國立勤益科技大學
National Chin-Yi University of Technology

Sedra/Smith

Microelectronic Circuits 6/E

Chapter 2: Operational Amplifiers

【Outline】

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2.2 The Inverting Configuration

2.3 The Noninverting Configuration

2.4 Difference Amplifiers

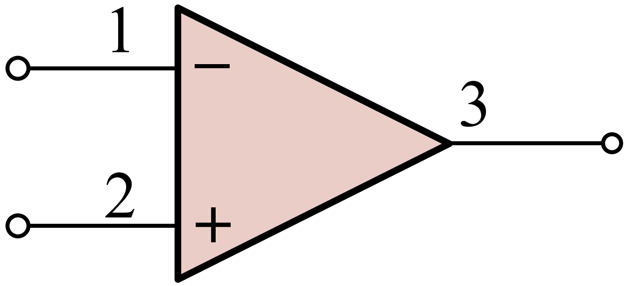
2.5 Integrators and Differentiators

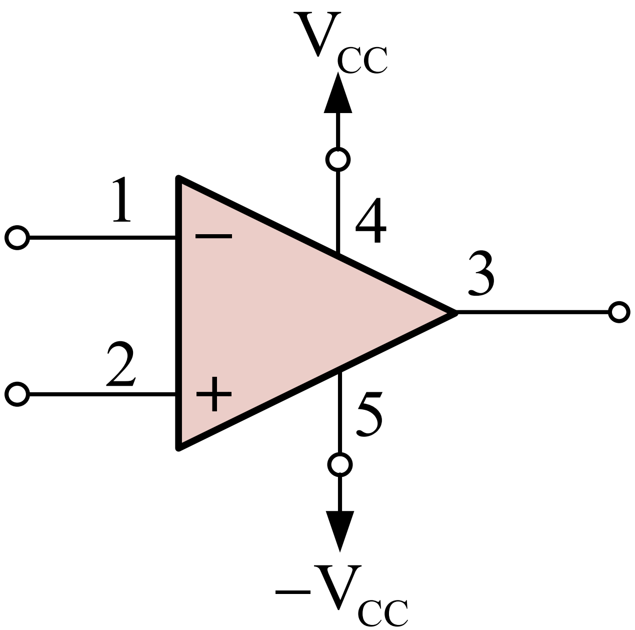
2.6 DC Imperfections

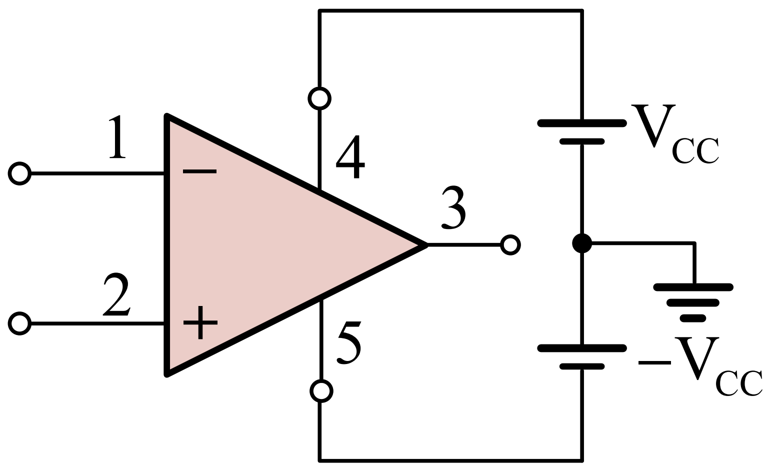
2.7 Effect of Finite Open-Loop Gain and Bandwidth on Circuit Performance

2.8 Large-Signal Operation of Op Amp

2-1 The ideal op amp







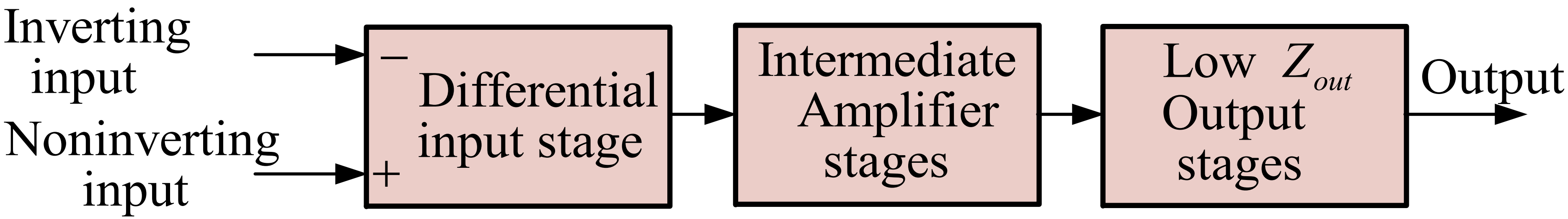
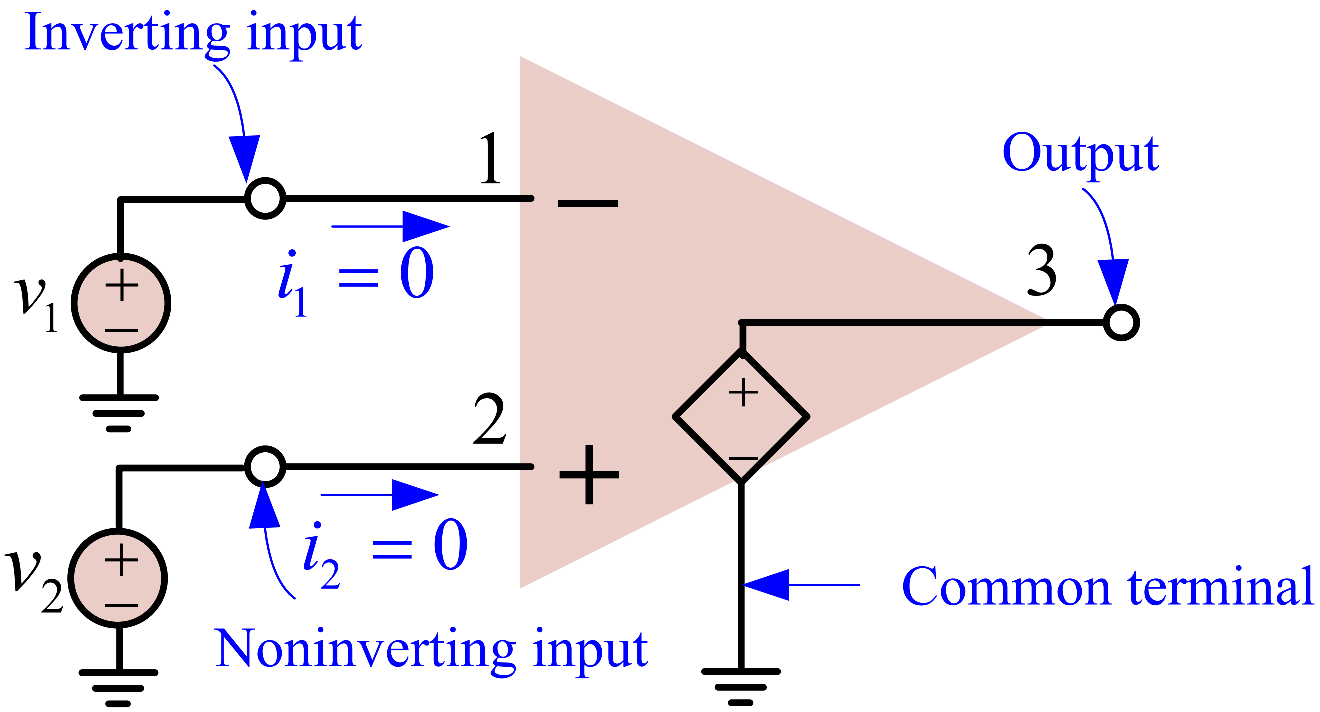


Figure 1. Block diagram of an operational amplifier

The properties associated with an ideal Amplifier are:

1. infinite voltage gain ($A_v \to \infty$)
2. Infinite input impedance ($Z_{in} \to \infty$)
3. Zero output impedance($Z_{out} \to 0$)
4. Output voltage $V_{out} = 0$ when input voltages $V_1 = V_2$
5. Infinite bandwidth (no delay of the signal through the amplifier)

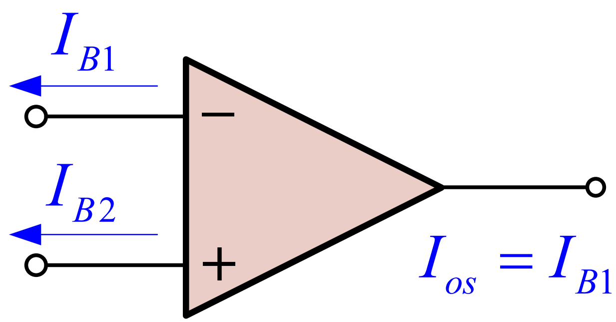
2.1.2 Function and Characteristics of the ideal Op Amp



(virtual short circuit: $v_i = 0, I_i = 0, R_{in} = \infty$)

Some Specifications

1. Open loop gain (A_{ol}): Usually several thousand.
2. Input offset voltage (V_{os}): Small, usually a few millivolts.
3. Input offset current (I_{os}): Usually between a few and several hundred nanoamps.



$$I_{os} = I_{B1} - I_{B2}$$

4. Input resistance (R_{in}):Typically greater than one megohm, but it can be as high as several hundred megohms.
5. Output resistance (R_{out}): Usually less than a few hundred ohms.
6. Slew rate (S): The maximum rate of output voltage change given in volts per microsecond.

