difference

Voltage Substractor or Difference Amplifier



Applying KCL at node 'a',

$$\frac{V_1 - V_3}{R_1} = \frac{V_3 - V_o}{R_2}$$

$$\left(\frac{1}{R_1} + \frac{1}{R_2}\right)V_3 - \frac{V_1}{R_1} = \frac{V_o}{R_2} \qquad (1)$$

Applying KCL at node 'b',

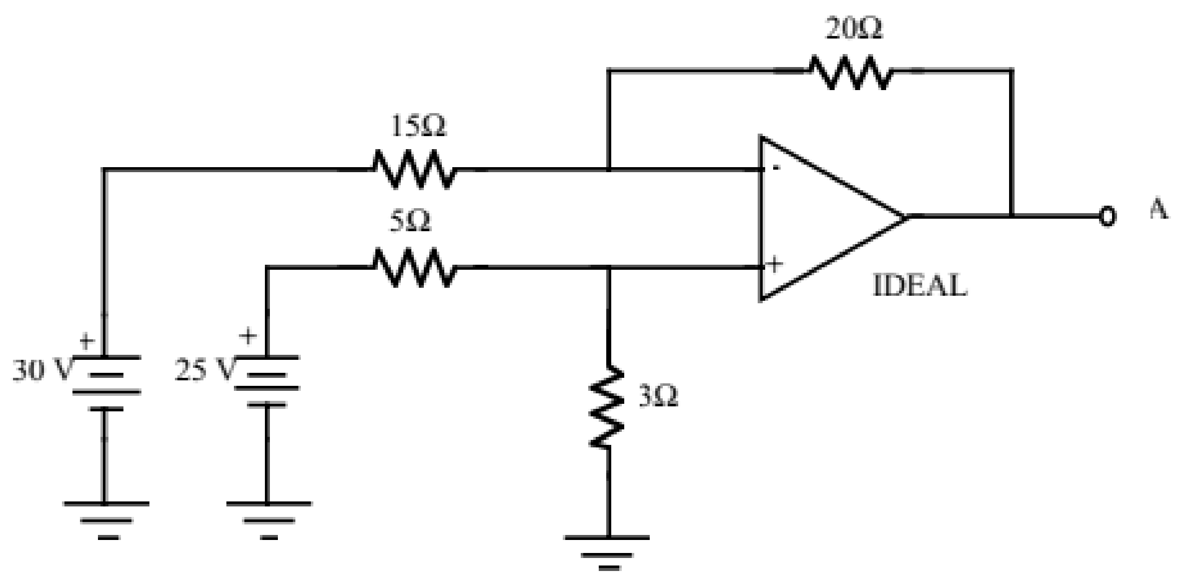
$$\frac{V_2 - V_3}{R_1} = \frac{V_3}{R_2} \qquad \left(\frac{1}{R_1} + \frac{1}{R_2}\right)V_3 - \frac{V_2}{R_1} = 0$$

Subtracting eqn. (2) from eqn.(1)

$$\frac{V_2 - V_1}{R_1} = \frac{V_0}{R_2} \qquad \boxed{V_0 = R_2\frac{(V_2 - V_1)}{R_1}}$$

Classroom problem:

For the difference amplifier circuit shown, determine the output voltage at terminal A.



By voltage division,

$$v_{in+} = 25V\left(\frac{3\Omega}{5\Omega + 3\Omega}\right) = 9.375V$$

By the virtual short circuit between the input terminals, v_{in-} = 9.375 V
Using **Ohm's** law, the current through the 15 Ω resistor is

