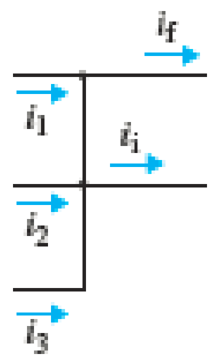
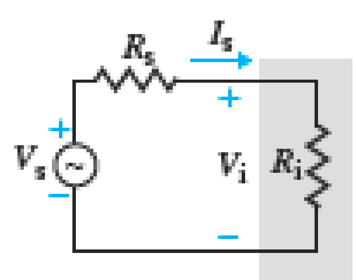
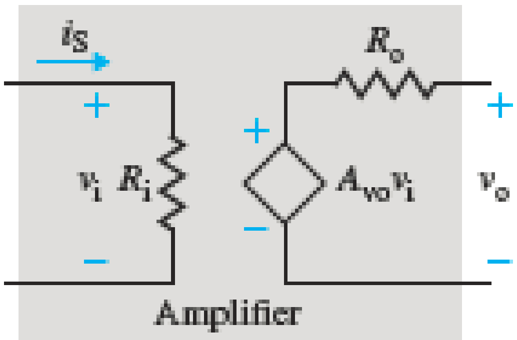
Operational Amplifiers and Applications

Review

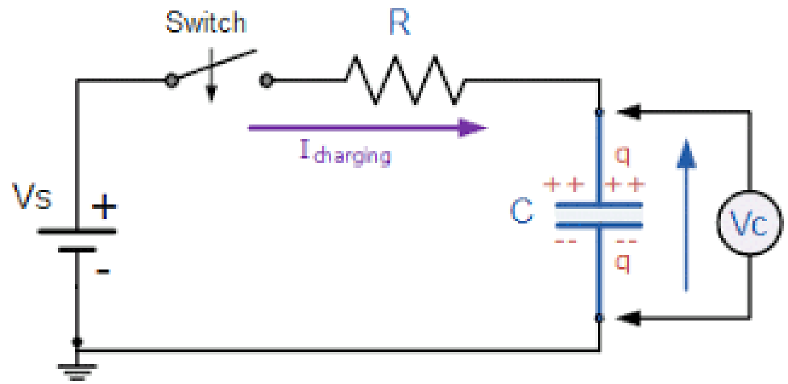
Fundamentals of basic circuits and what we learned in Chapter 1

The current i through resistance R is related to its voltage v by Ohm's law		$v = iR$
According to Kirchoff's current law, the sum of all currents at a node must be zero, or the currents coming in to the node must equal to the current going out		$i_1 + i_2 + i_3 = i_f + i_i$
According to the voltage divider rule between two resistances R_s and R_i, the output voltage V_i across resistance R_i is related to the input voltage V_s by		$V_i = \dfrac{R_i}{R_i + R_s} V_s$

Review

The model and parameters of a voltage amplifier are		Voltage gain A_{vo}, Input resistance R_i, output resistance R_o
If voltage amplifiers with gains of $A_1, A_2, \ldots A_n$ are cascaded, the overall gain is the product of the gain of each stage.		$A_{vo} = A_1 A_2 \ldots A_n$

Review



The instantaneous current $i(t)$ through an RC circuit for a step voltage V_s	$i = \frac{V_S}{R}(1 - e^{-t/RC})$
The voltage v_c of a capacitor C is related to its current i by	$v_c = \frac{1}{C}\int i\, dt$
The current i of a capacitor C is related to its voltage v_c by	$i = C\frac{dv_c}{dt}$

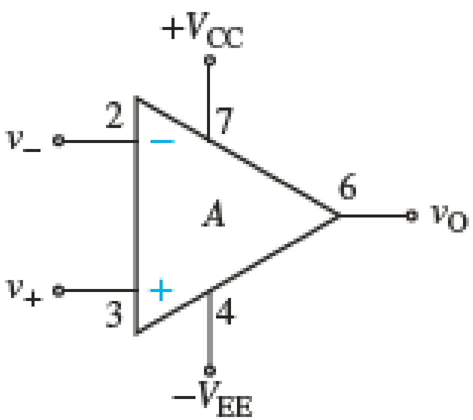
Review

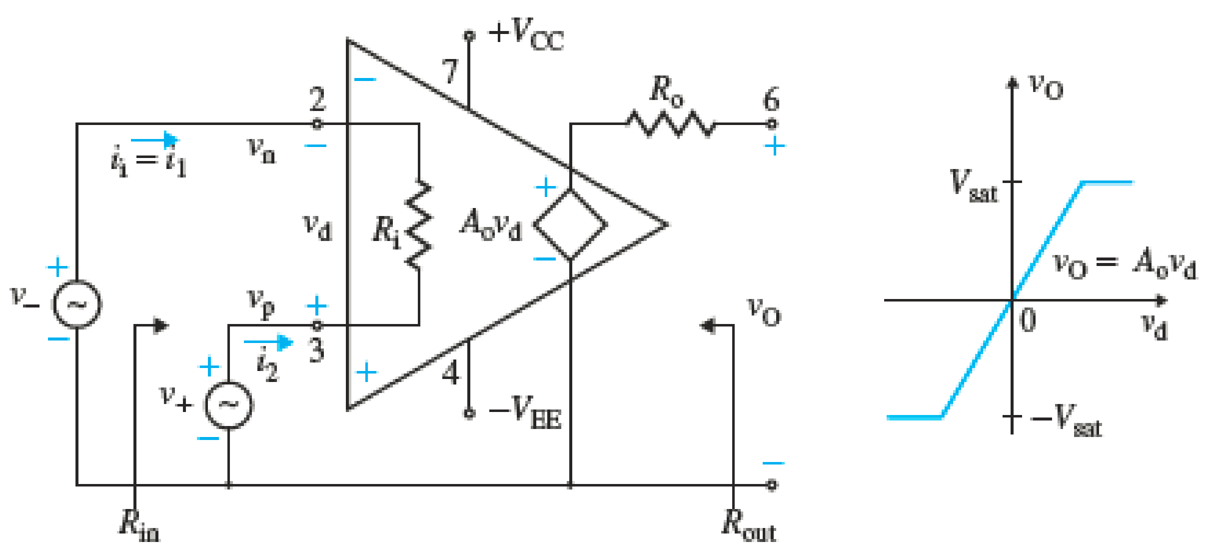
The impedance of a capacitor at a frequency ω or f, X_C	$X_c = \frac{1}{j\omega C}$ *or* $\frac{1}{j2\pi fC}$
The cutoff frequency of an RC circuit	$f_L = \frac{1}{2\pi RC}$
The cutoff frequency is defined as the frequency at which the gain rises or falls to 70.7% $(1/\sqrt{2})$ of the band-pass gain, A_{BP}.	70.7% $(1/\sqrt{2})$
The vector representation of a sinusoidal voltage with a peak magnitude V_m, $V_m \sin(2\pi ft + \varphi)$	$V_m \angle \varphi$
The derivative of $V_m \sin(\omega t)$, $\frac{d}{dt}(V_m \sin \omega t)$	$\omega V_m(\cos \omega t)$, or $\omega V_m \angle 90°$

Characteristics of Ideal Op-Amps - Op-Amp Circuit Model

- The output voltage of an op-amp is directly proportional to the small-signal differential input voltage.

