ENG2210
Electronic Circuits

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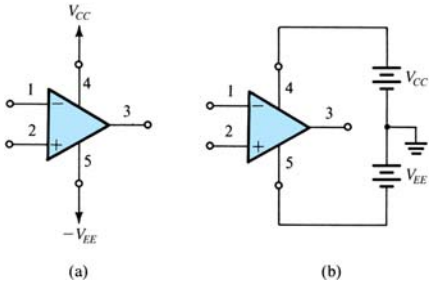
Chapter 2 Operational Amplifiers

- Objectives
- Learn the terminal characteristics of the op amp
- Learn how to analyze circuits containing op amps
- Learn how to design amplifiers having precise characteristics
- How to design circuits (summing, integrator, differentiator, ..)
- Nonideal characteristics of the op amps and how these limits affect performance

Introduction

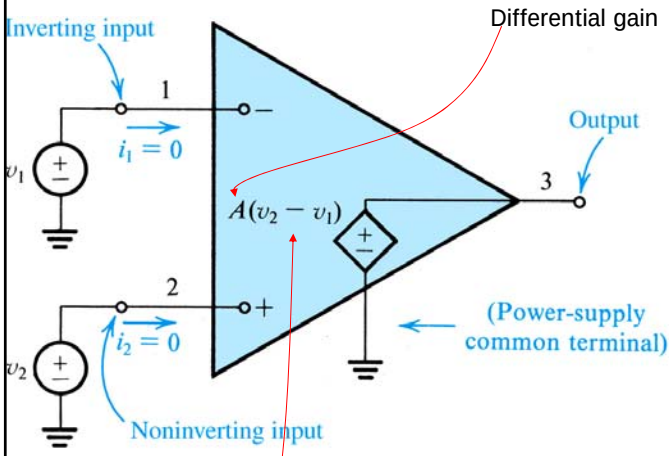
- Very cheap
- Versatile, could be used to design many circuits
- Actual op amps have characteristics that are very close to the ideal one.
- Consists of many transistors, but we will not into the details of how it is made.
- Direct Coupled Amplifiers ?

Introduction



- 2 inputs one output
- Amplify difference of inputs
- VCC and VEE are typically 12 V

Ideal Op Amp



A= ∞

V2-v1 = 0

Input current =0

Input R =∞

Output R =0

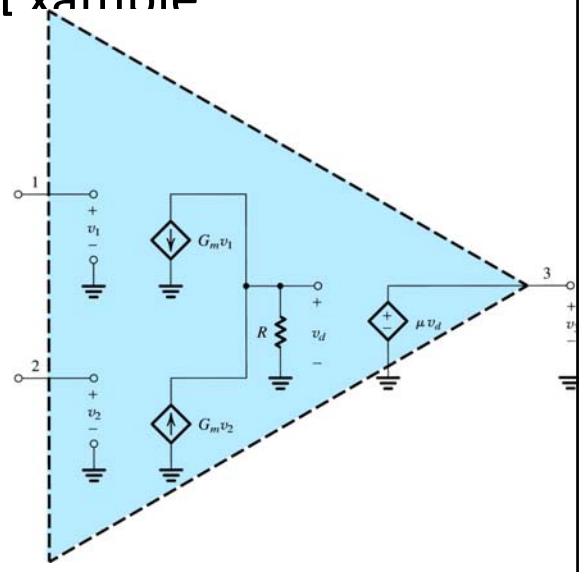
Infinite B.W.

Common mode input signal

$V_{Icm} = ½(v_1 + v_2)$

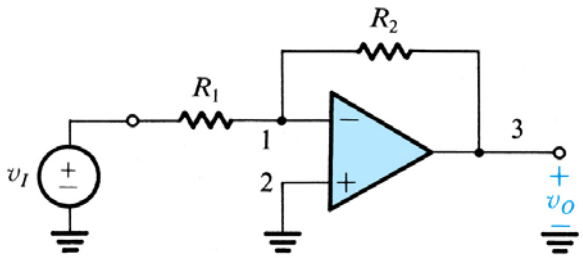
Example

Find v_3 in terms of v_1 and v_2

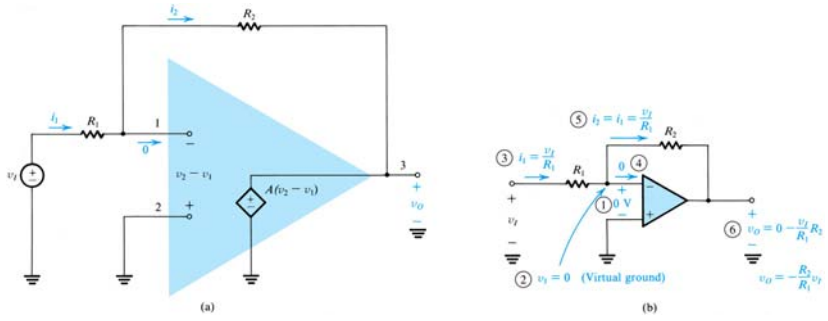


The inverting Configuration

- Input signal is connected to the inverted input
- Feedback resistor from output to inverted input
- Non-inverted input grounded