7. $\text{CMRR} = \dfrac{A_d}{A_{cm}}$

2.1.3 Differential and Common-Mode Signal

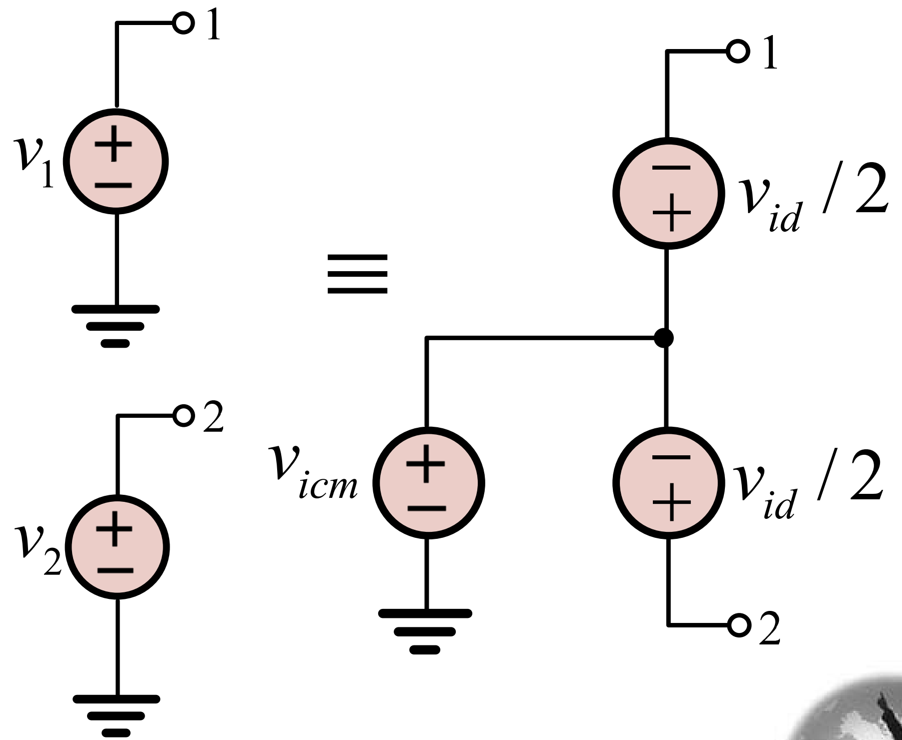
The difference input signal v_{id} :

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

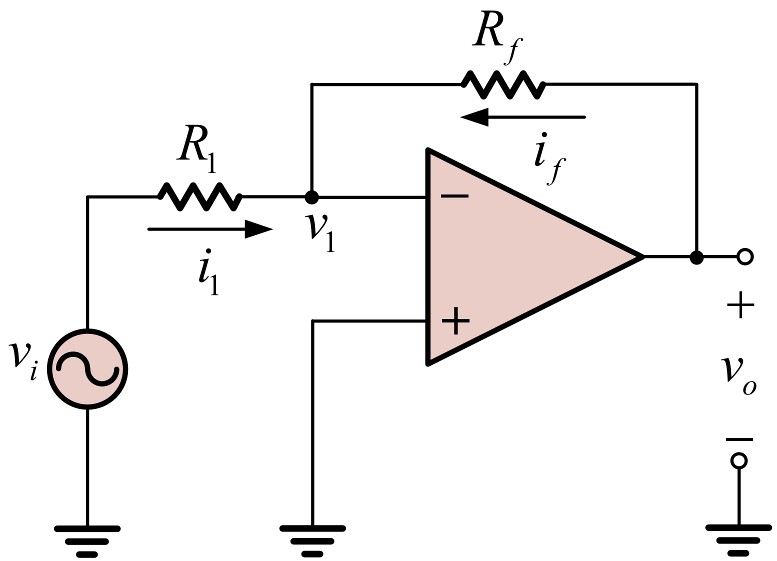
The Common-mode input signal v_{icm} :

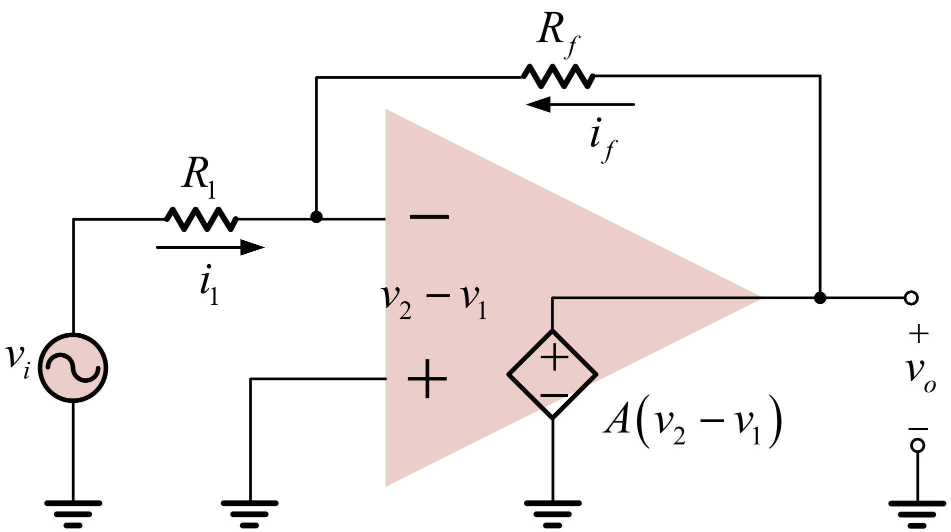
$$v_{icm} = \left(v_2 + v_1\right)/2$$

$$\Rightarrow \begin{cases} v_1 = v_{icm} - v_{id}/2 \\ v_2 = v_{icm} + v_{id}/2 \end{cases}$$



2.2 The inverting configuration





$$v_2 - v_1 = \frac{v_o}{A} = 0$$

(virtual short circuit:

$v_i = 0, I_i = 0, R_{in} = \infty$)

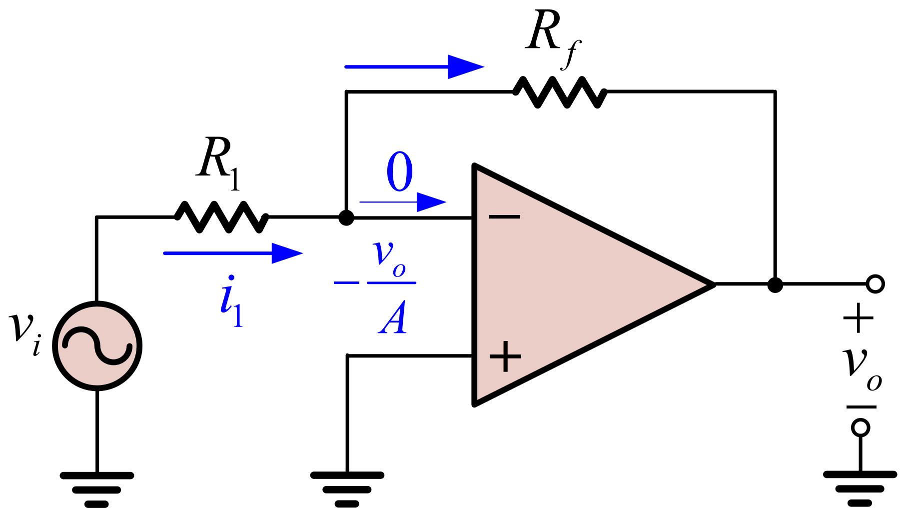
$$i_1 = \frac{v_i - v_1}{R_1} = \frac{v_i - 0}{R_1} = \frac{v_i}{R_1}$$