$$v_o = A_o v_d = A_o (v_p - v_n)$$

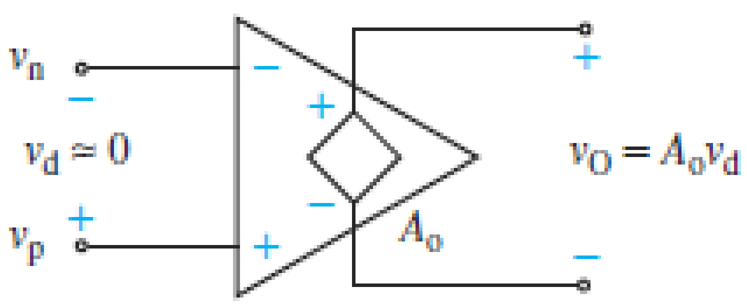




(a) Equivalent circuit (b) Transfer characteristic

Ideal Op-Amp Model

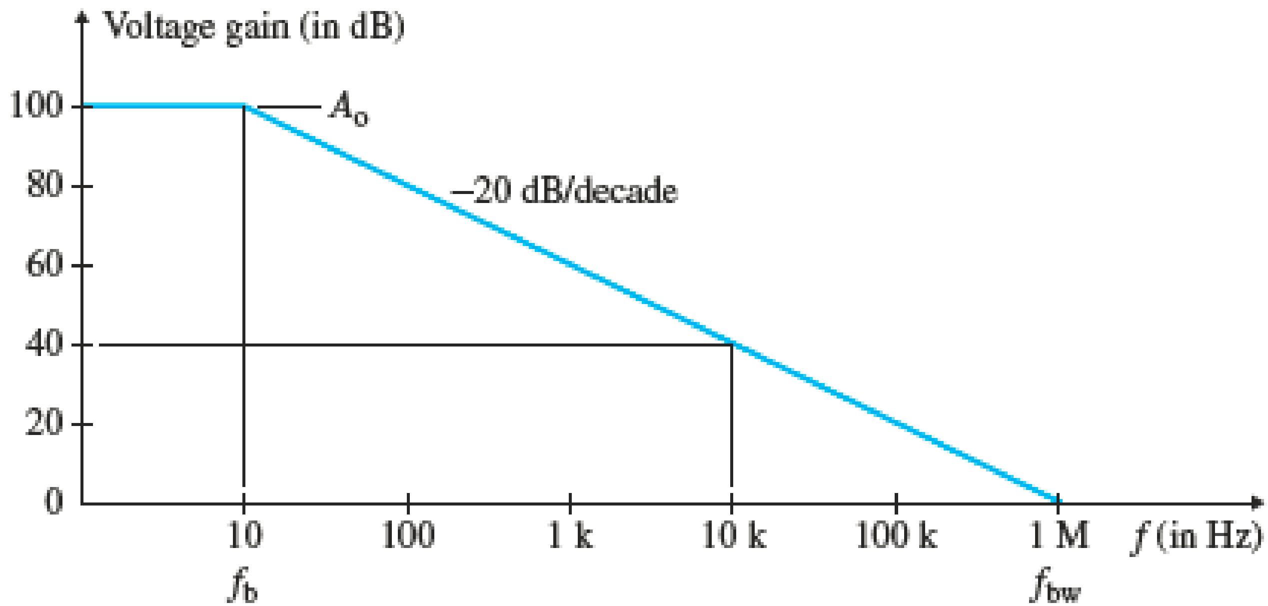
- The open-loop voltage gain is infinite: $A_o = \infty$.
- The input resistance is infinite: $R_i = \infty$.
- The amplifier draws no current: $i_i = 0$.
- The output resistance is negligible: $R_o = 0$.
- The gain A_o remains constant and is not a function of frequency.
- The output voltage does not change with changes in power supplies. This condition is generally specified in terms of the power supply sensitivity (PSS): PSS = 0.



Op-Amp Frequency Response

- The differential voltage gain of an op-amp has the highest value at DC or low frequencies. The gain decreases with frequency.

$$A_o(j\omega) = \frac{A_o}{1 + j\omega/\omega_b} = \frac{A_o}{1 + jf/f_b}$$

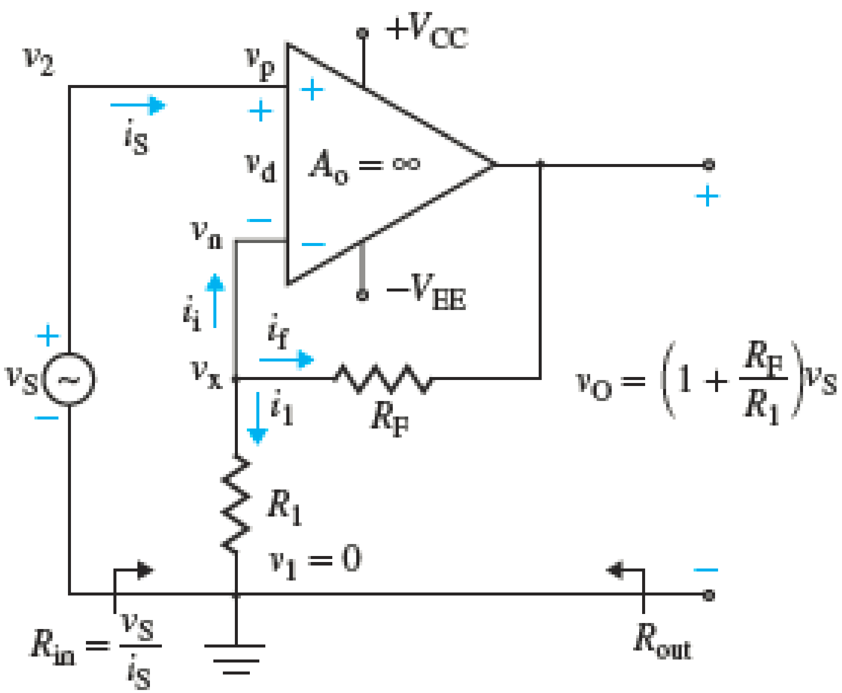


Non-inverting Amplifiers

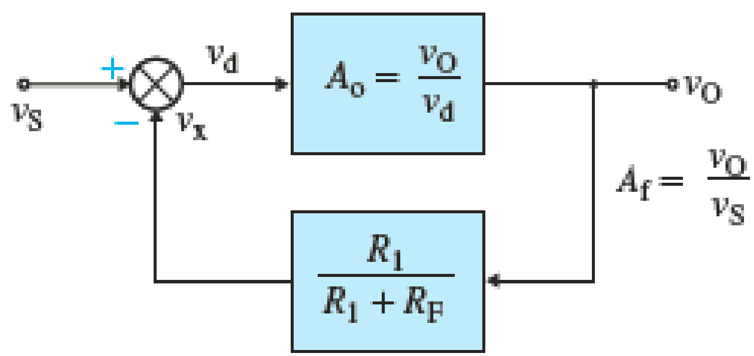
- The input voltage is connected directly to the noninverting terminal.
- Closed-loop voltage gain A_f:

$$\boxed{A_f = \frac{v_o}{v_s} = 1 + \frac{R_F}{R_1}}$$

$$\boxed{v_x = \frac{R_1}{R_1 + R_f} v_o = v_s}$$



(a) Noninverting configuration



(b) Closed-loop feedback

Input and Output Resistances

- Since the current drawn by the amplifier is zero, the effective input resistance of the amplifier is very high, tending to infinity.

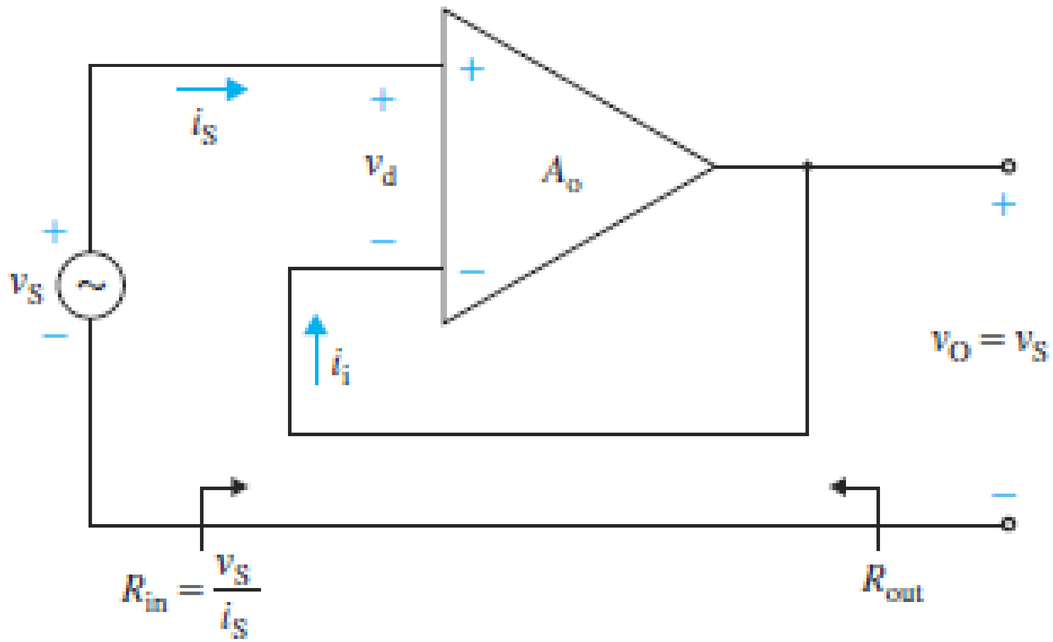
$$R_{in} = \frac{v_S}{i_S} = \infty$$

- The effective output resistance:

$$R_{out} = R_o \approx 0$$

Voltage Follower

- If $R_F = 0$ *or* $R_1 = \infty$ then $A_f = 1$
- Used as the *buffer stage* between a low impedance load and a source requiring a high impedance load.

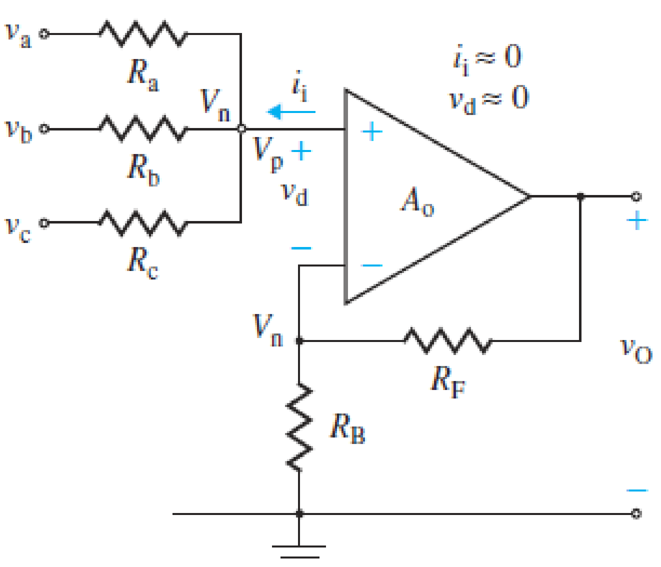


Non-inverting Summing Amplifiers

$$v_p = \frac{R_b \| R_c}{R_a + R_b \| R_c} v_a + \frac{R_a \| R_c}{R_b + R_a \| R_c} v_b + \frac{R_a \| R_b}{R_c + R_a \| R_b} v_c$$

$$\boxed{v_o = \left(1 + \frac{R_F}{R_B}\right)\left(\frac{R_A}{R_a} v_a + \frac{R_A}{R_b} v_b + \frac{R_A}{R_c} v_c\right)}$$