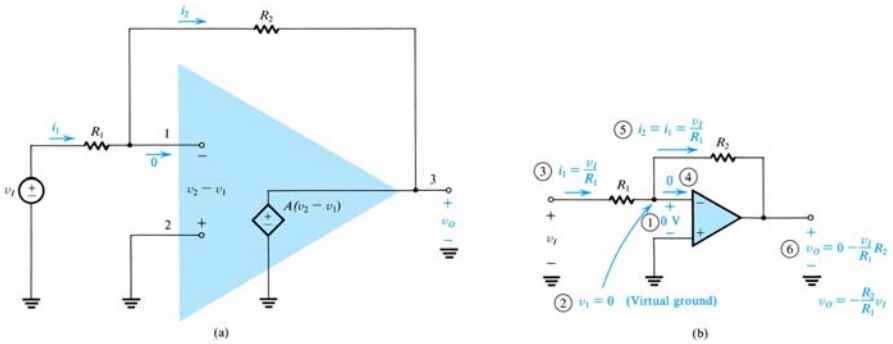


The Inverting Configuration



The Effect of Finite Open-Loop Gain

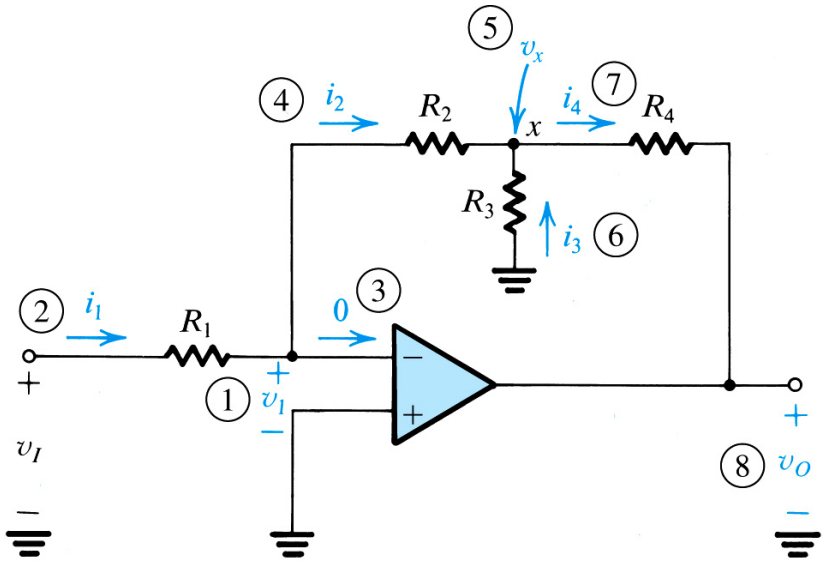
- What if A is finite
- Redo the last example assuming that A is finite



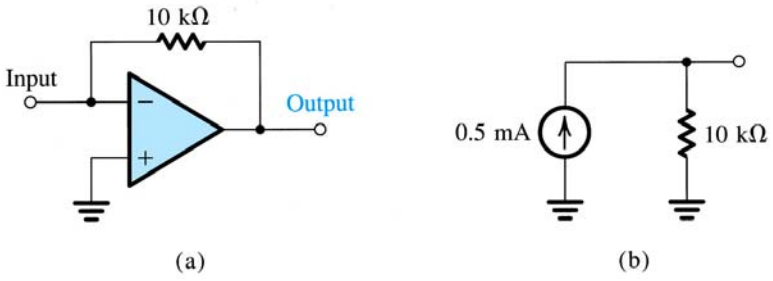
Input Resistance

- The input resistance of the iverting configuration is R_1
- R_1 must be very large (the input signals divided by R_1 and output resistance of the source)
- If R_1 is high, and we want a high gain, then R_2 may be impractically high

Example G = 100



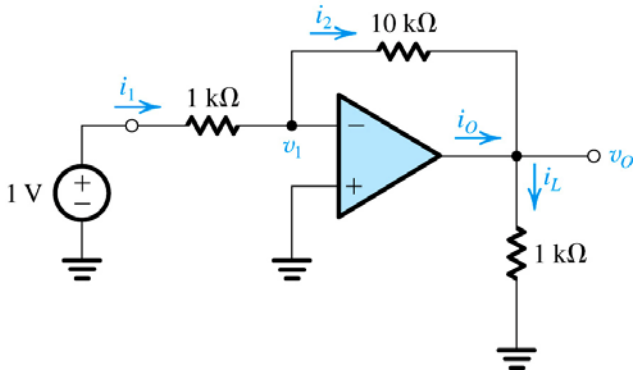
Example



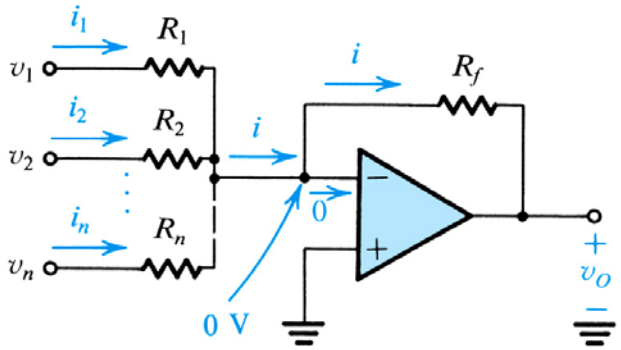
Transresistance amplifier)