$$v_o = v_1 + i_f R_f = v_1 - i_1 R_f$$

$$= 0 - \frac{v_i}{R_1} R_f$$

$$G = \frac{v_o}{v_i} = -\frac{R_f}{R_1}$$

2.2.2 Effect of Finite Open-Loop Gain

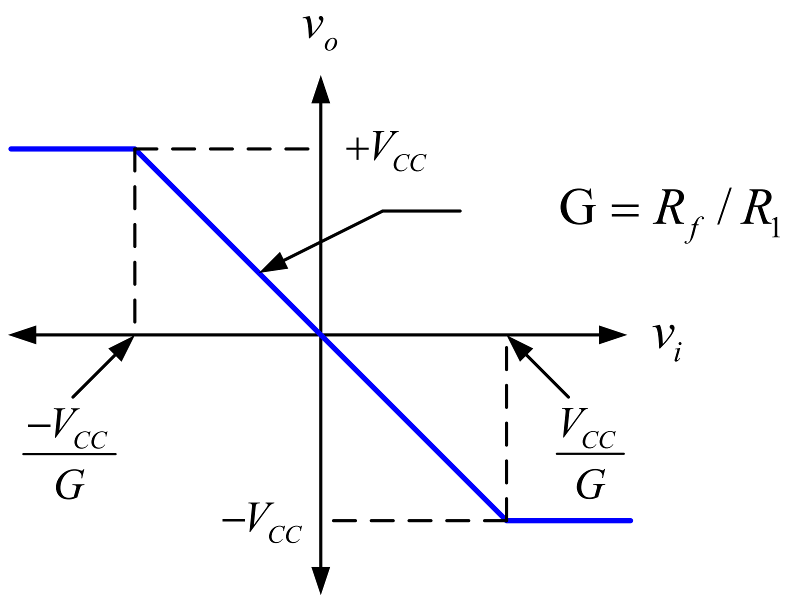


$$i_1 = \frac{v_i - (-v_o / A)}{R_1}$$

$$= \frac{v_i + v_o / A}{R_1}$$

$$v_o = -\frac{v_o}{A} - i_1 R_f$$

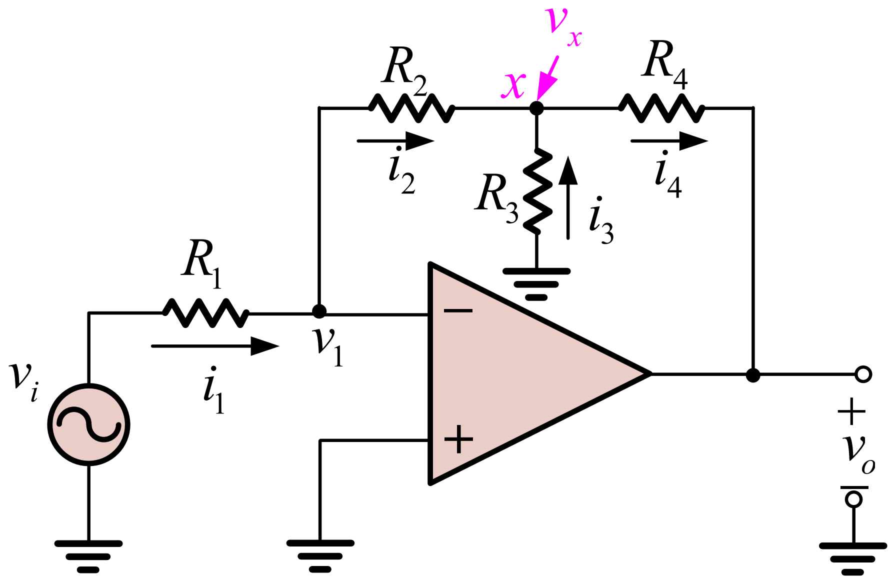
$$= -\frac{v_o}{A} - \left(\frac{v_i + v_o / A}{R_1}\right) R_f$$



$$G \equiv \frac{v_o}{v_i} = \frac{-R_f / R_1}{1 + (1 + R_f / R_1) / A} \qquad (2.5)$$

when $A \to \infty, G \to -R_f / R_1$

Example2.2: Assuming the op amp to be ideal, derive an expression for closed-loop gain $v_o / v_i = ?$



Solution

$$v_i = \frac{-v_o}{A} = \frac{-v_o}{\infty} = 0 \text{ (virtual short)}$$

$$i_1 = -\frac{v_i - v_1}{R_1} = \frac{v_i}{R_1}$$

$$i_2 = i_1 = \frac{v_i}{R_1}$$

$$v_x = v_1 - i_2 R_2 = 0 - \left(\frac{v_i R_2}{R_1}\right)$$

$$= -v_i R_2 / R_1$$

$$i_3 = \frac{0 - v_x}{R_3} = \frac{R_2}{R_1 R_3} v_i$$

$$i_4 = i_2 + i_3 = \frac{v_i}{R_1} + \frac{R_2}{R_1 R_3} v_i$$

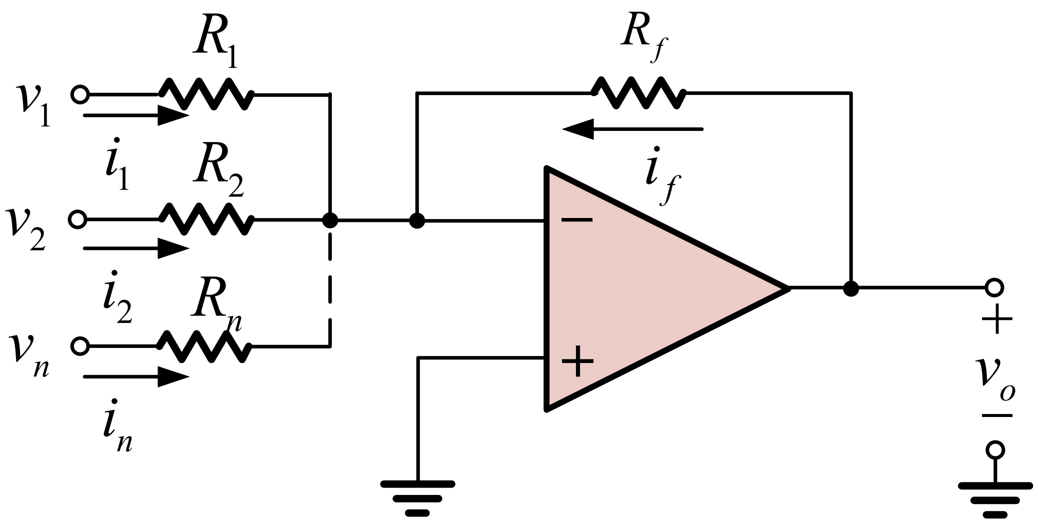
$$v_0 = v_x - i_4 R_4$$

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

$$\frac{v_0}{v_i} = -\frac{R_2}{R_1}\left(1 + \frac{R_4}{R_2} \frac{R_4}{R_3}\right)$$

▲

2.2.4 An Important Application – The Weighted Summer



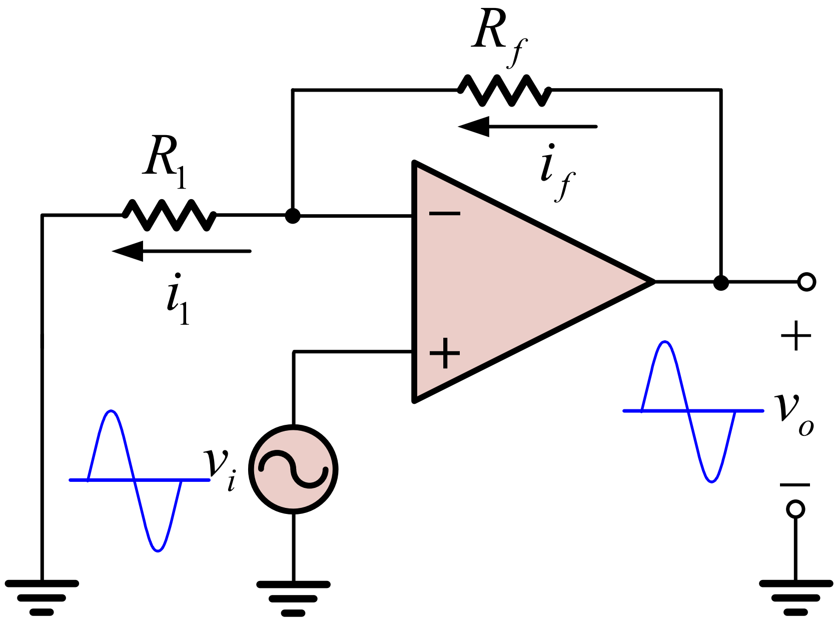
$$i_1 = \frac{v_1}{R_1}, i_2 = \frac{v_2}{R_2}, I_n = \frac{v_n}{R_n}, \quad I_f = \frac{v_o}{R_f}$$