where $R_A = (R_a \| R_b \| R_c)$

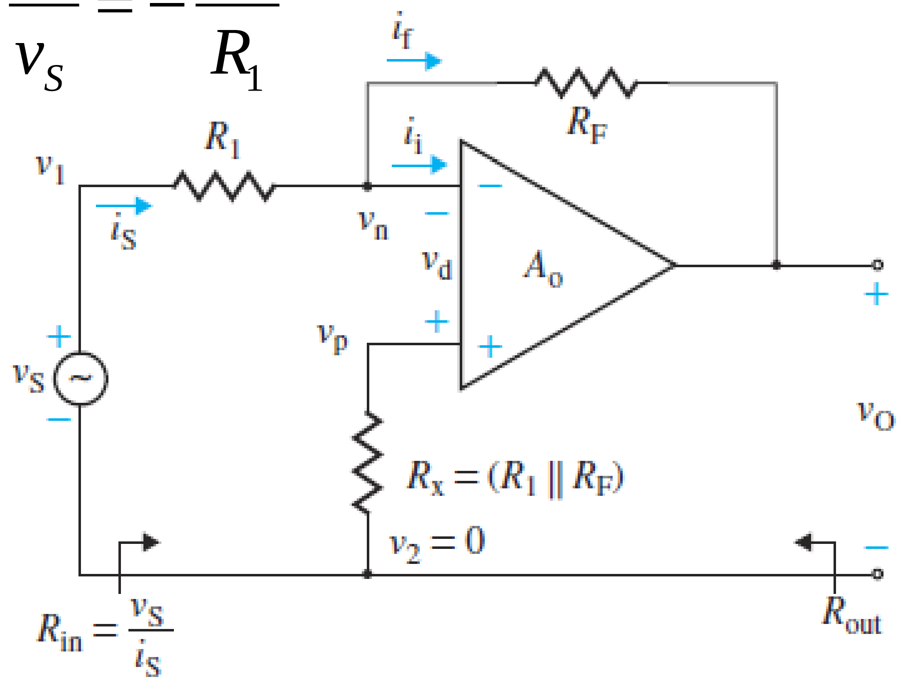


Inverting Amplifiers

- The input voltage is connected to the inverting terminal and the non-inverting terminal is connected to the ground directly or through a resistance.

- Closed-Loop Gain: $A_f = \dfrac{v_O}{v_S} = -\dfrac{R_F}{R_1}$

$$\frac{v_o}{R_F} = -\frac{v_s}{R_1}$$

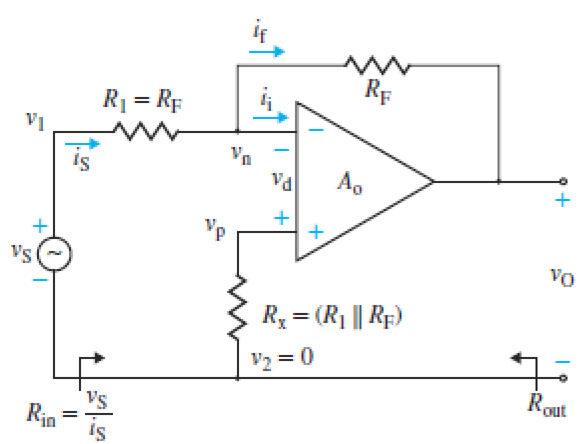


Input and Output Resistances

- The effective input resistance R_{in} of the amplifier:

$$R_{in} = \frac{v_S}{i_S} = \frac{v_S}{(v_S + v_d)/R_1} \approx R_1$$

- **Op-Amp Inverter**: An inverter is often used to invert the polarity of a signal.



Effect of Finite Op-Amp Gain on Closed-Loop Gain

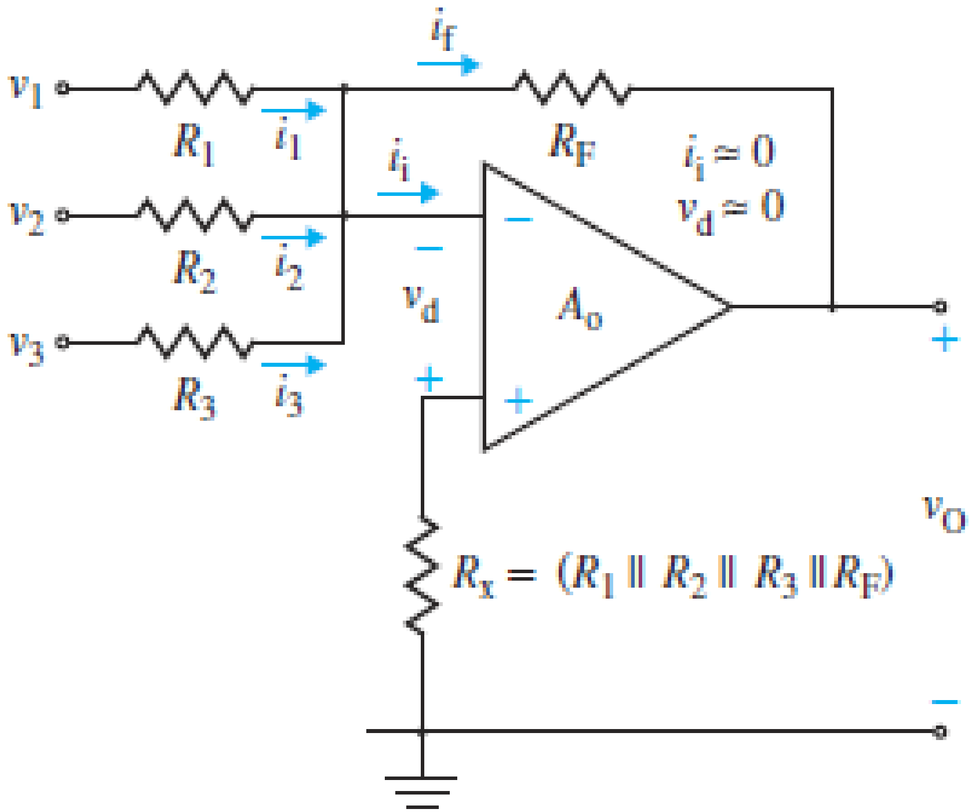
- Closed-loop voltage gain:

$$A_f = \frac{v_O}{v_S} = -\frac{R_F / R_1}{1 + (1 + R_F / R_1) / A_o} = -\frac{R_F}{R_1(1 + x)}$$

Inverting Summing Amplifiers

- Output voltage:

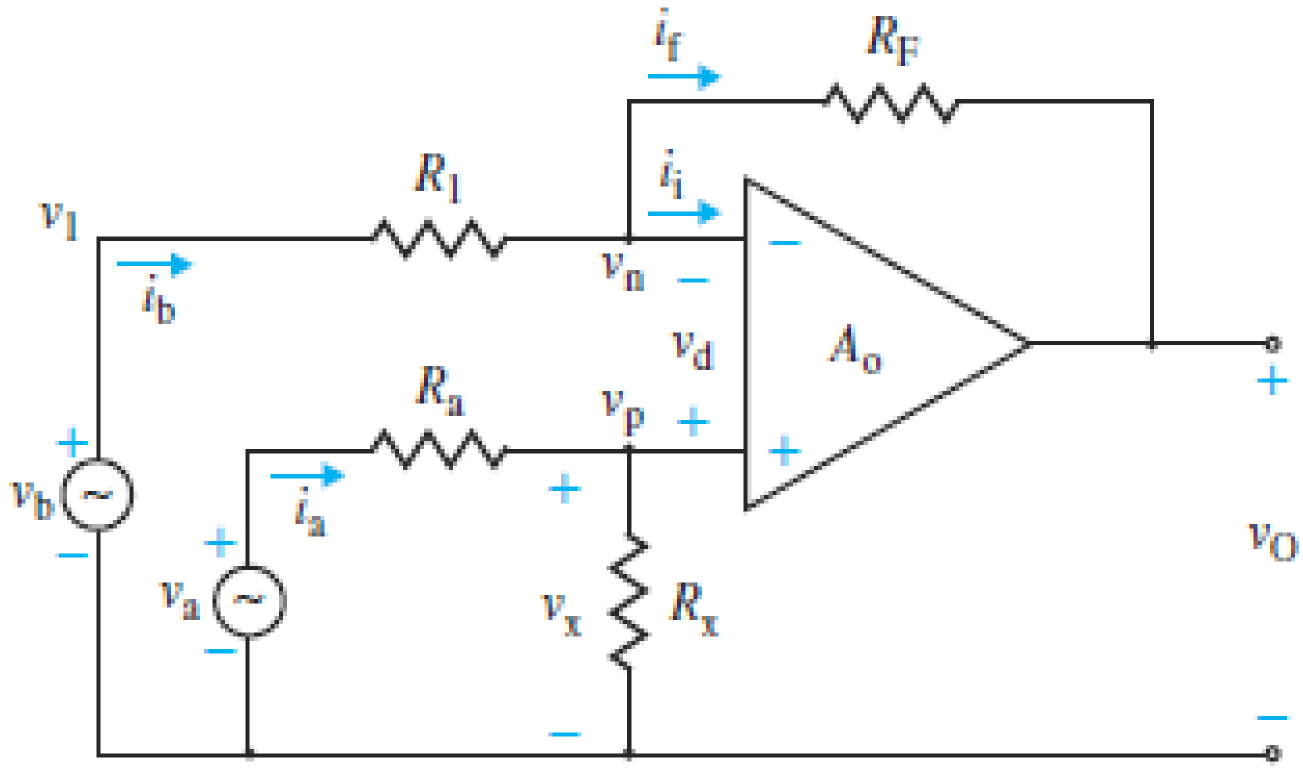
$$v_o = -\left(\frac{R_F}{R_1}v_1 + \frac{R_F}{R_2}v_2 + \frac{R_F}{R_3}v_3\right)$$