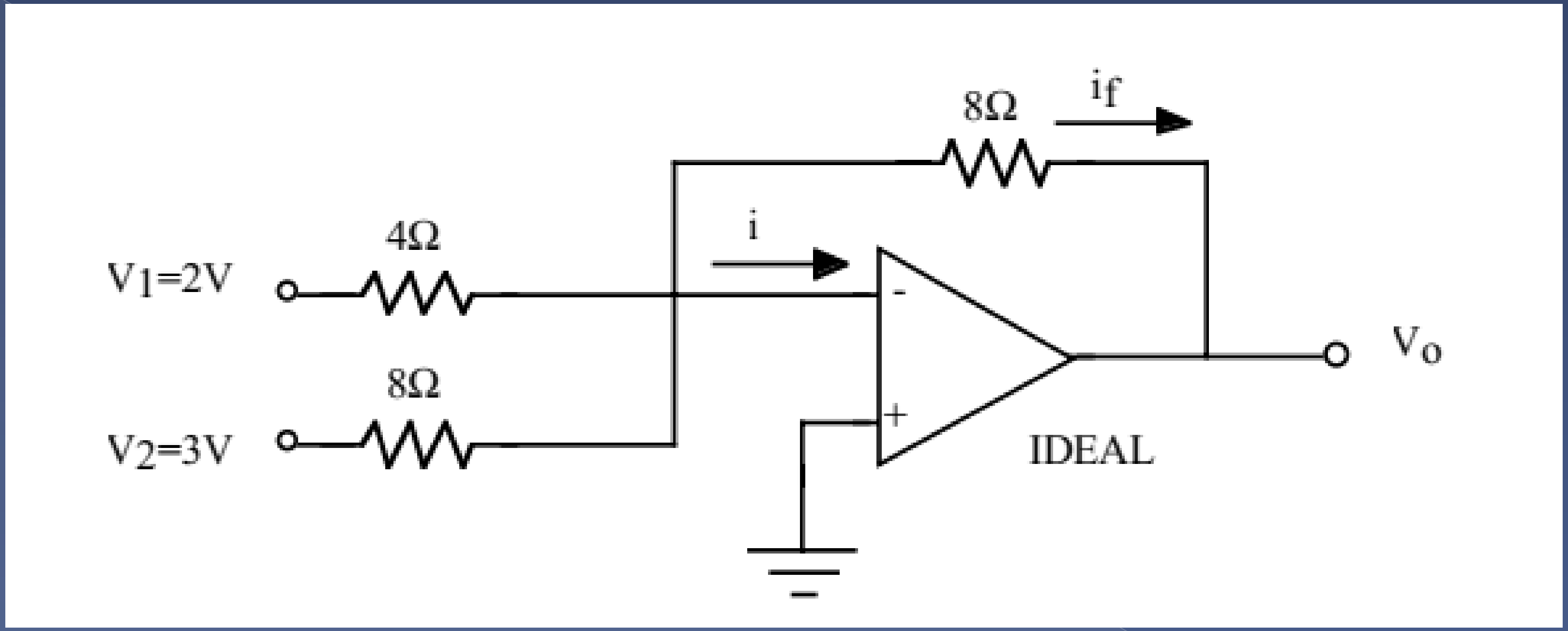
$$I_{15} = \left(\frac{30V - 9.375V}{15\Omega}\right) = 1.375V$$

The input impedance is infinite; therefore, $I_{in-}=0$ and $I_{15}=I_{20}$.

Use Kirchoff's voltage law to find the output voltage at A.

$v_A=v_{in-} - 20I_{20}$ = 9.375 V - (20Ω)(1.375 A) = -18.125 V

Classroom problem:



2. What is the current, i?

3. What is the output voltage, v_o?

Sol:

Solution 2:

The input current in an op amp is so small that it is assumed to be zero.

Solution 3:

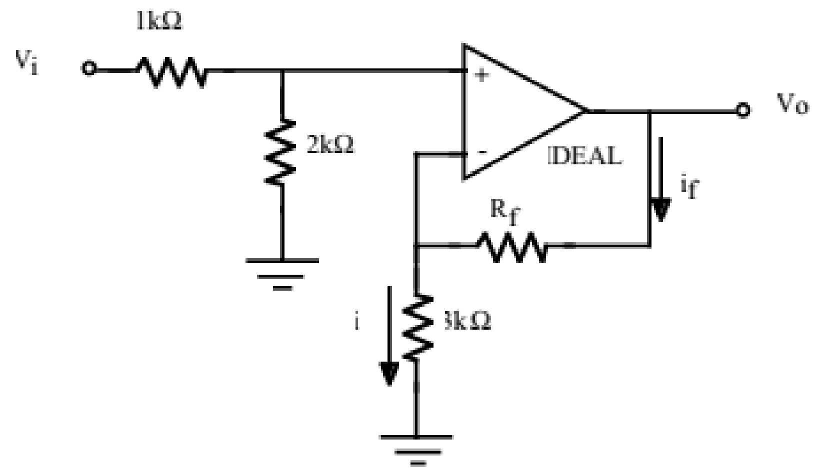
This op amp circuit is a summing amplifier. Since i=0,

$$i_f = \frac{v_1}{R_1} + \frac{v_2}{R_2} = \frac{3\ \text{V}}{8\ \Omega} + \frac{2\ \text{V}}{4\ \Omega} = 0.875\ \text{A}$$