Transresistance: Transfer resistance the ratio between change of voltage at the output to change of the current at the input

Example

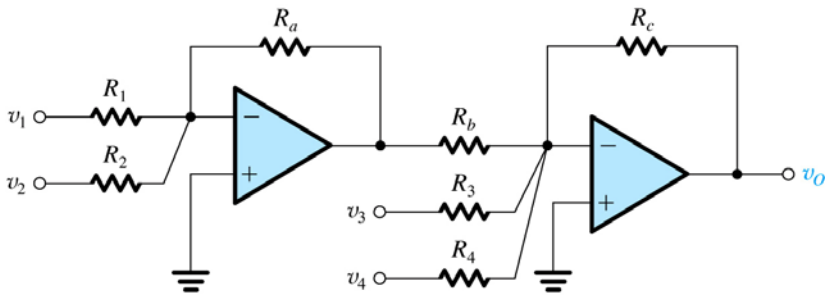


Weighted Summer

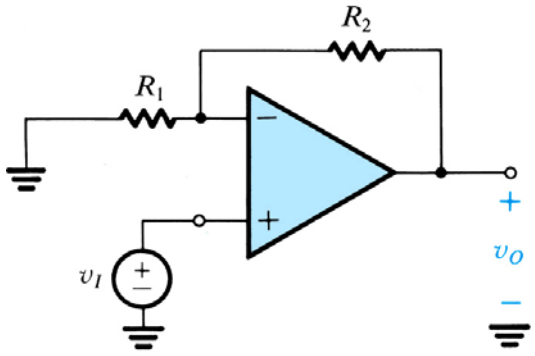


$$v_O = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \cdots + \frac{R_f}{R_n}v_n\right)$$

Weighted Summer



The Noninverting Configuration



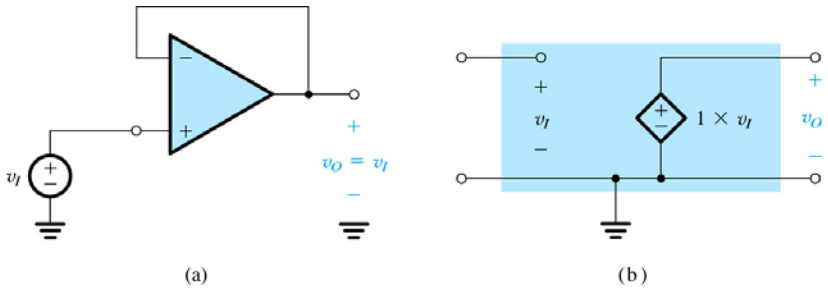
Exercise: Repeat if the gain is not infinte

Input and Output Resistance

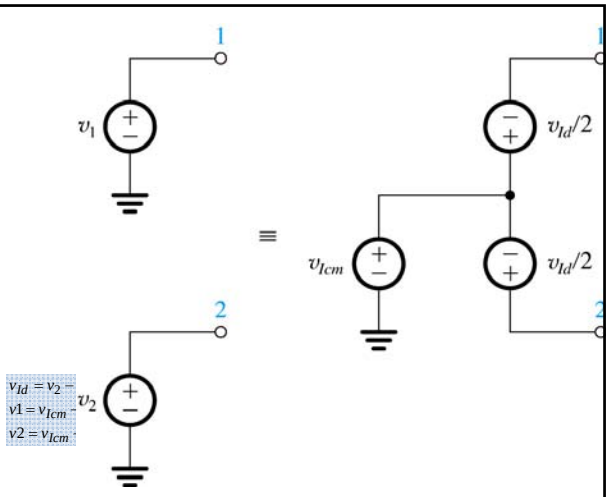
- No current flows into the +ve input of the op amp, input resistance is infinite
- Output resistance is zero

Voltage Follower

- Unity gain – Buffer Amplifier
- Infinite input R, and zero output R



Differential and Common Mode Signals



Difference Amplifiers

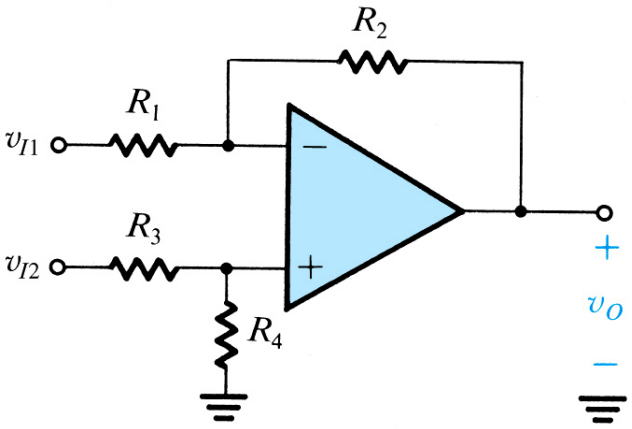
- Amplify the difference between the 2 signals and rejects signals that are common to both inputs. Ideally,
- $v_o = A_d v_{Id} + A_{cm} v_{Icm}$
- A_d is the differential gain, A_{cm} is the common gain
- Because of the very high gain, we can not use the opamp as a difference amplifier
- Common mode rejection ration CMRR