Difference Amplifiers

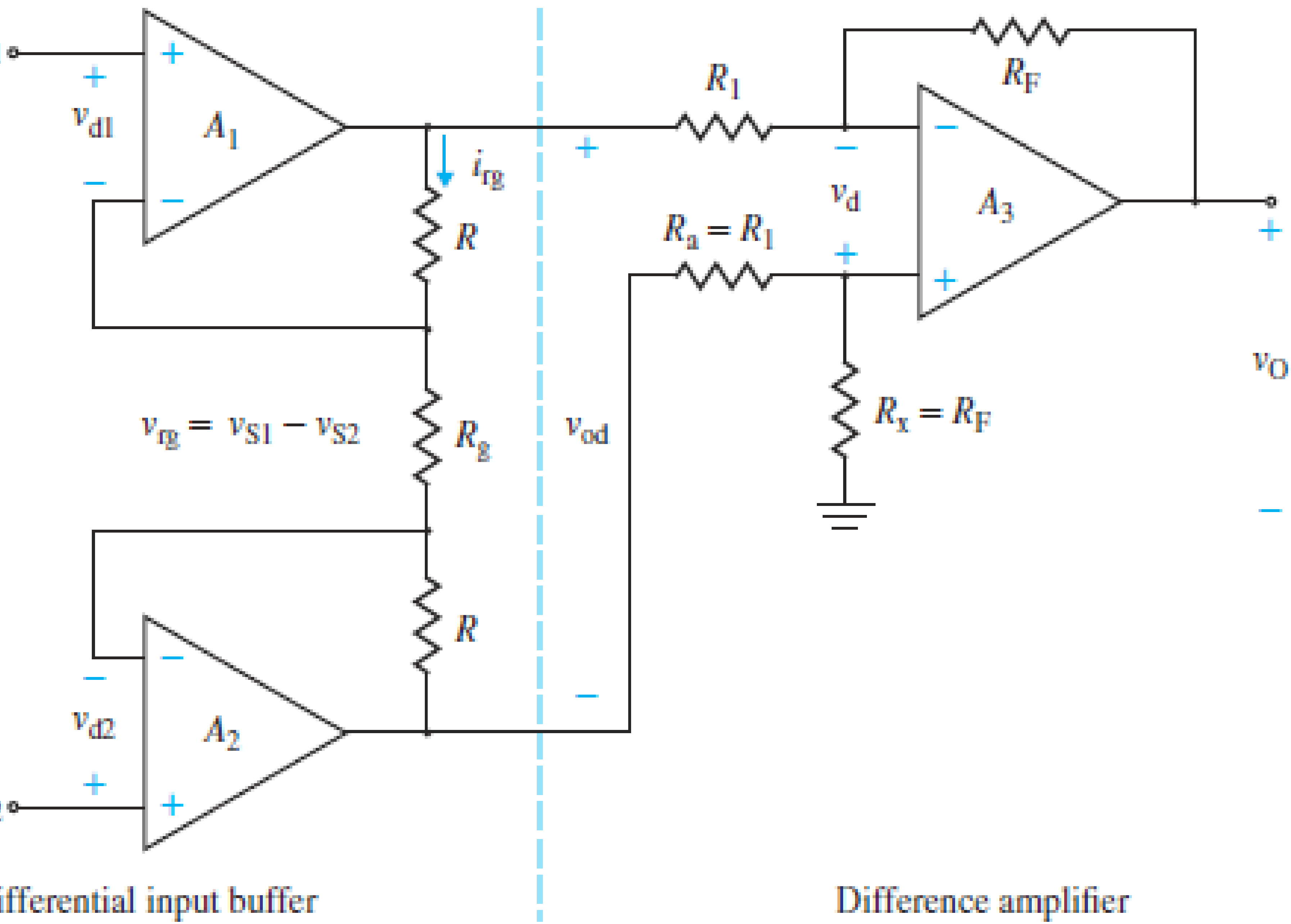
- Two input voltages (v_a and v_b) are applied—one to the non-inverting terminal and another to the inverting terminal.
- Closed-Loop Gain of Difference Amplifiers:

$$v_o = \boxed{-\frac{R_F}{R_1} v_b} + \boxed{\left(1+\frac{R_F}{R_1}\right)\left(\frac{R_x}{R_x + R_a}\right) v_a}$$



Instrumentation Amplifiers

- **Instrumentation amplifier:** dedicated difference amplifier with an extremely high input impedance.
- Its gain can be precisely set by a single resistance.
- Closed-Loop Gain of Instrumentation Amplifiers:



v_d1
A_1
i_rg
R
v_rg = v_S1 − v_S2
R_g
R
v_d2
A_2
v_od
R_1
R_F
R_a = R_1
v_d
A_3
R_x = R_F
v_O
ifferential input buffer
Difference amplifier

Instrumentation Amplifiers

$$v_{od} = i_{rg}(R_g + 2R) = \frac{v_{S1} - v_{S2}}{R_g}(R_g + 2R) = (v_{S1} - v_{S2})\left(1 + \frac{2R}{R_g}\right)$$

Using Eq. (3.82), we can calculate the output voltage v_O as

$$v_O = -v_{od}\frac{R_F}{R_1} = -(v_{S1} - v_{S2})\left(1 + \frac{2R}{R_g}\right)\left(\frac{R_F}{R_1}\right)$$

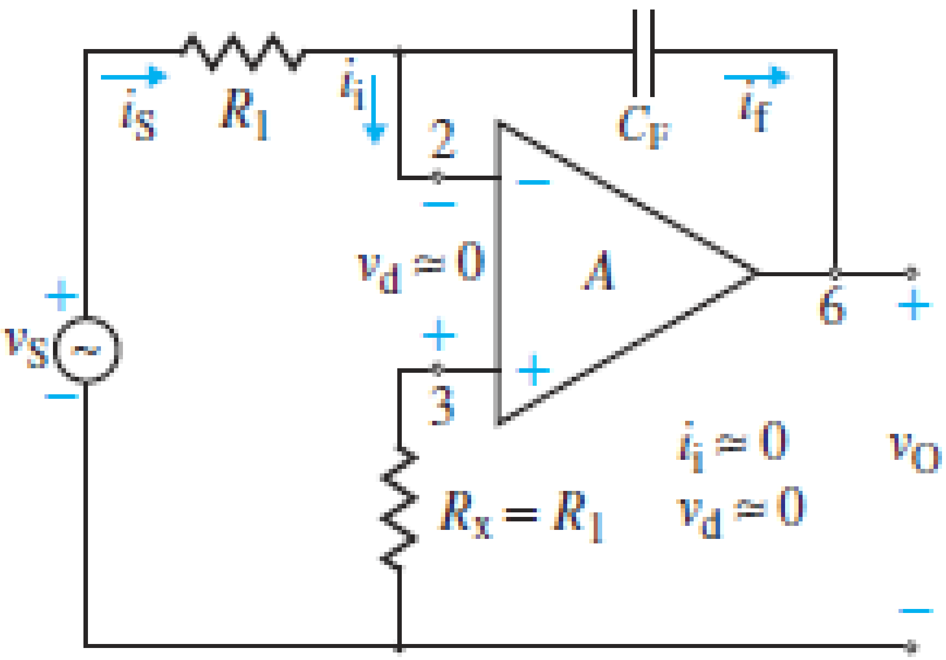
$$\boxed{A_f = (1 + \frac{2R}{R_g})(\frac{R_F}{R_1})}$$

CENGAGE Learning

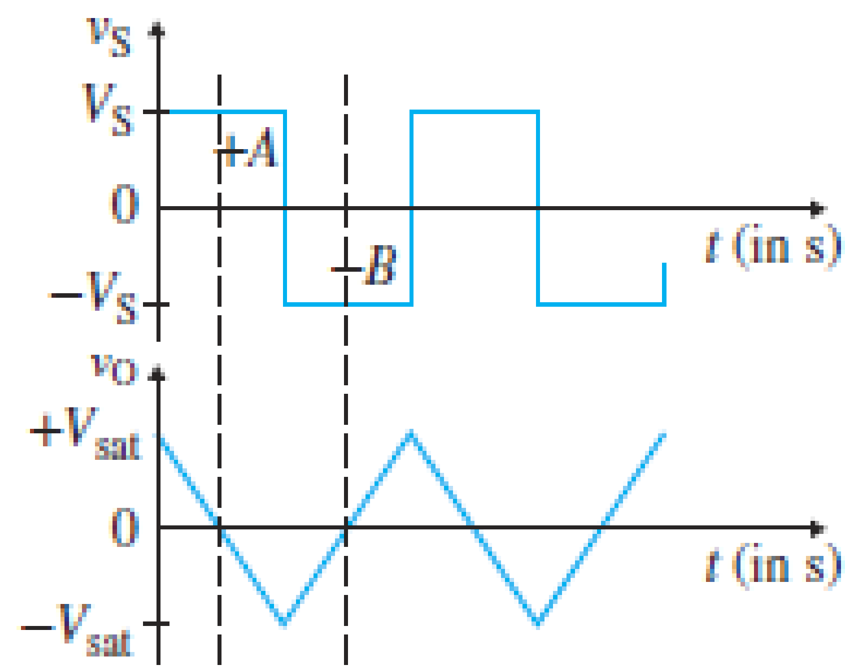
Integrators

- If the resistance R_F in the inverting amplifier is replaced by a capacitance C_F, the circuit will operate as an integrator.