$v_o = -i_f R_f = -(0.875\ \text{A})(8\ \Omega) = -7\ \text{V}$

Classroom problem:

4. For the ideal op amp shown, what should be the value of resistor R_f to obtain a gain of 5?



solution

Solution:

By voltage division, $v_{in+} = v_i\left(\frac{2k\Omega}{3k\Omega}\right) = \frac{2}{3}v_i$

By the virtual short circuit, $v_{in-} = v_{in+} = \frac{2}{3}v_i$

$$i = \frac{v_{in-}}{3k\Omega} = \frac{\frac{2}{3}v_i}{3k\Omega}$$

Since the op amp draws no current, i_f=i

$$\frac{v_o - v_{in-}}{R_f} = \frac{\frac{2}{3}v_i}{3k\Omega}$$

But, $v_o = 5v_i$.

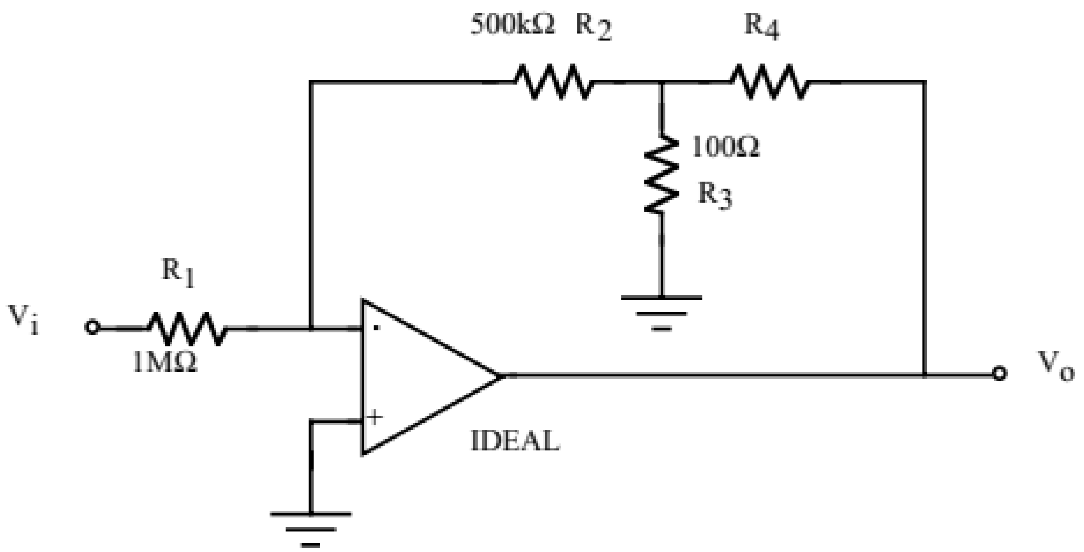
$$\frac{5v_i - \frac{2}{3}v_i}{R_f} = \frac{\frac{2}{3}v_i}{3k\Omega}$$