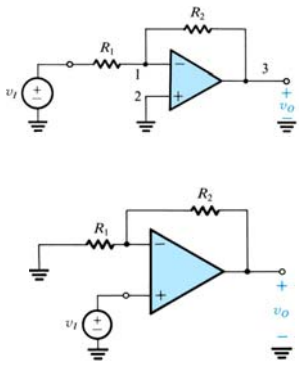
$$CMRR = 20\log\frac{|A_d|}{|A_{cm}|}$$

Difference Amplifiers

- The gain for the inverting mode is $-R_2/R_1$
- For the noninverting $1+R_2/R_1$
- We can combine these together, but we have to attenuate the noninverting input for the to make it equal in magnitude to the inverting input.

Difference Amplifier

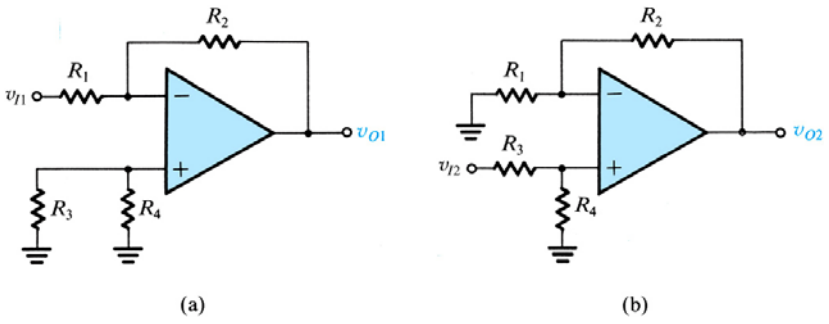




Attenuated by $R_3||R_4$

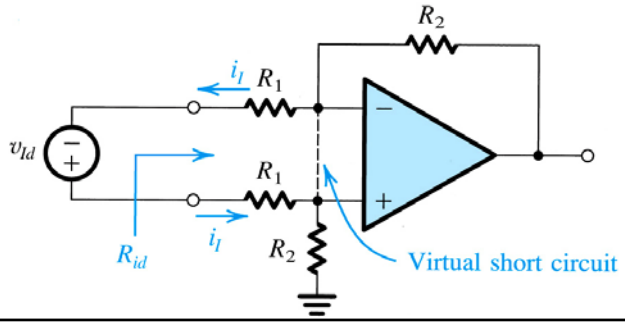
Difference Amplifiers

- Using Superposition



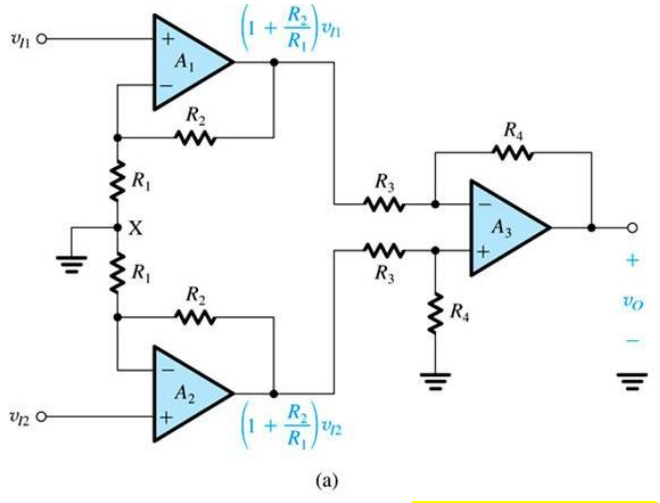
Input Resistance

- $R_{id} = 2R_1$
- For large gain (R_2/R_1) R_1 is small (relatively
- Instrumentation Amplifier solves this



Instrumentation Amplifier

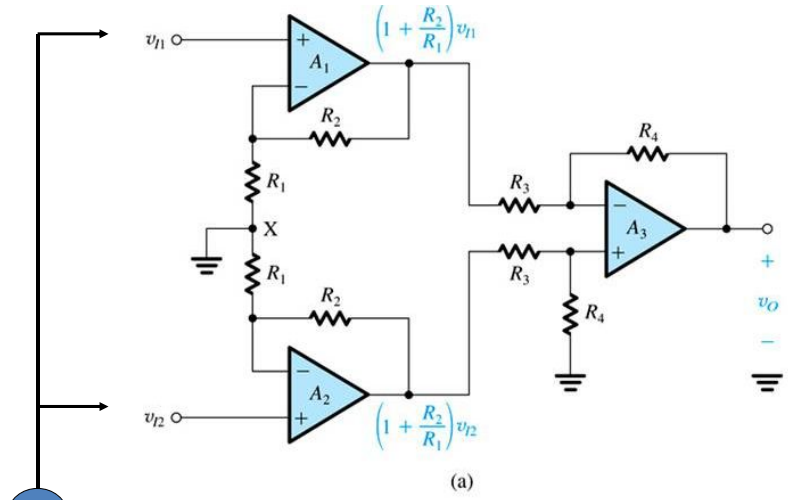
- The problem with the difference amplifier is low input resistance.
- We can use a voltage follower to buffer the 2 inputs thus solving this problem.
- We can also get some voltage gain from these 2 extra op amps.