$$v_O(t) = -\frac{1}{R_1 C_F}\int_0^{\tau} v_S\,dt - v_C(t=0)$$



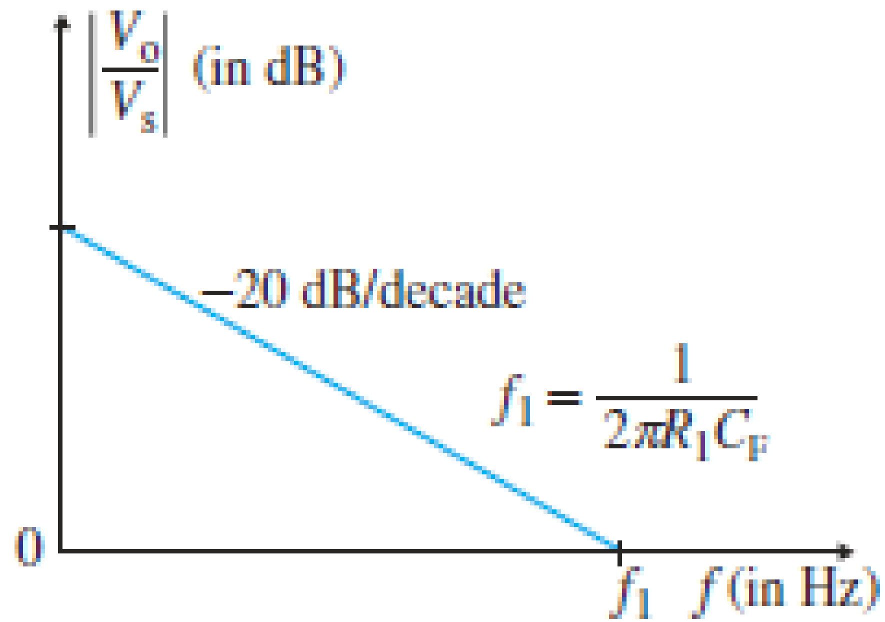
(a) Circuit



(b) Waveforms

Integrators

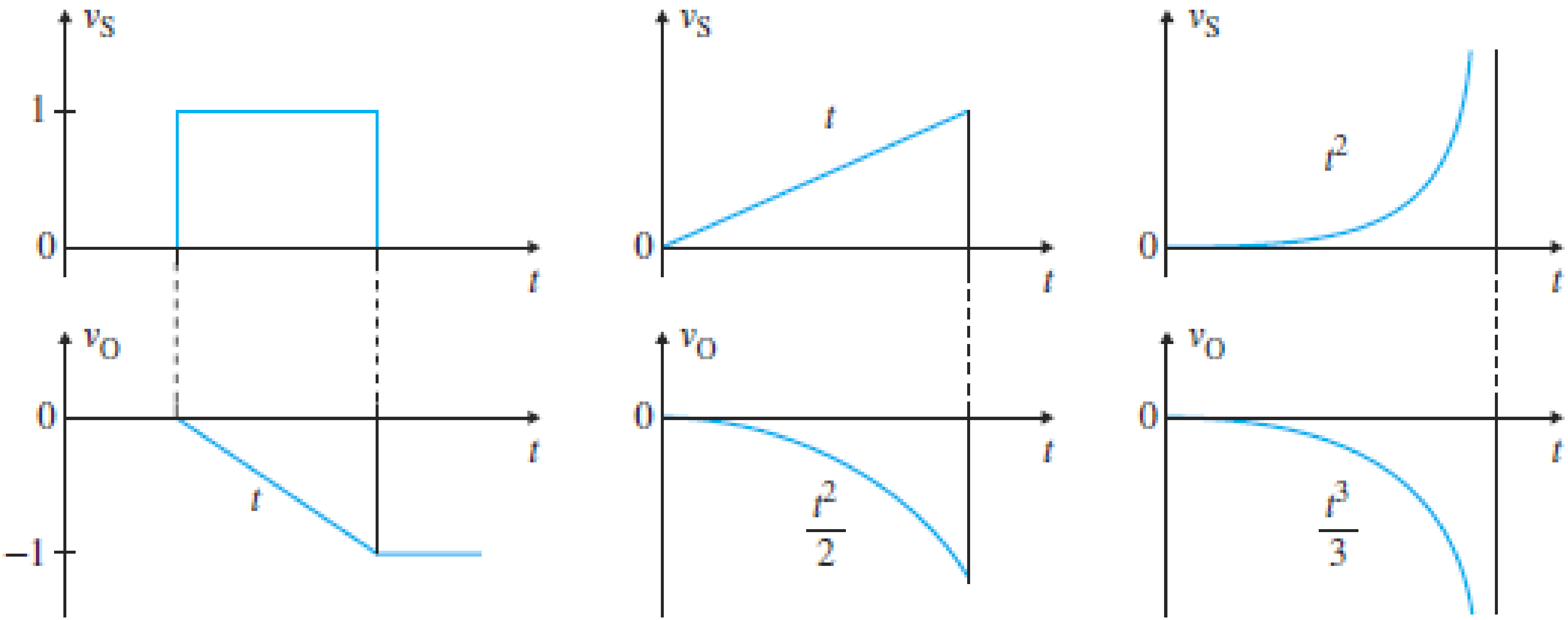
$$v_O(t) = -\frac{1}{R_1 C_F}\int_0^{\tau} v_S\,dt - v_C(t=0)$$



(c) Magnitude plot

Frequency Response of an Ideal Integrator

- The voltage gain: $$A_f(j\omega) = \frac{V_o(j\omega)}{V_s(j\omega)} = -\frac{1}{j\omega C_F R_1}$$



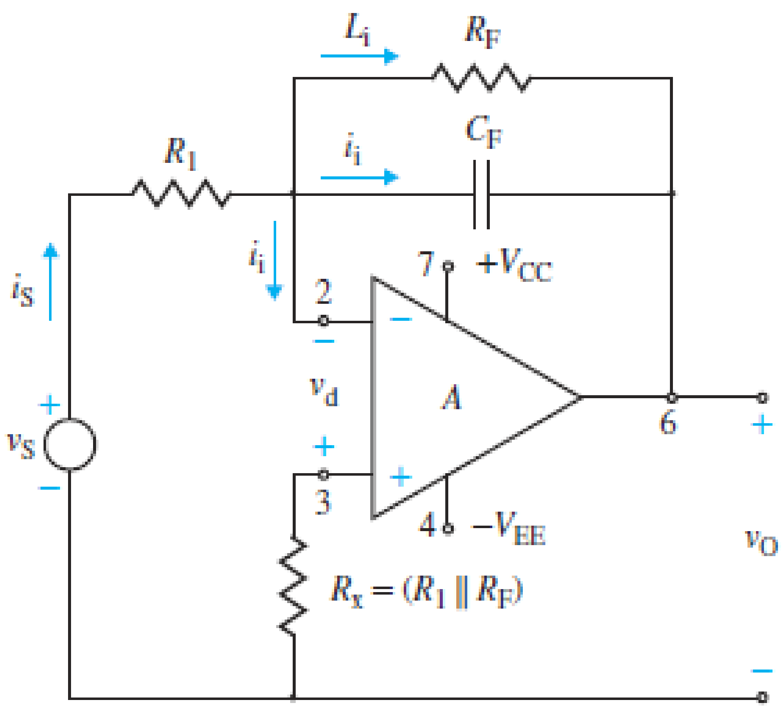
Closed-Loop Gain of a Practical Integrator

- **Voltage gain:**

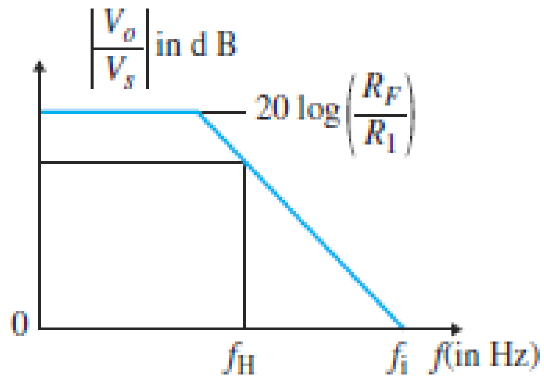
$$A_f(j\omega) = \frac{V_o(j\omega)}{V_s(j\omega)} = -\frac{R_F / R_1}{1 + j\omega C_F R_F}$$