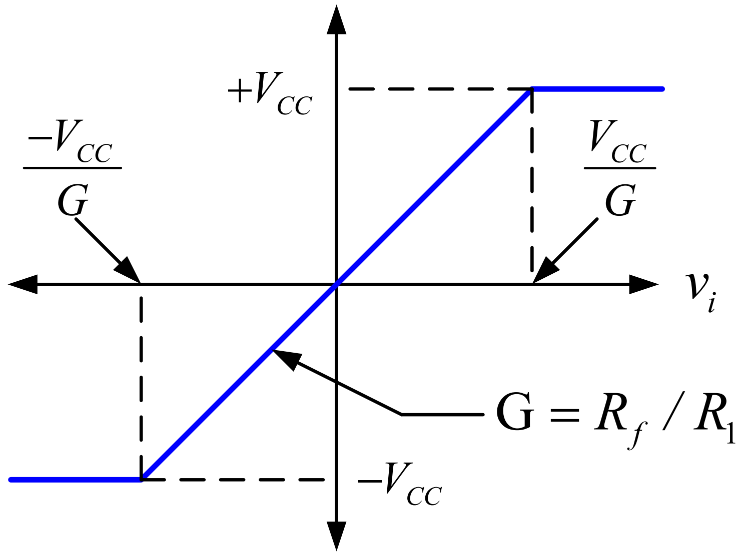
$$I_f = -(I_1 + I_2 + \cdots + I_3) \quad \Rightarrow \frac{v_o}{R_f} = -\left(\frac{v_1}{R_1} + \frac{v_2}{R_2} + \cdots + \frac{v_n}{R_n}\right)$$

$$v_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \cdots + \frac{R_f}{R_n}v_n\right) \qquad (2.7)$$

If $R_1 = R_2 = \cdots = R_n = R_f$ Then $v_o = -(v_1 + v_2 + \cdots + v_n)$

2.3 The Noninverting Configuration





$$i_1 = \frac{v_i}{R_1}, \quad i_f = \frac{v_o - v_i}{R_f}$$

$$i_1 = i_f \Rightarrow \frac{v_i}{R_1} = \frac{v_o - v_i}{R_f} \qquad \Rightarrow v_o = (1 + \frac{R_f}{R_1})v_i$$

2.3.3 Effect of Finite Open-Loop Gain

$$v_- = v_i - (v_o / A)$$

$$i_1 = \frac{v_i - (v_o / A)}{R_1}, i_f = \frac{v_o - [v_i - (v_o / A)]}{R_f} = \frac{v_o - v_i + (v_o / A)}{R_f},$$

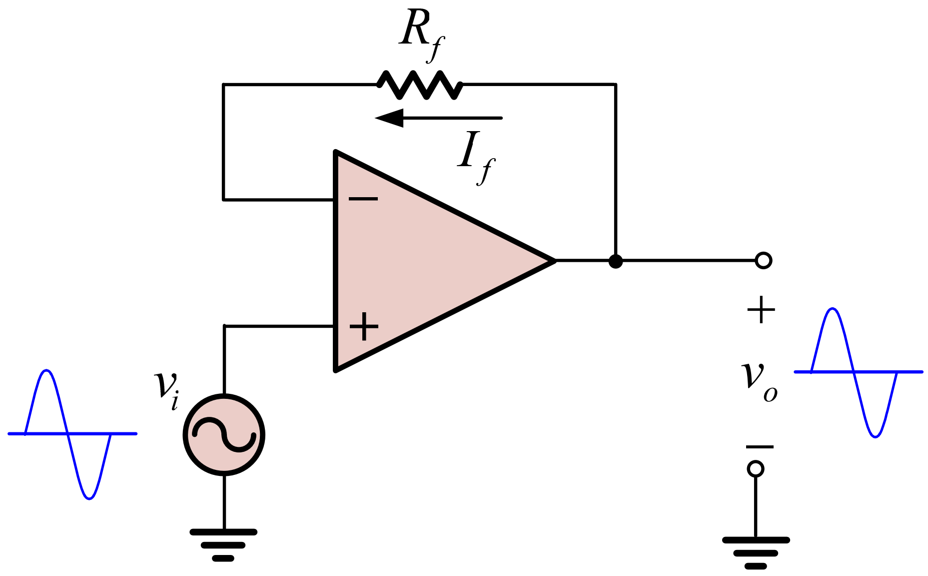
$$i_1 = i_f \Rightarrow \frac{v_i - (v_o / A)}{R_1} = \frac{v_o - v_i + (v_o / A)}{R_f}$$

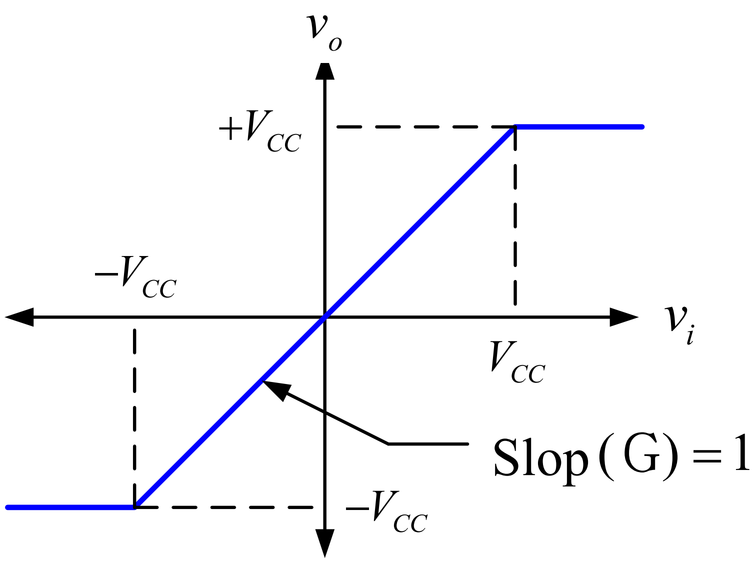
$$v_i A(R_1 + R_f) = v_o \left[(1 + A)R_1 + R_f \right]$$

$$G \equiv \frac{v_o}{v_i} = \frac{1 + (R_f / R_1)}{1 + \frac{1 + (R_f / R_1)}{A}} \qquad (2.11)$$

when $A \to \infty, G \to 1 + (R_f / R_1)$

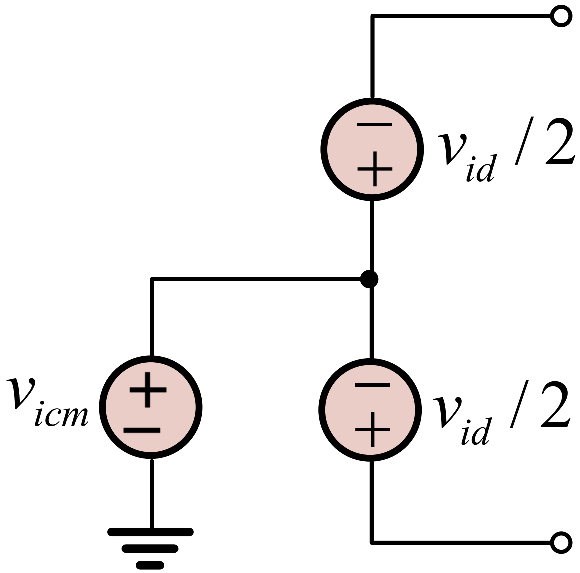
2.3.4 The Voltage Follower





$$v_o = v_i, \quad R_{in} = \infty, \quad R_{out} = 0$$

2.4 Difference Amplifiers



$$v_{i1} = v_{icm} - v_{id}/2$$

$$v_{id} = v_{i1} - v_{i2}$$

$$v_{icm} = \left(v_{i1} + v_{i2}\right)/2$$

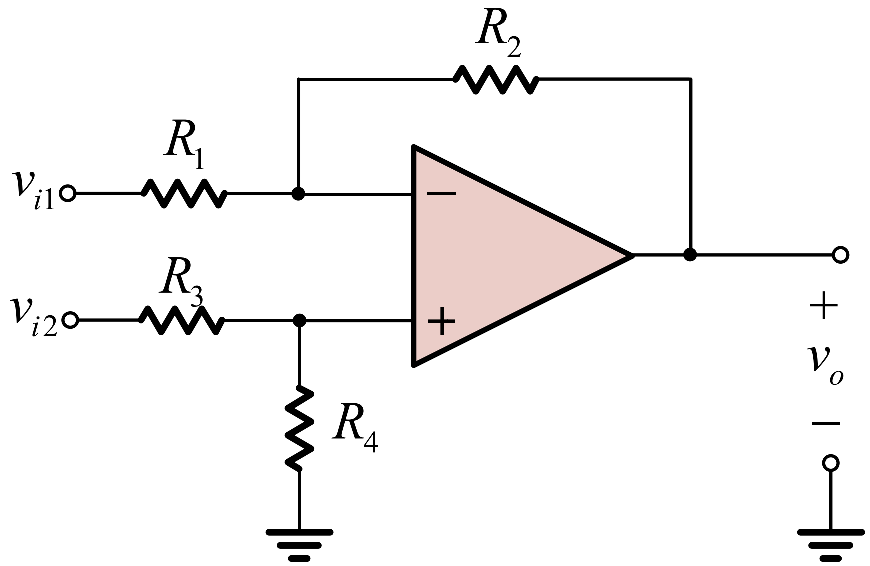
$$v_{i2} = v_{icm} + v_{id}/2$$

$$v_o = A_d v_{id} + A_{cm} v_{icm} = A_d v_{id} + A_d v_{id} \frac{A_{cm} v_{icm}}{A_d v_{id}}$$