$$\frac{\frac{13}{3}}{R_f} = \frac{\frac{2}{3}}{3k\Omega}$$

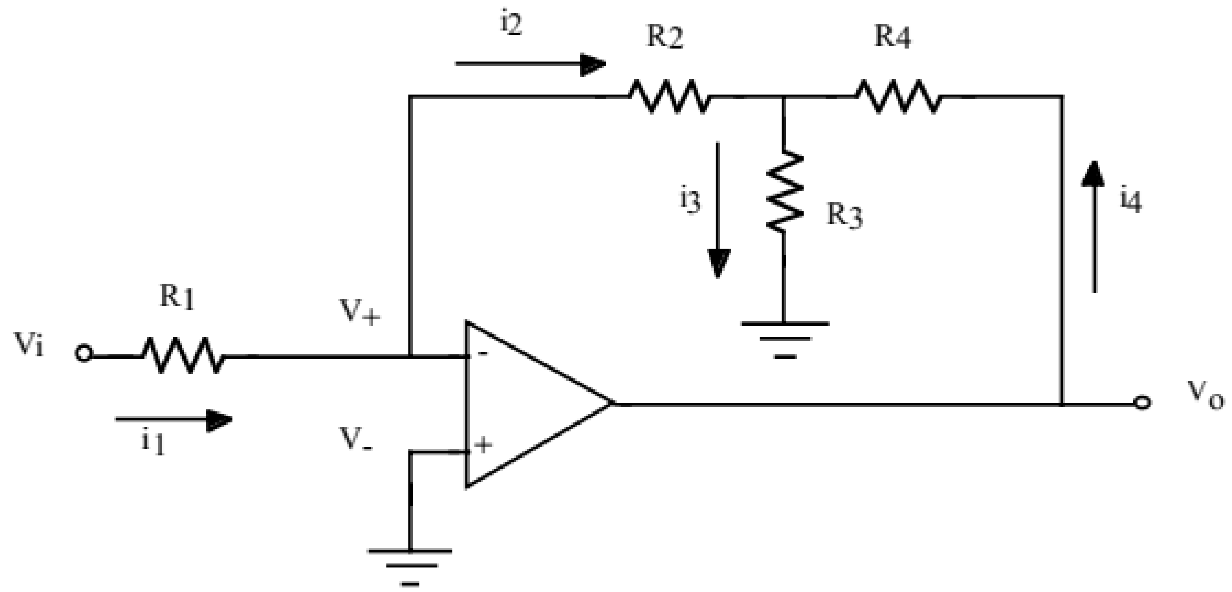
R_f=19.5 kΩ, Ans

problem

5. Evaluate the following amplifier circuit to determine the value of resistor R_4 in order to obtain a voltage gain (v_o/v_i) of -120.



Solution:



v_{in+} is grounded, so v_{in-} is also a virtual ground.

$v_{in-} = 0$

Since $v_{in-} = 0$, $v_i = i_1 R_1$ and $i_1 = v_i/R_1$.

Since $v_{in-} = 0$, $v_x = -i_2 R_2$ and $i_2 = -v_x/R_2$.

Similarly,
$v_x = -i_3 R_3$
$v_x - v_o = -i_4 R_4$

Solution

From Kirchhoff's current law,

$i_4 = i_2 + i_3$

$$\frac{v_x - v_o}{R_4} = \frac{-v_x}{R_2} + \frac{-v_x}{R_3}$$

Now, v_o=-120v_i.

Also, i_1=i_2, so

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

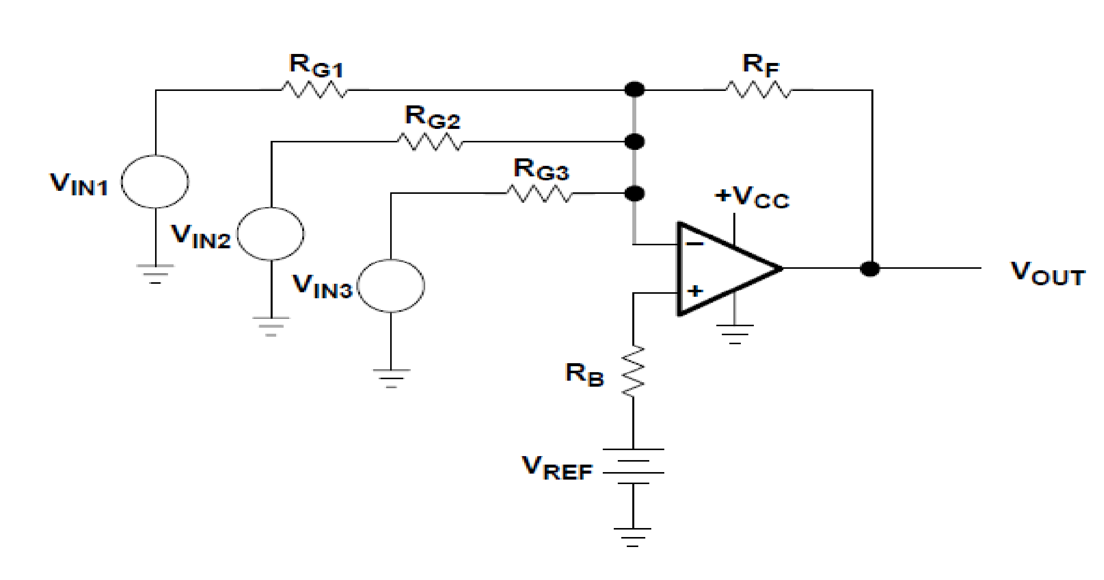
$$v_x = -\left(\frac{R_2}{R_1}\right)v_i$$