- **The cutoff frequency:**

$$f_H = -\frac{1}{2\pi R_F C_F}$$



(a) Circuit



(b) Magnitude plot

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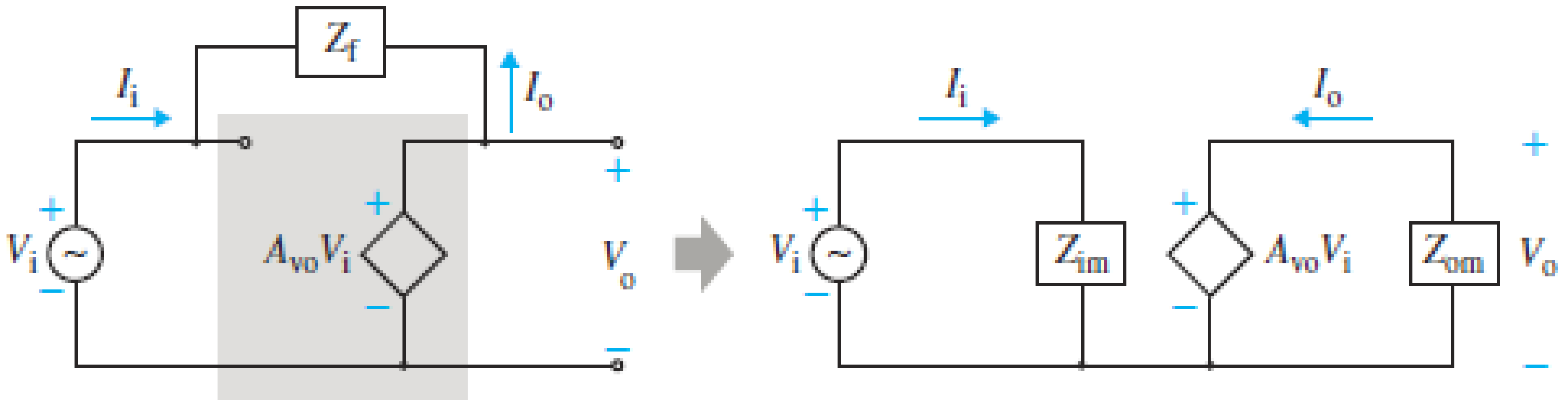
Miller's Theorem and Capacitance

- Miller's theorem simplifies the analysis of feedback amplifiers.
- If an impedance is connected between the input side and the output side of a voltage amplifier, this impedance can be replaced by two equivalent impedances—one connected across the input and the other connected across the output terminals.



(a) Feedback amplifier (b) Miller equivalent

Miller's Theorem and Capacitance (cont'd)

- Output impedance Z_{om} :

$$Z_{om} = \frac{V_o}{I_o} = \frac{Z_f}{1 - 1/A_{vo}}$$

- Equivalent Miller's input and output capacitances:

$$C_{im} = (1 - A_{vo})C_F$$

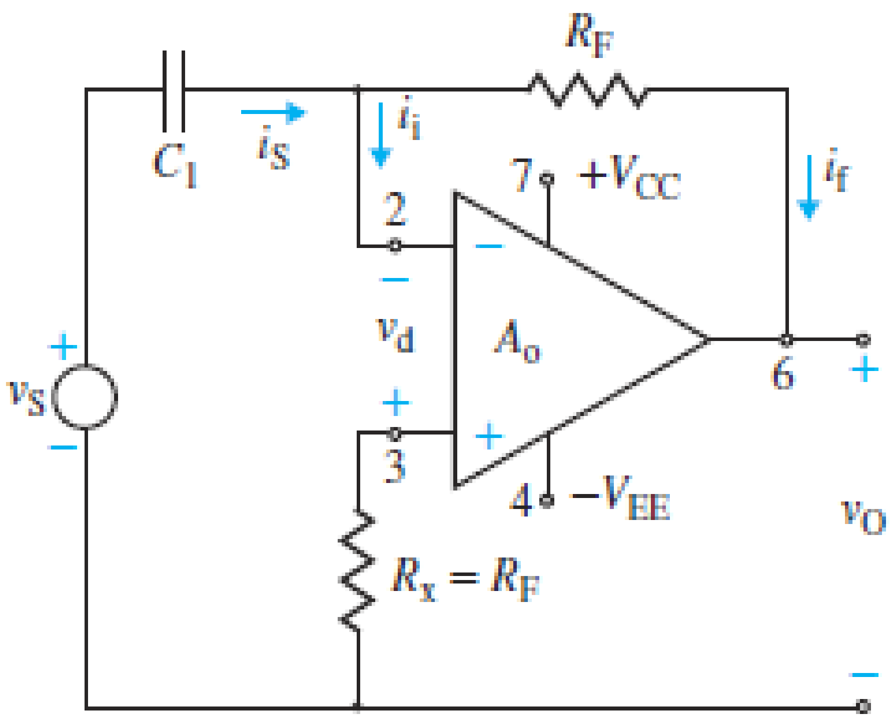
$$C_{om} = (1 - 1/A_{vo})C_F$$

Differentiators

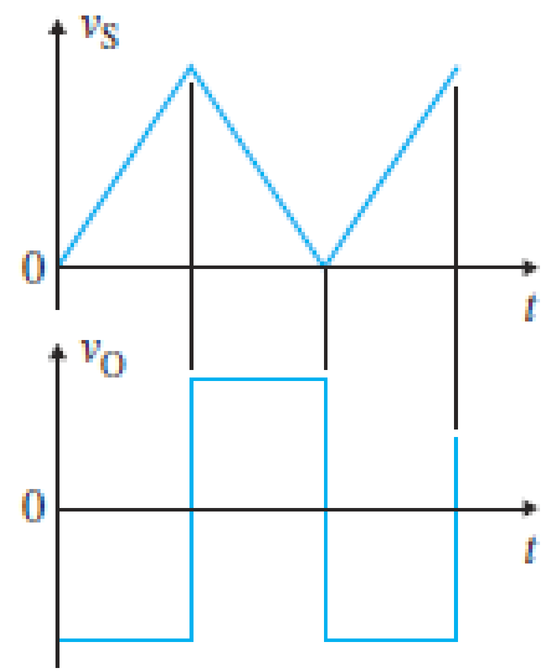
- If the resistance R_1 in the inverting amplifier is replaced by a capacitance C_1

- Closed-Loop Gain of an Ideal Differentiator:

$$v_O = -R_F C_1 \frac{dv_S}{dt}$$



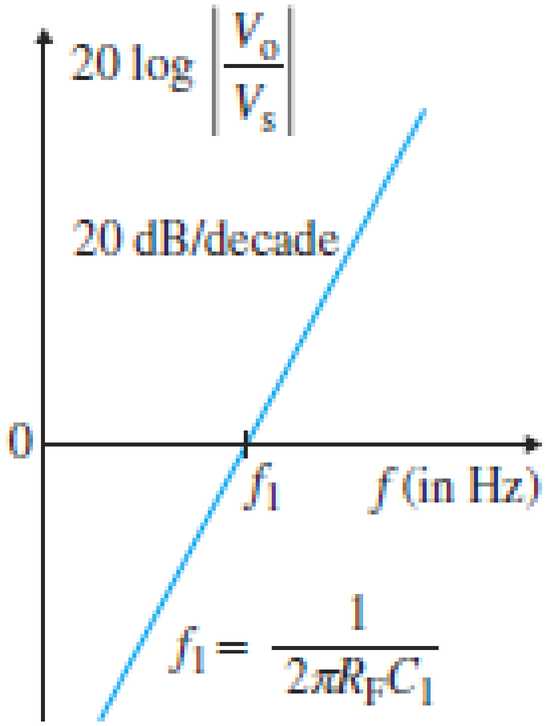
(a) Circuit



(b) Waveforms

Differentiators

- If the resistance R_1 in the inverting amplifier is replaced by a capacitance C_1
- Closed-Loop Gain of an Ideal Differentiator:



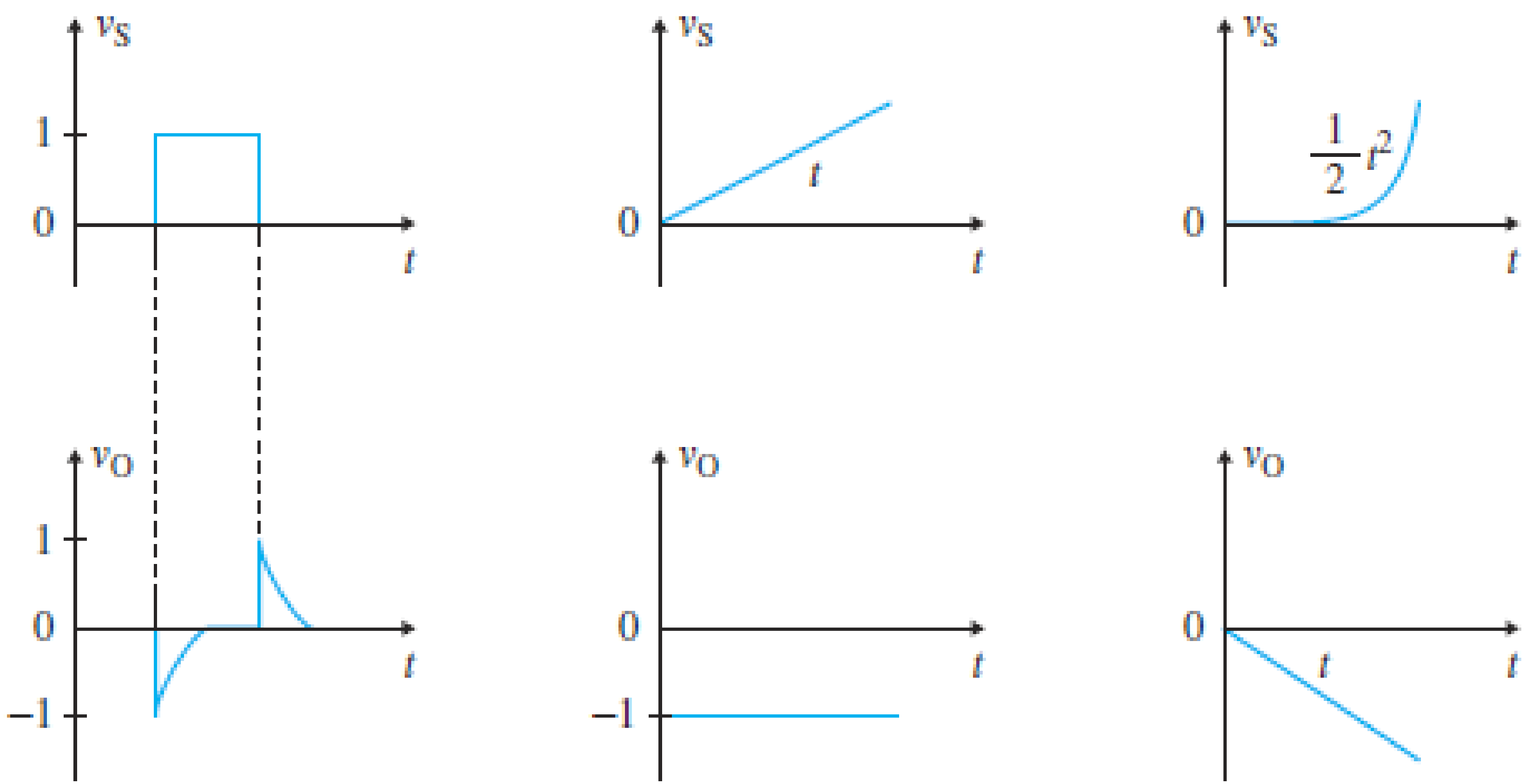
(c) Magnitude plot

$$v_O = -R_F C_1 \frac{dv_S}{dt}$$

Frequency Response of an Ideal Differentiator

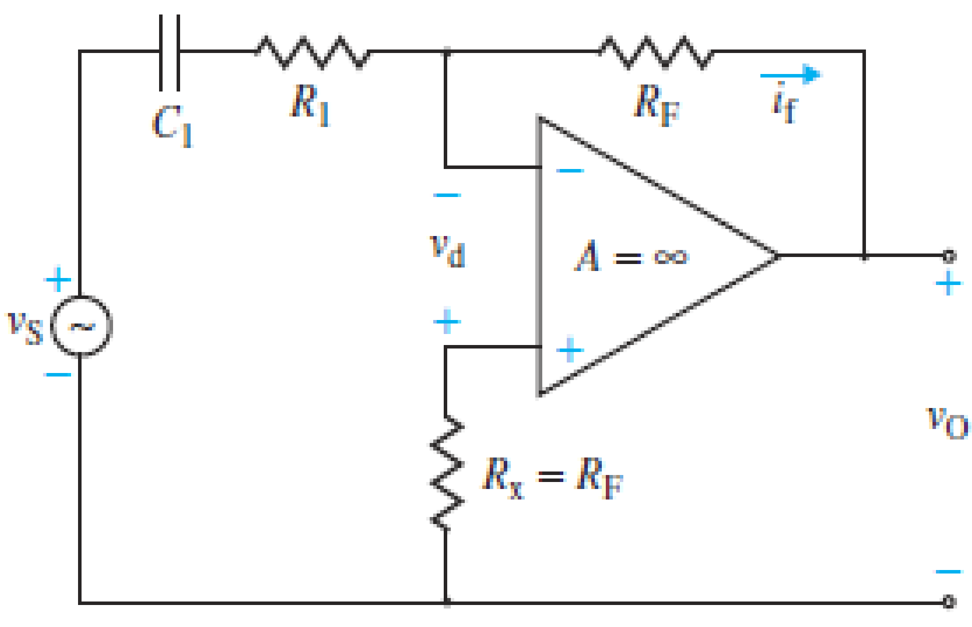
$$A_f(j\omega) = -j\omega C_1 R_F$$

- Voltage gain:

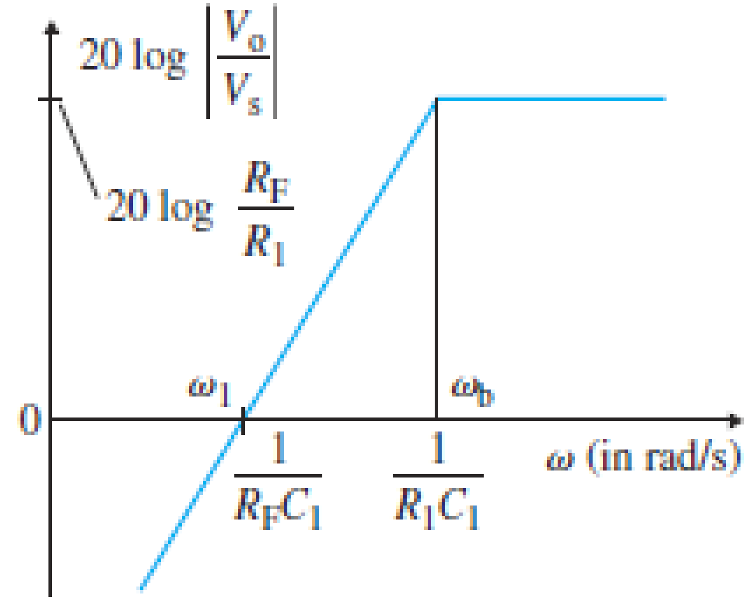


Closed-Loop Gain of a Practical Differentiator

$$A_f(j\omega) = -\frac{R_F C_1 j\omega}{1 + j\omega R_1 C_1}$$



(a) Circuit



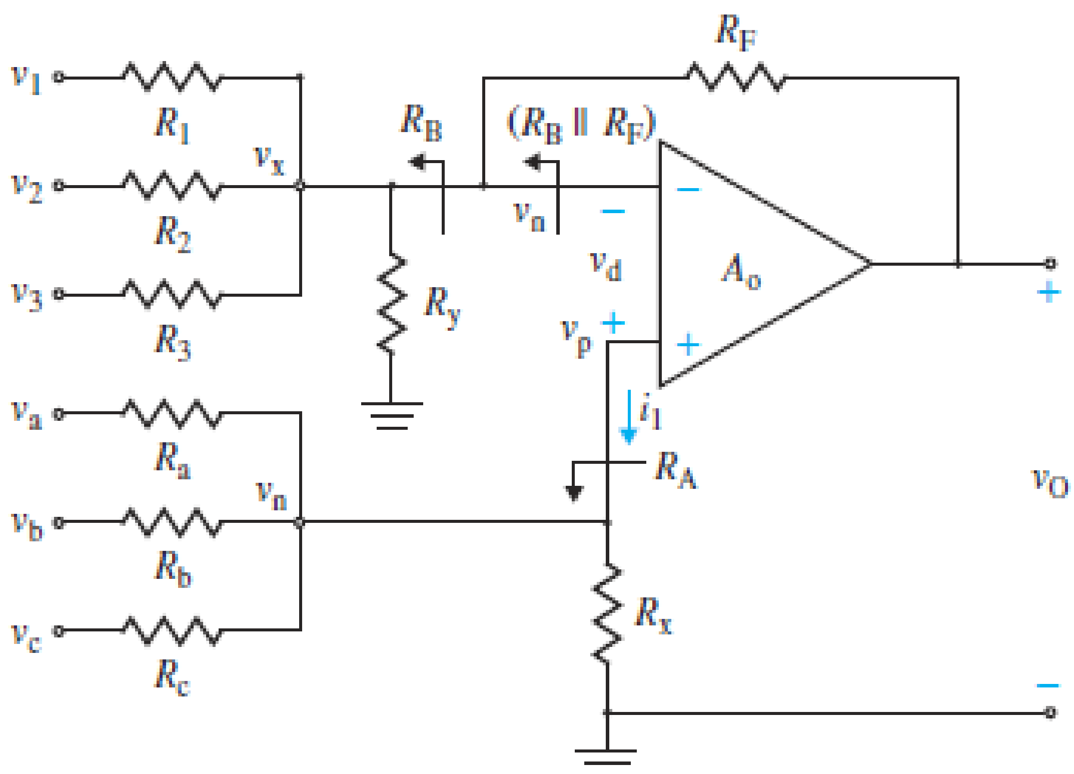
(b) Magnitude plot

Addition–Subtraction Amplifiers

$$v_o = \left(1+\frac{R_F}{R_B}\right)\left(\frac{R_A}{R_a}v_a + \frac{R_A}{R_b}v_b + \frac{R_A}{R_c}v_c\right) - \left(\frac{R_F}{R_1}v_1 + \frac{R_F}{R_2}v_2 + \frac{R_F}{R_3}v_3\right)$$