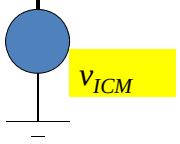


(a)

What is a mismatch between the 2 R_2's or R_1's

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

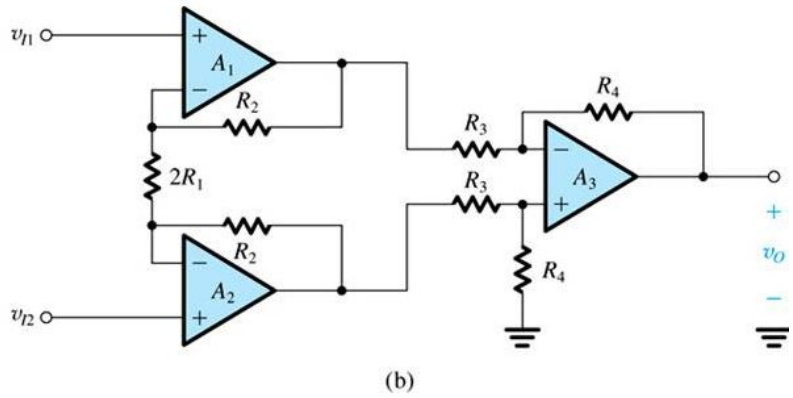




What is the effect of common mode amplification?

Problems

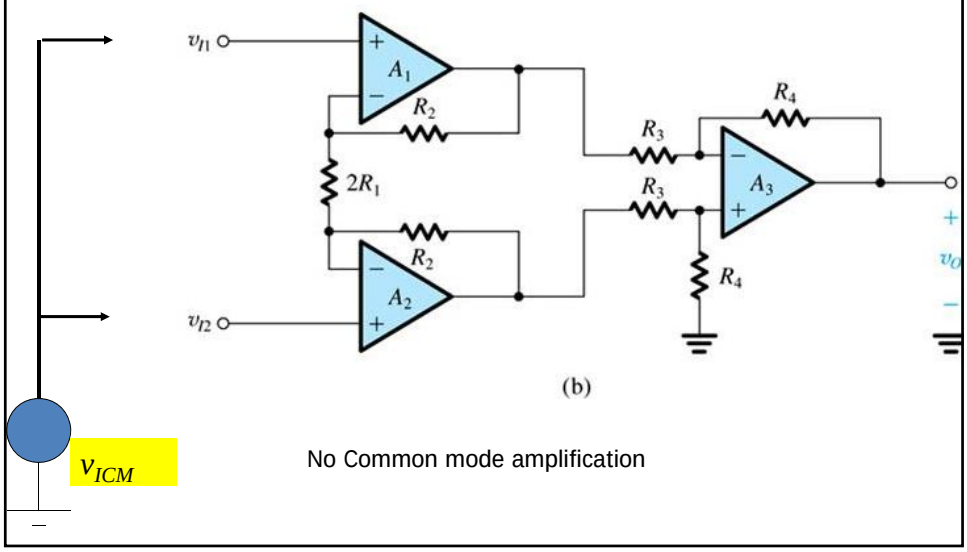
- The input common mode is amplified by the first stage, and need to be dealt with in the second (higher CMRR).
- The two amplifiers channels in the first stage have to be perfectly matched.
- To vary the differential gain, 2 resistors must be varied simultaneously.



(b)

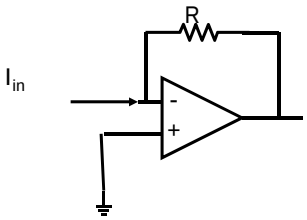
What is a mismatch between the 2 R_2's

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



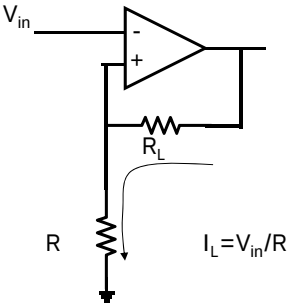
(b)

No Common mode amplification



Vout=-I_{in}R

Current to voltage converter



Voltage to current converter

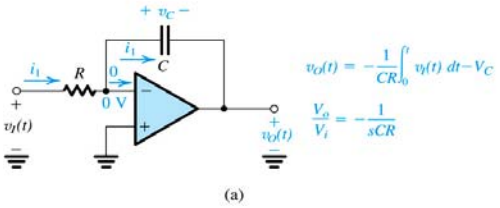
Integrator

- Consider the followir Ct.