$$\frac{-\left(\frac{R_2}{R_1}\right)v_i - (-120v_i)}{R_4} = \frac{\left(\frac{R_2}{R_1}\right)v_i}{R_2} + \frac{\left(\frac{R_2}{R_1}\right)v_i}{R_3}$$

$$\frac{120\left(\frac{R_1}{R_2}\right) - 1}{R_4} = \frac{1}{R_2} + \frac{1}{R_3} = \frac{R_2 + R_3}{R_2 R_3}$$

$$R_4 = \frac{120\left(\frac{R_1}{R_2}\right) - 1}{\frac{R_2 + R_3}{R_2 R_3}} = \frac{120\left(\frac{1x10^6\,\Omega}{5x10^5\,\Omega}\right) - 1}{\frac{5x10^5\,\Omega + 100\Omega}{(5x10^5\,\Omega)(100\Omega)}} = 2.39x10^4\,\Omega\ (24\ \text{k}\Omega)$$

Summing Amplifier

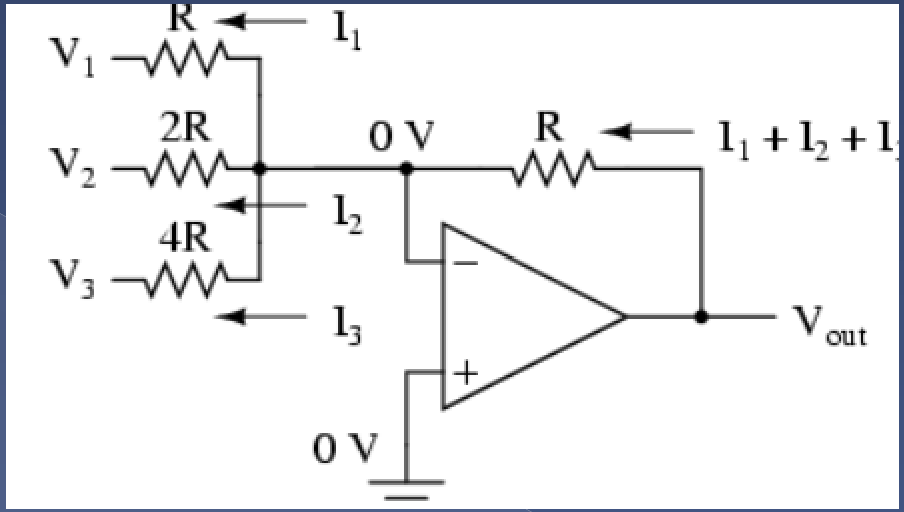


Output voltage

$$V_{OUT} = -\left(V_{IN1}\frac{R_F}{R_{G1}} + V_{IN2}\frac{R_F}{R_{G2}} + V_{IN3}\frac{R_F}{R_{G3}} + \ldots\right) + V_{REF}\left(1 + \frac{R_F}{R_{G1} \parallel R_{G2} \parallel R_{G3} \ldots}\right)$$

The summing amplifier does exactly as the name suggests by adding up the voltages given to it and producing an output voltage which is the sum of the input voltages scaled by the feedback resistance and input resistance

Summing Amplifier continued



$$V_o = -\left(\frac{R_f}{R_a}V_a + \frac{R_f}{R_b}V_b + \frac{R_f}{R_c}V_c\right)$$

Slew rate:

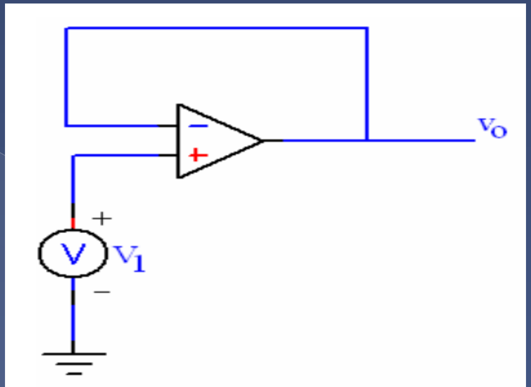
- Slew rate is defined as the maximum rate of change of output voltage per unit of time under large signal conditions and is expressed in volts / µsecs

$$\boxed{SR = \left(\frac{dV_o}{dt}\right)_{\max}}$$

- Slew rate indicates how rapidly the output of an OPAMP can change in response to changes in the input frequency with input amplitude constant. The slew rate changes with change in voltage gain and is normally specified at unity gain.