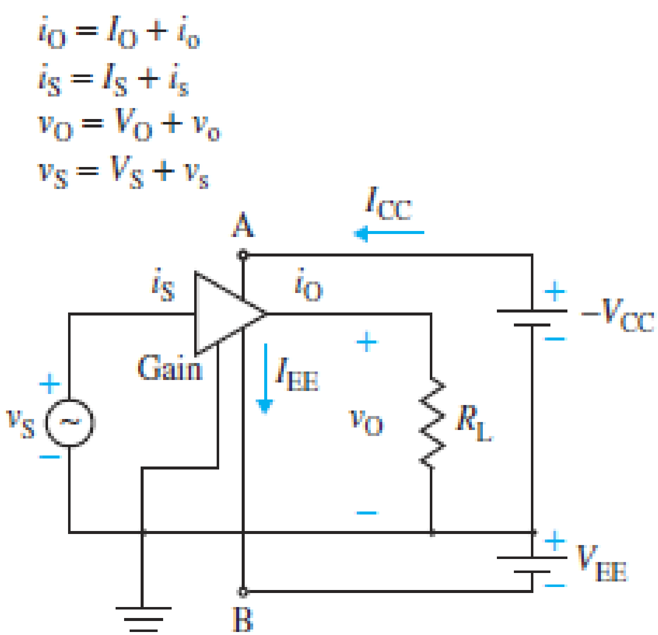
$$R_A = (R_a \,||\, R_b \,||\, R_c \,||\, R_x)$$

$$R_B = (R_1 \,||\, R_2 \,||\, R_3 \,||\, R_y)$$

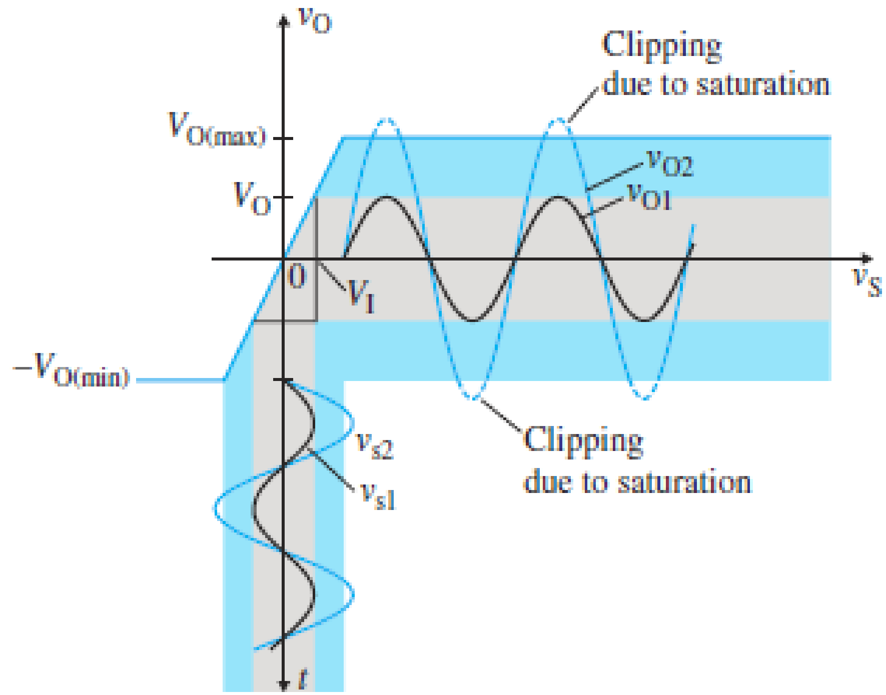


Large-Signal Operations -Output Voltage Saturation

- The output voltage of the amplifier cannot exceed the positive saturation limit $V_{O(max)}$ and cannot decrease below the negative saturation limit $-V_{O(min)}$.
- As long as the amplifier operates with the saturation limits, the voltage gain can normally be assumed to be linear.



(a) Amplifier with DC supplies

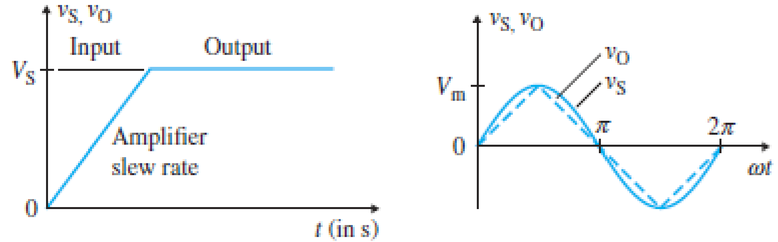


(b) Effect of saturation

Some Definitions on Op-Amps

- **Rise Time:** the time required for the output voltage to rise from 10% to 90% of the steady-state value.

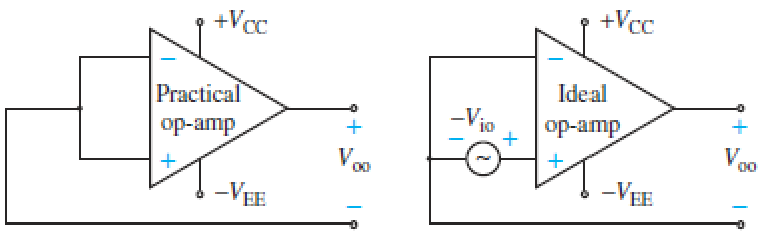
- **Slew rate (SR):** the maximum rate of rise of the output voltage per unit time, and it is measured in volts per microsecond.



(a) Step input (b) Sinusoidal input

Input Offset Voltage

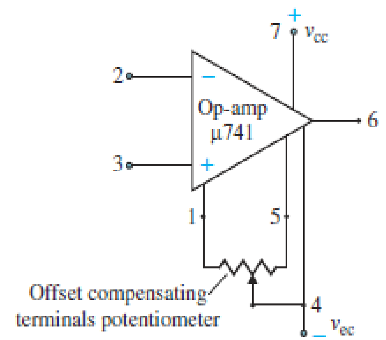
- If the input terminals of an op-amp are tied together and connected to the ground, a certain DC voltage exits at the output. This voltage is called the output offset voltage V_{oo}.
- Any differential signal between the input terminals is amplified and gives the output voltage V_{oo}.



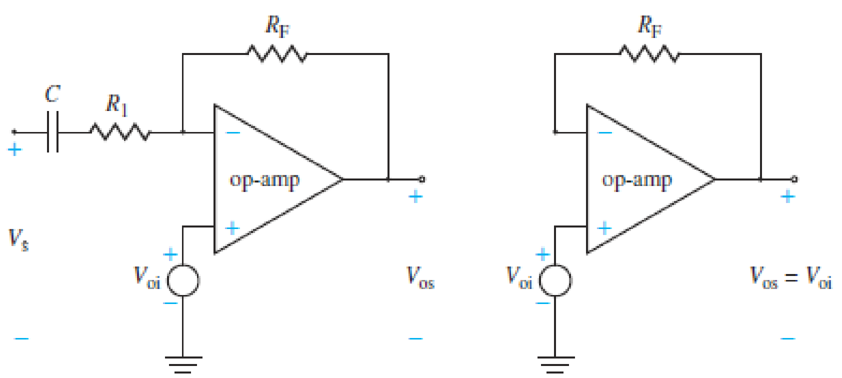
(a) Input terminals grounded (b) Input offset voltage

Minimizing Output Offset Voltage

- Two ways to minimize the output offset voltage:
- (a) Compensating Network:



- (b) Capacitor Coupling:



(a) Circuit (b) Equivalent

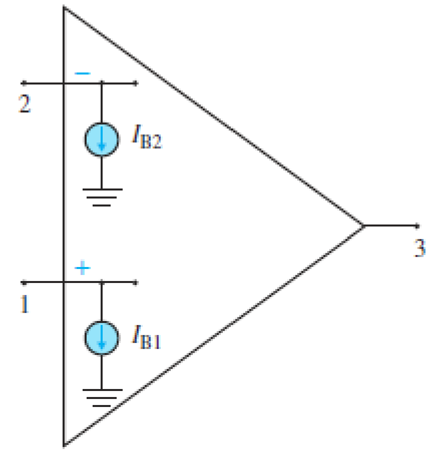
Input Offset Current

- The DC input base currents will be equal only if the internal transistors have equal current gains (betas).
- The average value I_B is called the input bias current and is given by:

$$I_B = \frac{I_{B1} + I_{B2}}{2}$$

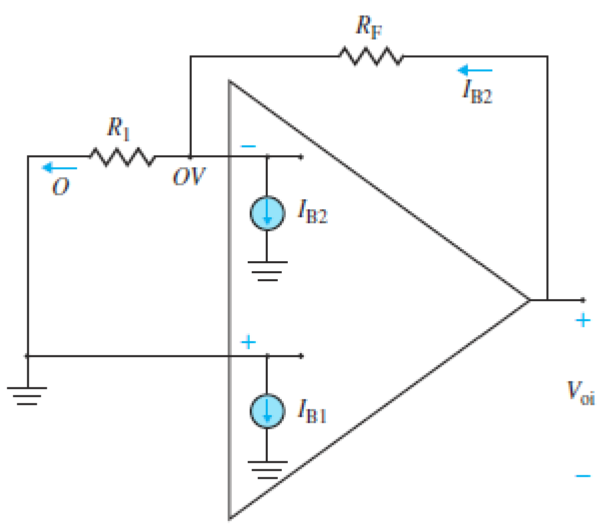
- Input offset current

$$I_{io} = | I_{B1} - I_{B2} |$$



Effect of Input Offset Current

$$V_+ = -R_x I_{B1}$$



Op-Amp Circuit Design

The design sequence:

- **Step 1.** Study the problem.
- **Step 2.** Create a block diagram of the solution.
- **Step 3.** Find a hand-analysis circuit-level solution.
- **Step 4.** Use PSpice/Multisim/SPICE for verification.
- **Step 5.** Construct the circuit in the lab and take measurements.

Chapter 2 Summary

- An op-amp is a high-gain differential amplifier that can perform various functions in electronic circuits.
- The analysis of an op-amp circuit can be simplified by assuming ideal characteristics. An ideal op-amp has a very high voltage gain, a very high input resistance, a very low output resistance, and a negligible input current.
- The characteristics of practical op-amps differ from the ideal characteristics, but analyses based on the ideal conditions are valid for many applications and provide the starting point for practical circuit design.
- Although the DC model of op-amps can be used to analyze complex op-amp circuits, it does not take into account the frequency dependence and op-amp nonlinearities.