$$= A_d v_{id} \left(1 + \frac{A_{cm} v_{icm}}{A_d v_{id}}\right) = A_d v_{id} \left(1 + \frac{1}{\text{CMRR}} \frac{v_{icm}}{v_{id}}\right)$$

$$\text{CMRR} = \frac{|A_d|}{|A_{cm}|}, \quad \text{CMRR}_{dB} = 20 \log \frac{|A_d|}{|A_{cm}|} \qquad (2.14)$$

2.4.1 A Single Op-Amp Difference Amplifier



(1) Assume $v_{i1} = 0$,

$$\text{then } v_O{}' = v_+\left(1+\frac{R_2}{R_1}\right)$$

$$= \frac{R_4}{R_3+R_4}v_{i2}\left(1+\frac{R_2}{R_1}\right)$$

(2) Assume $v_{i2} = 0$,

$$\text{then } v_O{}'' = v_{i1}\left(-\frac{R_2}{R_1}\right)$$

$$v_o = v_O{}' + v_O{}''$$

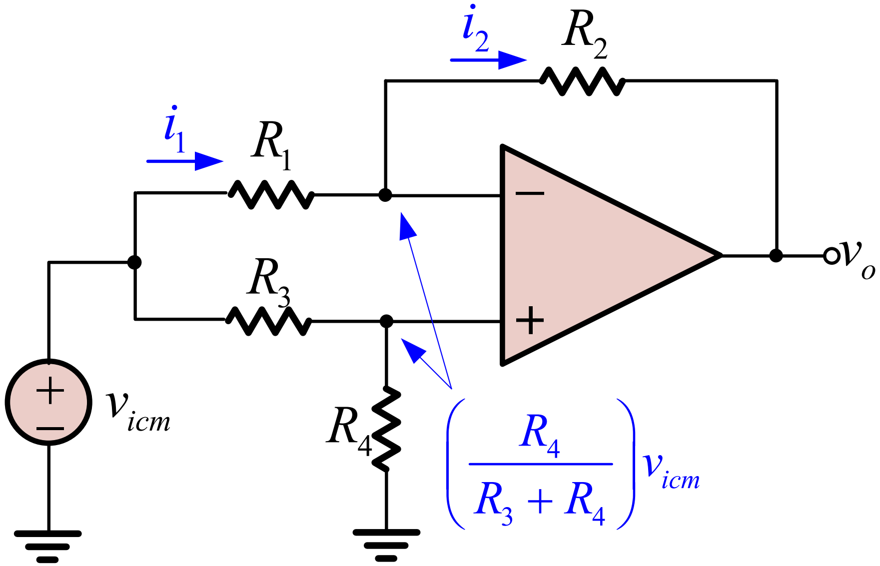
$$= \frac{R_4}{R_3+R_4}v_{i2}\left(1+\frac{R_2}{R_1}\right) + v_{i1}\left(-\frac{R_2}{R_1}\right)$$

If $R_1 = R_3 = R_a, \quad R_2 = R_4 = R_b$

$$\text{then } v_o = \frac{R_b}{R_a}\left(v_{i2} - v_{i1}\right) = \frac{R_b}{R_a}v_{id}$$

$$A_d = \frac{R_b}{R_a} \qquad (2.17)$$

A common-mode signal applied at the input



$$i_1 = i_2 = \frac{1}{R_1}\left[v_{icm} - \frac{R_4}{R_3+R_4}v_{icm}\right]$$

$$= \frac{1}{R_1}\frac{R_3}{R_3+R_4}v_{icm}$$

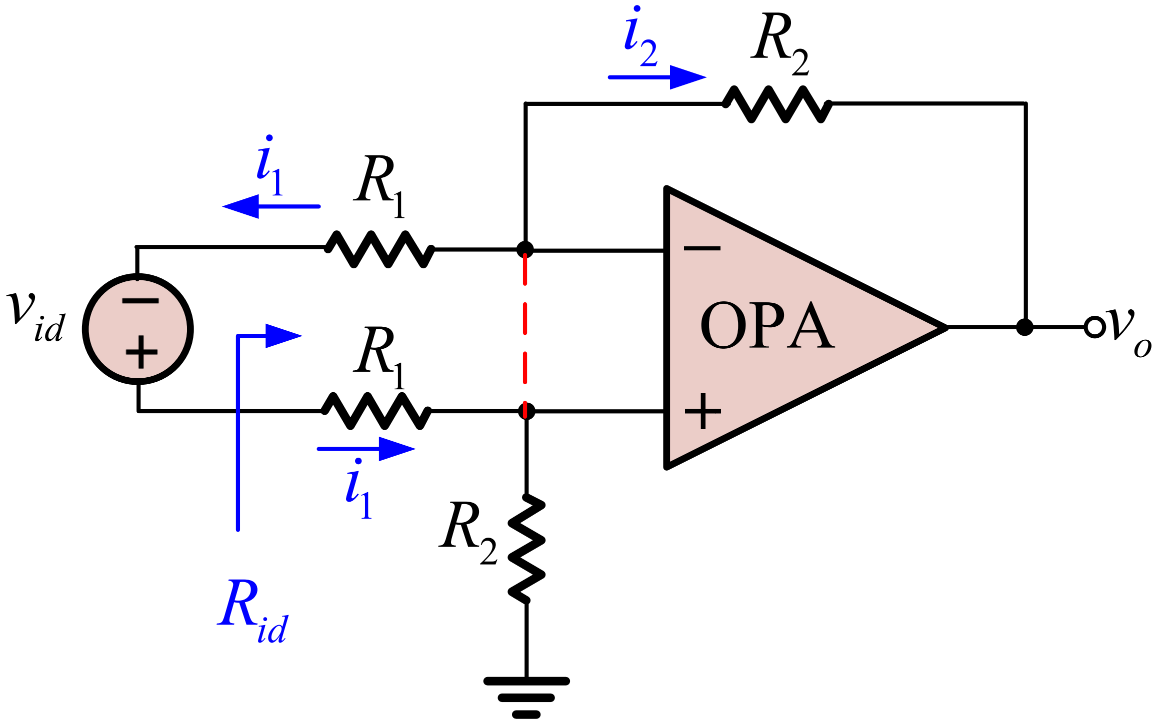
$$v_o = v_{icm}\frac{R_4}{R_3+R_4} - i_2 R_2$$

$$= \frac{R_4}{R_3+R_4}v_{icm} - \frac{R_2}{R_1}\frac{R_3}{R_3+R_4}v_{icm}$$

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

$$A_{cm} = \frac{v_o}{v_{icm}} = \frac{R_4}{R_3+R_4}\left(1 - \frac{R_2}{R_1}\frac{R_3}{R_4}\right), \quad (2.19)$$