Voltage Follower

- The lowest gain that can be obtained from a non-inverting amplifier with feedback is 1



$$V_o = V_{in}$$

- When the non-inverting amplifier gives unity gain, it is called voltage follower because the output voltage is equal to the input voltage and in phase with the input voltage. In other words the output voltage follows the input voltage.

- Voltage follower has very high input impedance and very low output impedance hence used as a buffer amplifier for interfacing high impedance source and low impedance load.

Common-Mode Rejection Ratio(CMRR)

- **Differential Inputs** When separate inputs are applied to the op-amp, the resulting difference signal is the difference between the two inputs.

$$V_d = V_{i_1} - V_{i_2}$$

- **Common Inputs:** When both input signals are the same, a common signal element due to the two inputs can be defined as the average of the sum of the two signals.

$$V_c = \frac{1}{2}(V_{i_1} + V_{i_2})$$

Common-Mode Rejection Ratio(CMRR)

- **Output Voltage**

$$V_o = A_d V_d + A_c V_c$$

where V_d = difference voltage g
V_c = common voltage giv
A_d = differential gain of t
A_c = common-mode gain

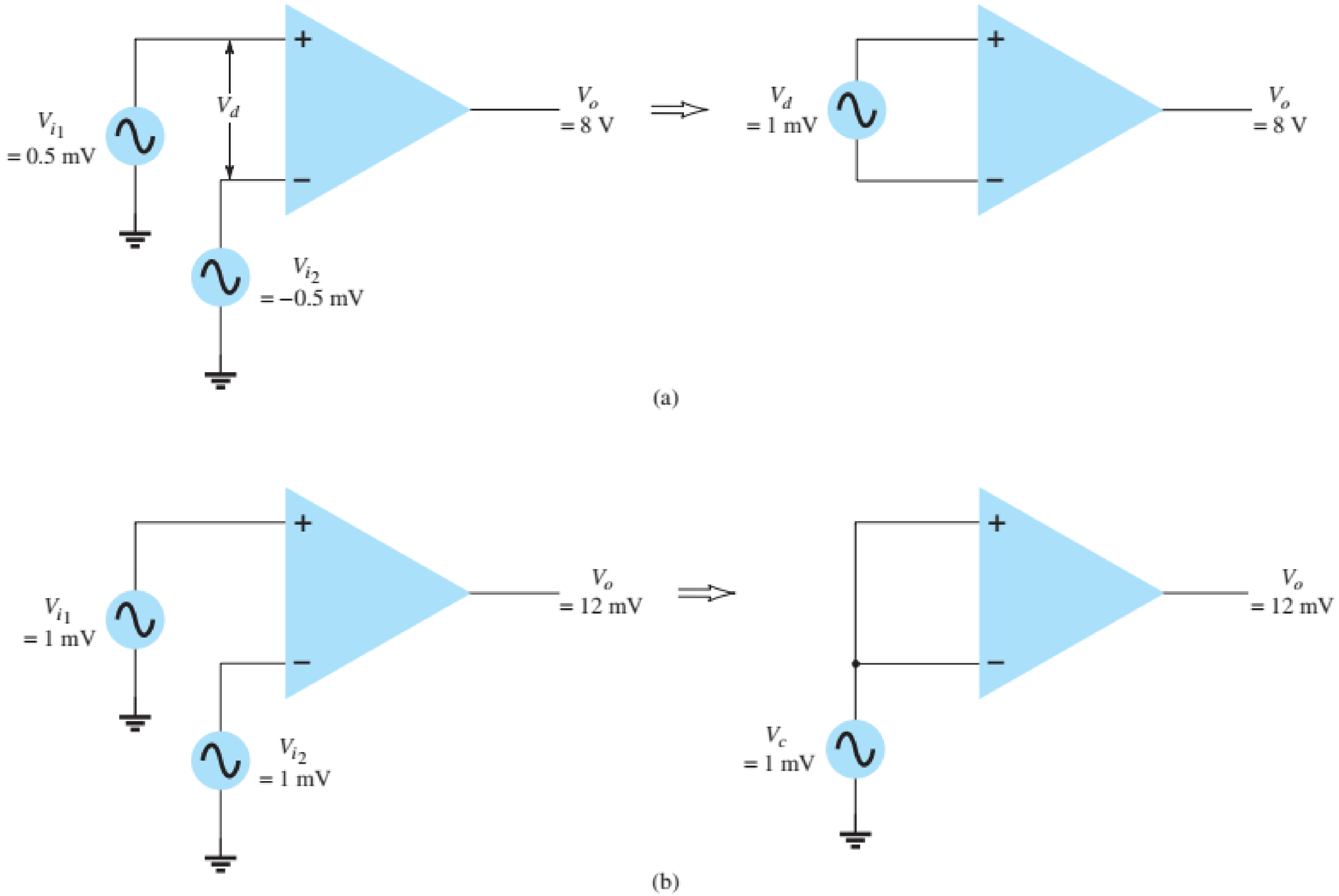
- Common-Mode Rejection Ratio

$$\text{CMRR} = \frac{A_d}{A_c}$$

$$\text{CMRR (log)} = 20 \log_{10} \frac{A_d}{A_c}$$

EX

EXAMPLE 10.21 Calculate the CMRR for the circuit measurements shown in Fig. 10.52.



(a) Differential and (b) common-mode operation.

Solution: From the measurement shown in Fig. 10.52a, using the procedure in step 1 above, we obtain

$$A_d = \frac{V_o}{V_d} = \frac{8\ \text{V}}{1\ \text{mV}} = 8000$$

The measurement shown in Fig. 10.52b, using the procedure in step 2 above, gives us