$$v_0 = -\frac{1}{RC}\int_0^t v_i(\tau)d\tau - V_0$$

$$\frac{V_0}{V_i} = -\frac{1}{sCR}$$

$$\frac{V_0(j\omega)}{V_i(j\omega)} = -\frac{1}{j\omega CR}$$



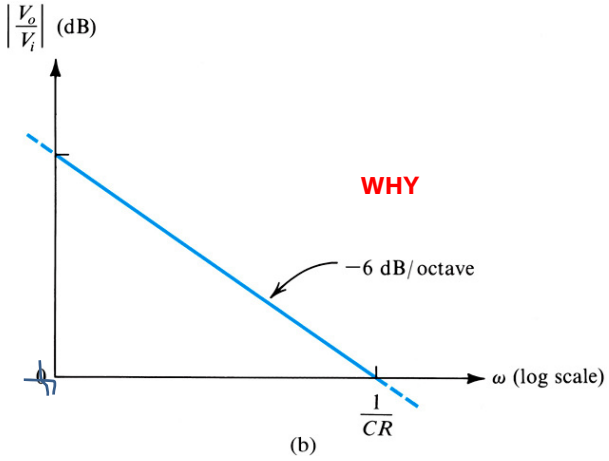
Integrator

$$v_0 = -\frac{1}{RC}\int_0^t v_i(\tau)d\tau - V_0$$

$$\frac{V_0}{V_i} = -\frac{1}{sCR}$$

$$\frac{V_0(j\omega)}{V_i(j\omega)} = -\frac{1}{j\omega CR}$$

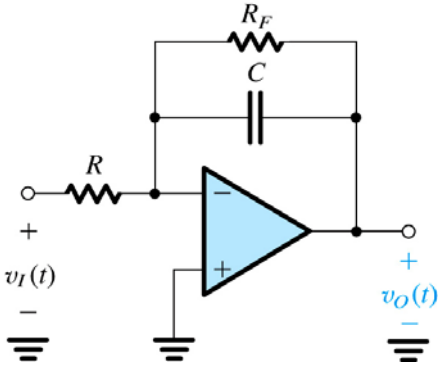
Some problems, what is the gain at DC?



Integrator

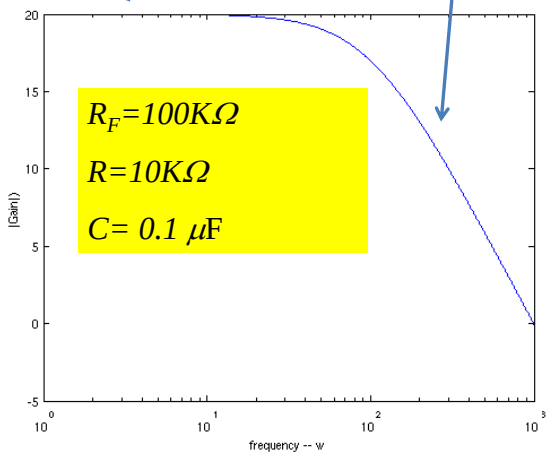
$$\frac{V_0}{V_i} = -\frac{R_F \big/ R}{1 + sCR_2}$$

$$\frac{V_0(j\omega)}{V_i(j\omega)} = -\frac{R_F}{R}\frac{1}{1 + j\omega CR_F}$$



Constant gain at DC

Integrator



R_F=100KΩ

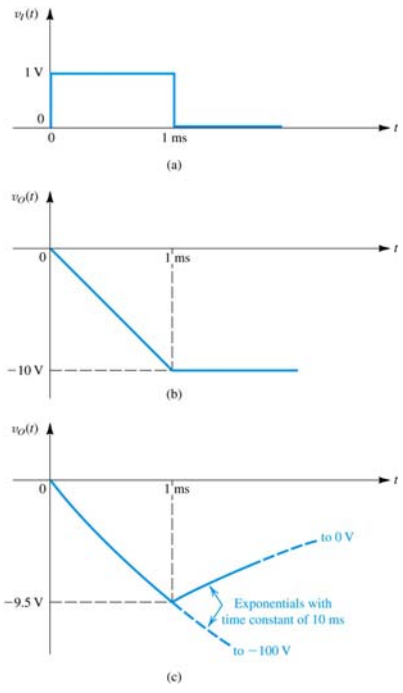
R=10KΩ

C= 0.1 μF

R_F=1 MΩ

R=10KΩ

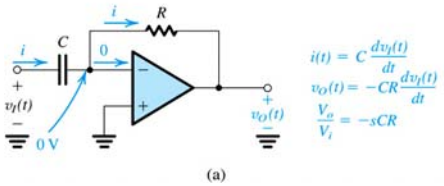
C= 10 nF



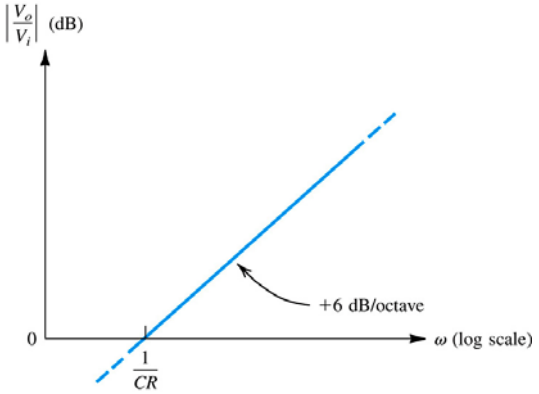
Differentiator

- An ideal differentiator

$$i(t) = C\frac{dv_I(t)}{dt}$$
$$v_O(t) = -CR\frac{dv_I(t)}{dt}$$
$$\frac{V_o}{V_i} = -sCR$$