If $R_1 = R_3, \quad R_2 = R_4. \Rightarrow A_{cm} = 0$

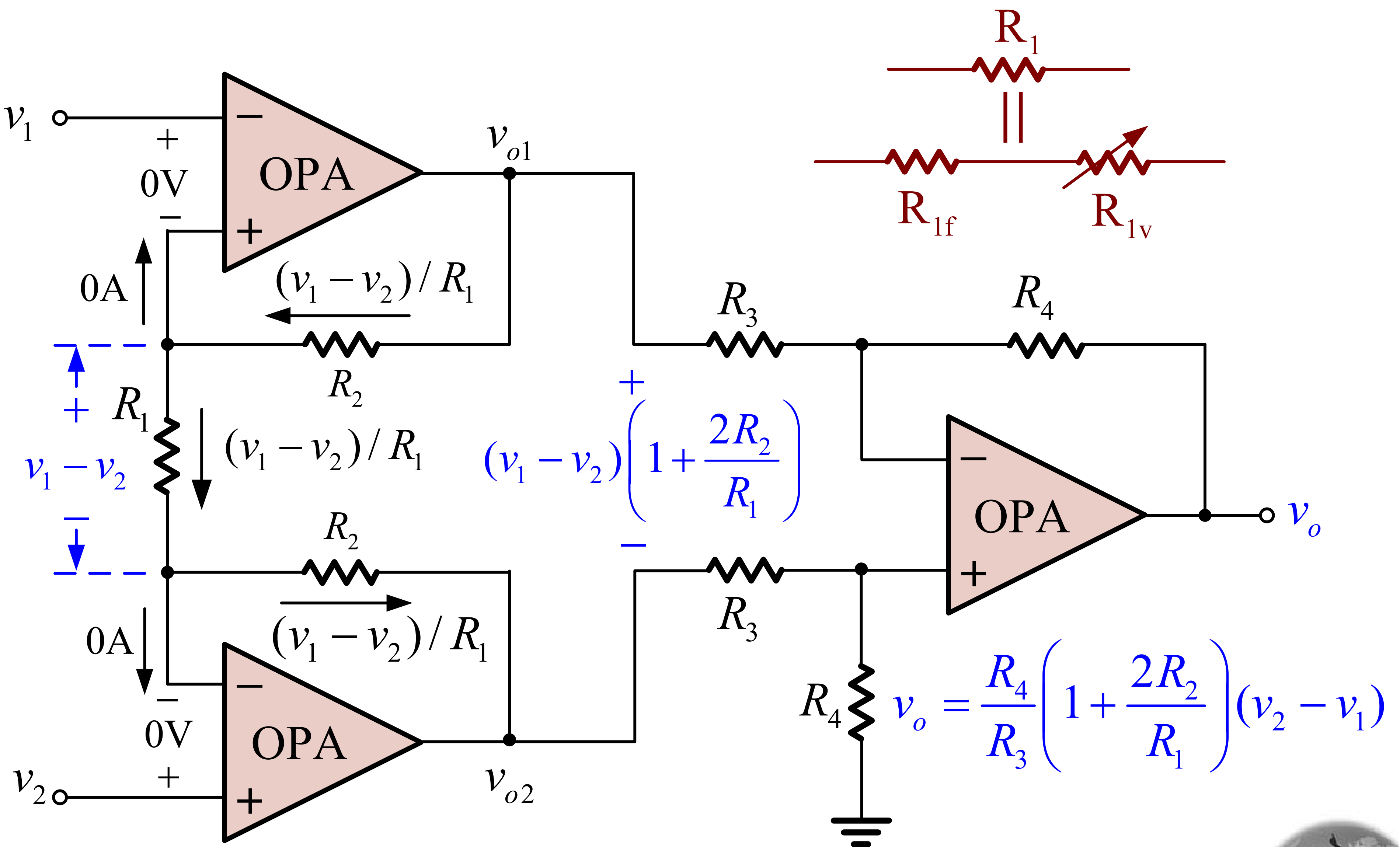


$$R_{id} \equiv \frac{v_{id}}{i_i}$$

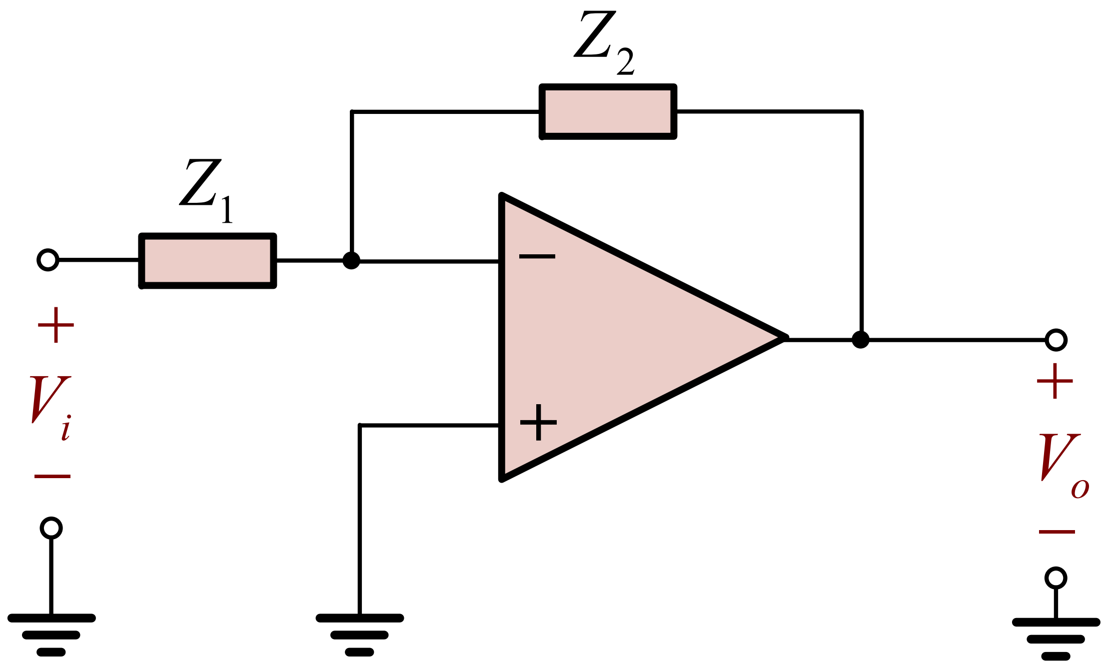
$$v_{id} = R_i i_1 + R_1 i_1$$

$$R_{id} = 2R_1 \qquad (2.20)$$

2.4.2 A Superior Circuit — The Instrumentation Amplifier



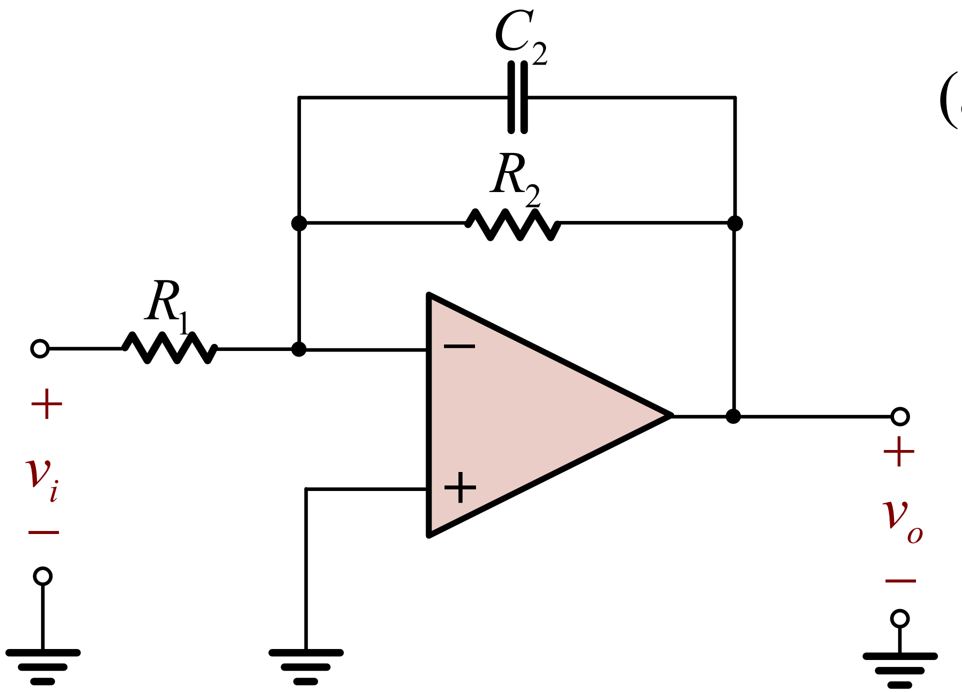
2.5 Integrators and Differentiators



$$\frac{V_o}{V_i} = -\frac{Z_2}{Z_1}$$

Example 2.4

For the circuit in Fig.2.23, (a) derive the transfer function. $v_o(s)/v_i(s)$



Solution:

(a) $$\frac{v_o(s)}{v_i(s)} = -\frac{1}{z_1(s)Y_2(s)}$$

$$= -\frac{1}{R_1\left(\frac{1}{R_2} + sC_2\right)}$$

$$= -\frac{R_2/R_1}{1 + sC_2R_2}$$ ▲

$$\omega_0 = \frac{1}{C_2R_2}$$

(b) find the dc gain

The dc gain $\mathrm{K} = -\dfrac{R_2}{R_1}$

(c) Evaluate 3-dB frequency

the 3-dB frequency $\omega_0 = \dfrac{1}{C_2 R_2}$

(d) design the circuit to obtain a dc gain of 40 dB, a 3-dB frequency of 1 kHz, and input resistance of 1 kΩ.