$$A_c = \frac{V_o}{V_c} = \frac{12\ \text{mV}}{1\ \text{mV}} = 12$$

Using Eq. (10.28), we obtain the value of CMRR,

$$\text{CMRR} = \frac{A_d}{A_c} = \frac{8000}{12} = \mathbf{666.7}$$

which can also be expressed as

$$\text{CMRR} = 20 \log_{10} \frac{A_d}{A_c} = 20 \log_{10} 666.7 = \mathbf{56.48\ dB}$$

CMRR

$$V_o = A_d V_d + A_c V_c = A_d V_d \left(1 + \frac{A_c V_c}{A_d V_d}\right)$$

$$\boxed{V_o = A_d V_d \left(1 + \frac{1}{\text{CMRR}} \frac{V_c}{V_d}\right)}$$

EXAMPLE 10.22 Determine the output voltage of an op-amp for input voltages of $V_{i_1} = 150\ \mu\text{V}$ and $V_{i_2} = 140\ \mu\text{V}$. The amplifier has a differential gain of $A_d = 4000$ and the value of CMRR is:

a. 100.
b. 10^5.

SOL

$$V_d = V_{i_1} - V_{i_2} = (150 - 140)\,\mu\text{V} = 10\,\mu\text{V}$$

$$V_c = \frac{1}{2}(V_{i_1} + V_{i_2}) = \frac{150\,\mu\text{V} + 140\,\mu\text{V}}{2} = 145\,\mu\text{V}$$

$$V_o = A_d V_d\left(1 + \frac{1}{\text{CMRR}}\frac{V_c}{V_d}\right)$$

$$= (4000)(10\,\mu\text{V})\left(1 + \frac{1}{100}\frac{145\,\mu\text{V}}{10\,\mu\text{V}}\right)$$

$$= 40\text{ mV}(1.145) = \mathbf{45.8\ mV}$$

b. $$V_o = (4000)(10\,\mu\text{V})\left(1 + \frac{1}{10^5}\frac{145\,\mu\text{V}}{10\,\mu\text{V}}\right) = 40\text{ mV}(1.000145) = \mathbf{40.006\ mV}$$

Outline of Presentation

- What is an Op-Amp?
- Characteristics of Ideal and Real Op-Amps
- Common Op-Amp Circuits
- Applications of Op-Amps
- References

Applications of Op-Amps

- Comparator as a A/D converter
- Summing Amplifier as D/A converter
- Filters
- Triangular Oscillator using Op-AMP
- Voltage Controlled Oscillator (VCO)

References

- Sedra and Smith
- NPTEL
- Jacob Milman

Thank you!