(a)



(b)

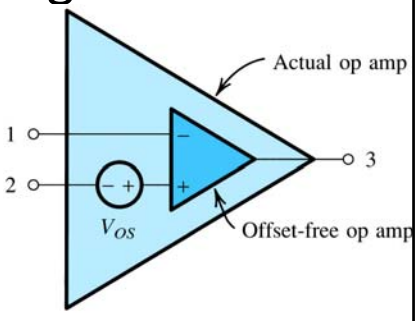
$$v_o = -CR\frac{dv_i(t)}{dt}$$
$$\frac{V_0}{V_i} = -sCR$$
$$\frac{V_0(j\omega)}{V_i(j\omega)} = -j\omega RC$$

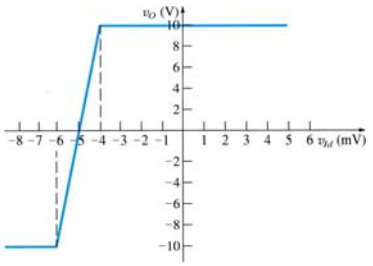
DC Imperfections

- Thus far, we considered the opamp to be ideal (except for finite A).
- In reality, we have to consider the effect of these *non-ideal* behavior of the opamp
- We will discuss FEW of these inperfections

Offset Voltage

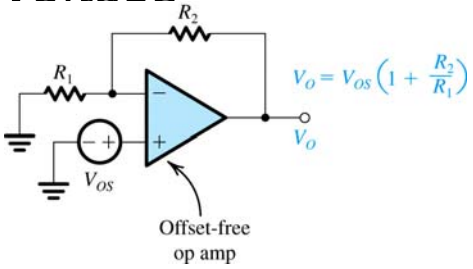
- If the 2 terminals are connected to ground, the output should be 0.
- Can be represented as the shown circuit.
- Due to mismatches in the input differential stage
- Data sheet specify V_{OS} but not its polarity
- Also, changes with temperature (µV/˚C)

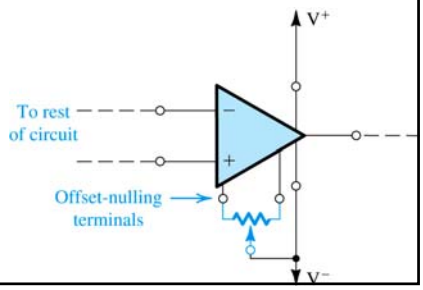




Offset Voltage

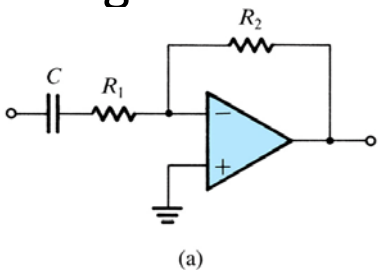
- V_o is not zero.
- The actual signal is superimposed in V_0.
- Limits the voltage swing.
- If amplifying DC even worse.
- Some opamps have 2 terminals for compensation.
- Still the problem of temp variation



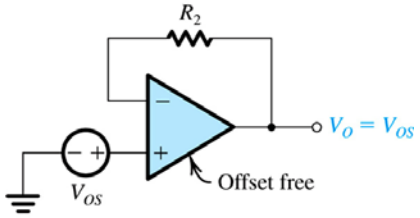


Offset Voltage

- We can use capacitive coupling.
- O.K. if we are not dealing with DC of low frequency.
- At DC gain is 1 (not $1+R_2/R_1$).
- At high frequency (high pass filter)



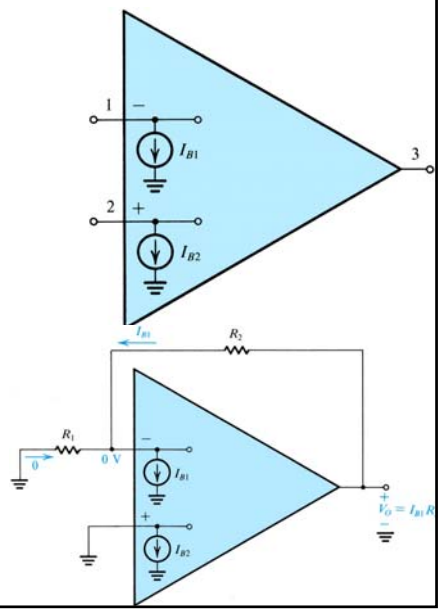
(a)



(b)

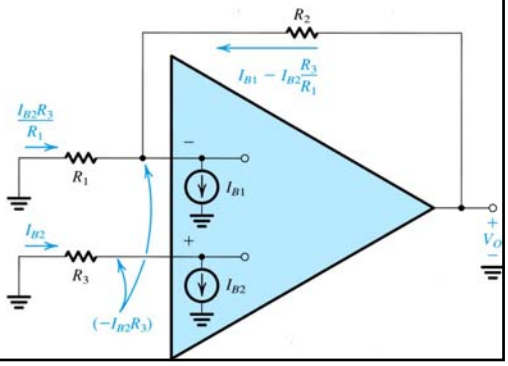
Input Bias and Offset Currents

- The opamp needs an input current to operate.
- Datasheet usually specify average value (input bias current) and the difference (input offset current).
- What is Vo?