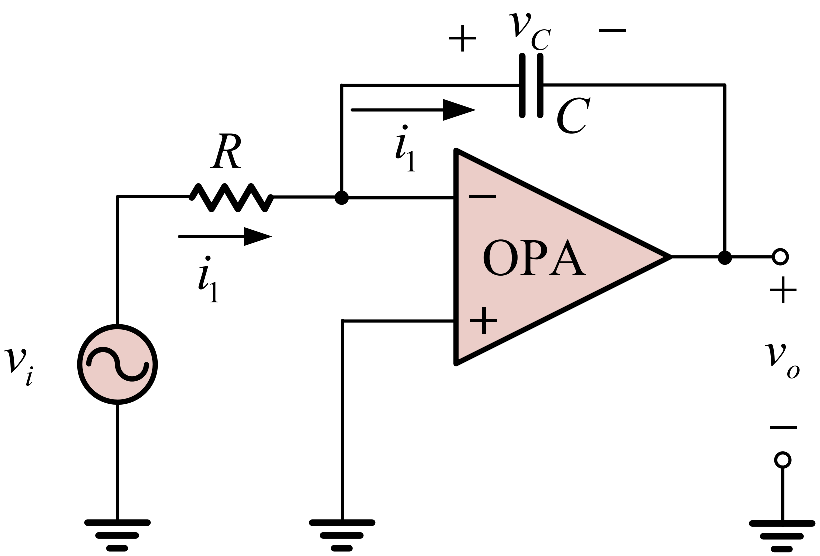
Solution:

In order to obtain a dc gain of 40 dB, we select $\mathrm{R_2/R_1} = 100$.

For an input resistance of 1 kΩ, we select $\mathrm{R_1} =$ 1 kΩ, and thus $\mathrm{R_2} = 100\mathrm{k\Omega}$, for a 3-dB frequency $f_0 = 1\mathrm{kHz}$, we select $\mathrm{C_2}$ from

$$\omega_0 = \frac{1}{C_2 R_2} \Rightarrow C_2 = \frac{1}{\omega_0 R_2} = \frac{1}{2\pi \times 1 \times 10^3 \times 100 \times 10^3} = 1.59n\mathrm{F}.$$

2.5.2 Inverting Integrator

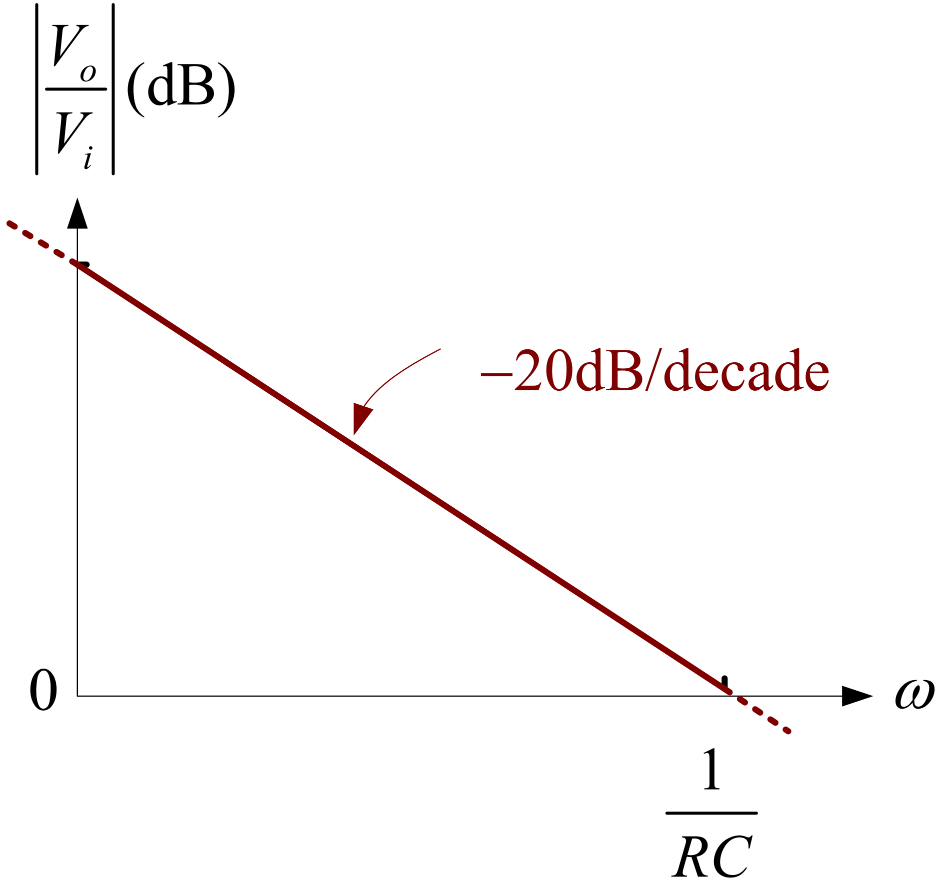


$$v_C(t) = V_C + \frac{1}{C}\int_0^t i_1(t)$$

$$v_o(t) = -v_C(t) = -V_C - \frac{1}{C}\int_0^t i_1(t)$$

We can be described alternatively in the frequency domain

by subtituting $Z_1(s) = R,$ and $\dfrac{1}{Z_2(s)} = Y(s) = sC$



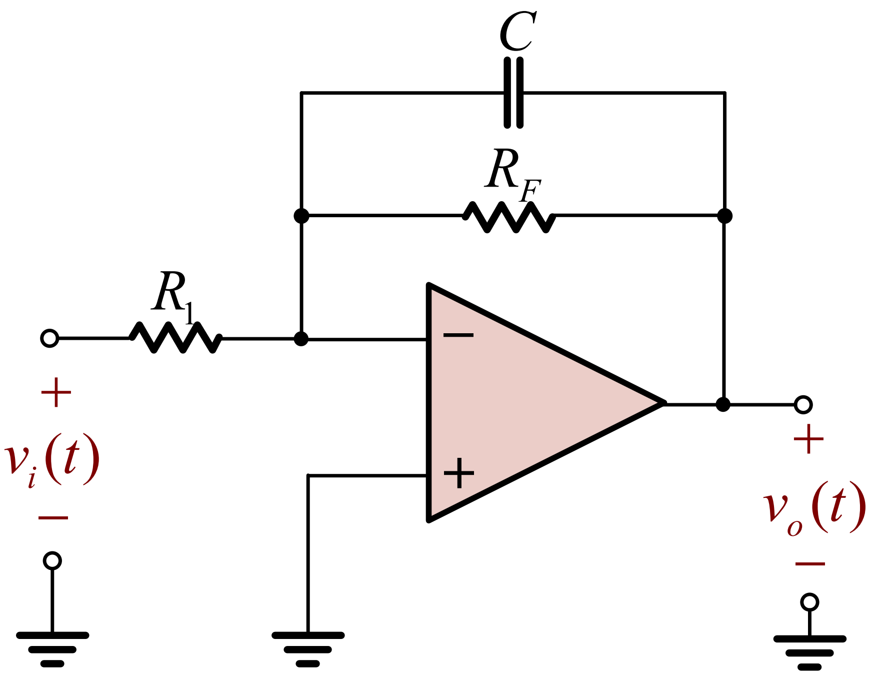
$$\frac{v_o(s)}{v_1(s)} = -\frac{1}{sRC}$$

$$\Rightarrow \frac{v_o(j\omega)}{v_1(j\omega)} = -\frac{1}{j\omega RC}$$

$$\left|\frac{v_o}{v_1}\right| = \frac{1}{\omega RC} = \frac{\omega_t}{\omega}, \quad \angle v_o / v_1 = 90^o$$