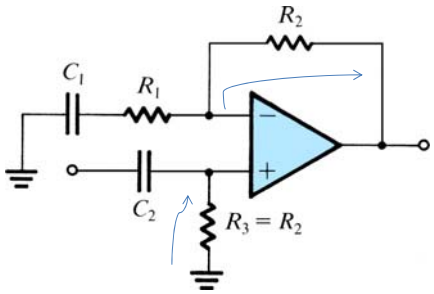
Input Bias and Offset Currents

- We can reduce the output DC voltage due to input bias current.
- R3 has a negligible effect from the signal point of view.



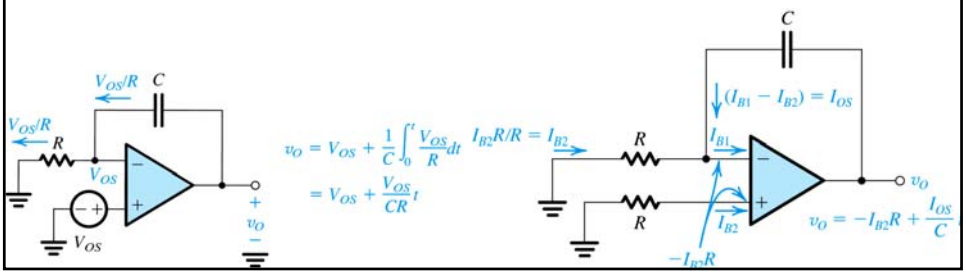
Input Bias and Offset Currents

- Always provide a dc path from each of the inputs to the ground



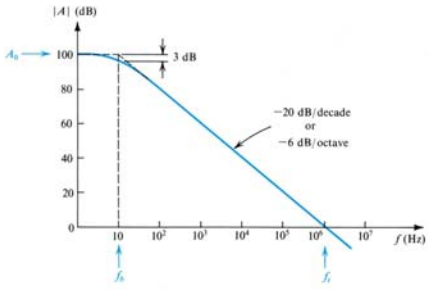
Effect of V_{os} and I_{os}

- The effect of V_{os} and I_{os} result in charging the capacitor and saturating the output
- Consider a shunt R with the C
- Although R is used to keep I_B from flowing into C, but not I_{os}



Finite Open Loop gain and B.W.

- The differential open loop gain is finite and decreases with frequency.
- If internally compensated, it behaves like a single time constant LPF



$$A(S) = \frac{A_0}{1 + \frac{s}{w_b}}$$

Finite Open Loop Gain

$$A(S) = \frac{A_0}{1 + s/\omega_b}$$

$$A(j\omega) = \frac{A_0}{1 + j\omega/\omega_b}$$

$$A(j\omega) = \frac{A_0\omega_b}{j\omega}$$

$\omega >> \omega_b$

$$|A(j\omega)| = \frac{A_0\omega_b}{\omega}$$

$$\omega_t = A_0\omega_b$$

Unity-gain BW or Gain BW product

Closed Loop Gain

$$\frac{V_0(s)}{V_i(s)} = \frac{-R_2/R_1}{1+(1+R_2/R_1)/A}$$

$$\frac{V_0(s)}{V_i(s)} = \frac{-R_2/R_1}{1+(1+R_2/R_1)/(A_0/(1+s/w_b))}$$

$$A >> R_2/R_1$$

$$\frac{V_0(s)}{V_i(s)} = \frac{-R_2/R_1}{1+\frac{s}{\omega_t/(1+R_2/R_1)}}$$

STC LPF with gain R2/R1

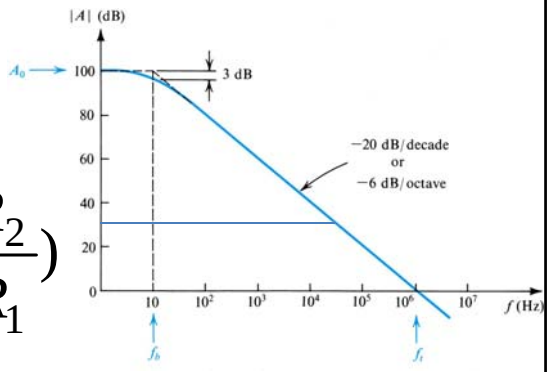
$\omega_{3dB}=\omega_t/(1+R_2/R_1)$

Closed Loop Gain non-inverting

This is equivalent to an STC LPF with a DC gain of $(1+R_2/R_1)$ and a 3dB frequency of

$$\frac{V_0(s)}{V_i(s)} = \frac{1+R_2/R_1}{1+\frac{s}{\omega_t/(1+R_2/R_1)}}$$

$$w_{3dB} = w_t/(1+\frac{R_2}{R_1})$$



Large Signal Operation

- The output of the opamp saturates at **rated output voltage** (+- 13)
- Also, three is a limit on the output current (datasheet). The opamp can not supply more than the output current limit. If this is the case, the voltage saturates at the limit.

Slew Rate

- The output can not change with a rate greater than the slew rate.
- The slew rate is specified in the datasheet in V/µs