the unity gain frequency ω_t as

$$\omega_t = \frac{1}{RC}$$



$$Z_1(s) = R$$

$$Z_2(s) = \frac{1}{\frac{1}{R_F} + sc} = \frac{R_F}{1 + sR_F C}$$

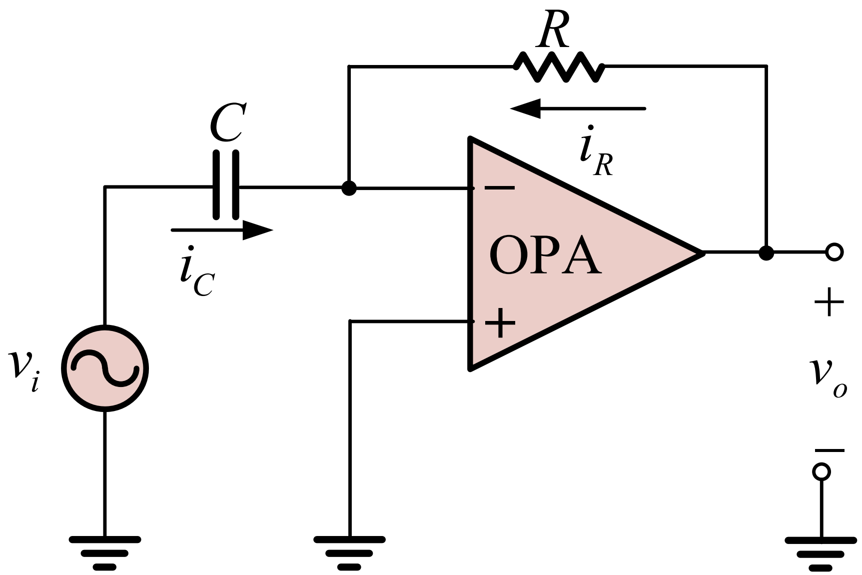
$$\frac{v_o(s)}{v_1(s)} = -\frac{\frac{R_F}{1 + sR_F C}}{R} = -\frac{R_F / R}{1 + sR_F C}$$

the Corner frequency ω as $\dfrac{1}{R_F C}$,

the dc gain as R_F / R

Fig2.42 The Miller integrator with a large resistance R_F connected in parallel with C in order to provide negative feedback and hence finite gain at dc

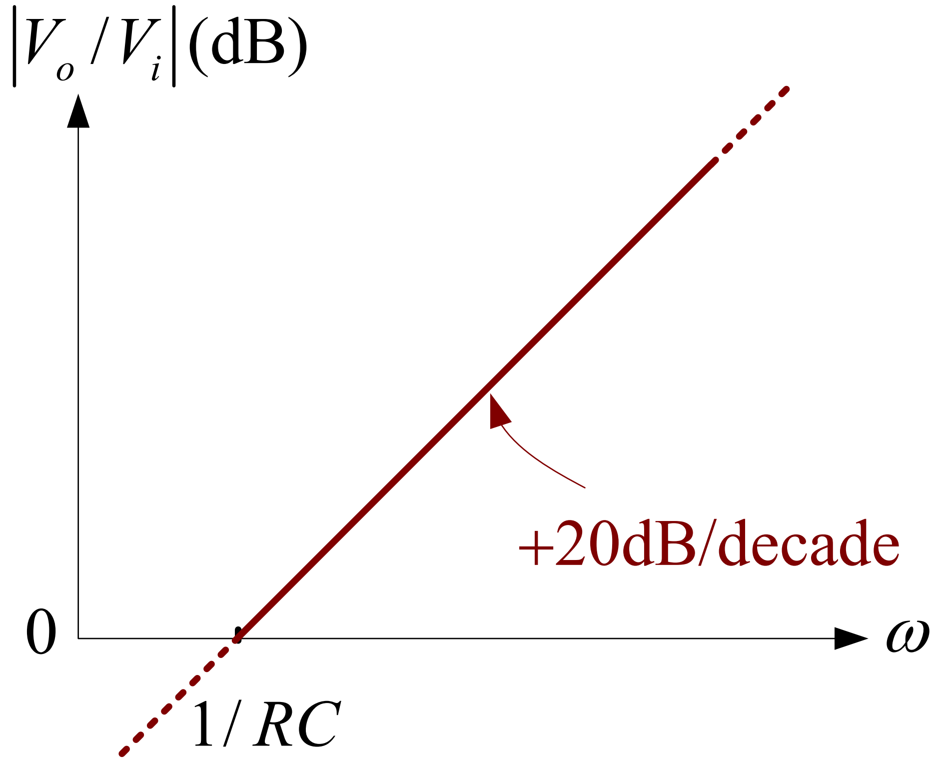
2.5.3 The Op-Amp Differentiator



$$Q = Cv_i, \quad i_C = \frac{dQ}{dt} \Rightarrow i_C = C\frac{dv_i}{dt}, \qquad I_R = \frac{v_o}{R}$$

$$-i_R = i_C \Rightarrow C\frac{dv_i}{dt} = -\frac{v_o}{R} \qquad \Rightarrow v_o = -RC\frac{dv_i}{dt}$$

The frequency domain transfer function of the differentiator circuit can be found by subtituting $Z_1(s) = \dfrac{1}{sC}$, and $Z_2(s) = R$



$$\frac{v_o(s)}{v_1(s)} = -sRC \Rightarrow \frac{v_o(j\omega)}{v_1(j\omega)} = -j\omega RC$$

$$\left|\frac{v_o}{v_1}\right| = \omega RC = \frac{\omega}{\omega_t},$$

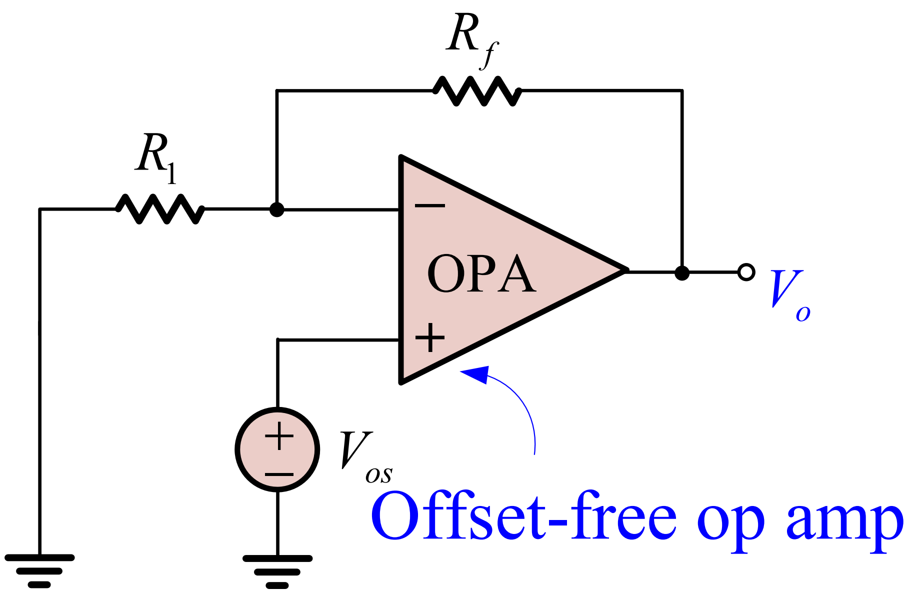
$$\angle v_o / v_1 = -90^o$$

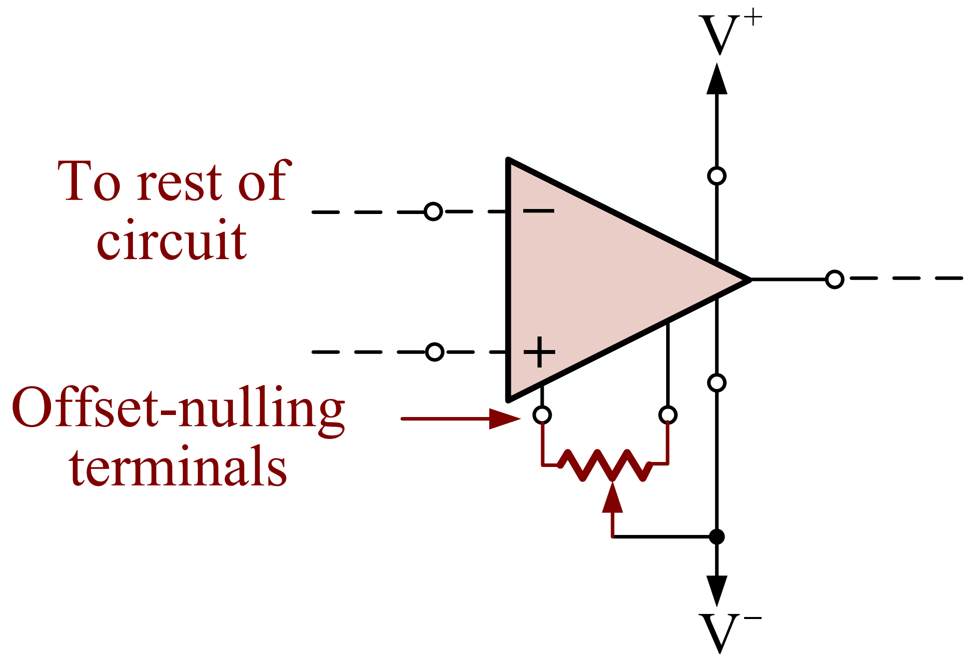
the unity gain frequency ω_t as

$$\omega_t = \frac{1}{RC}$$

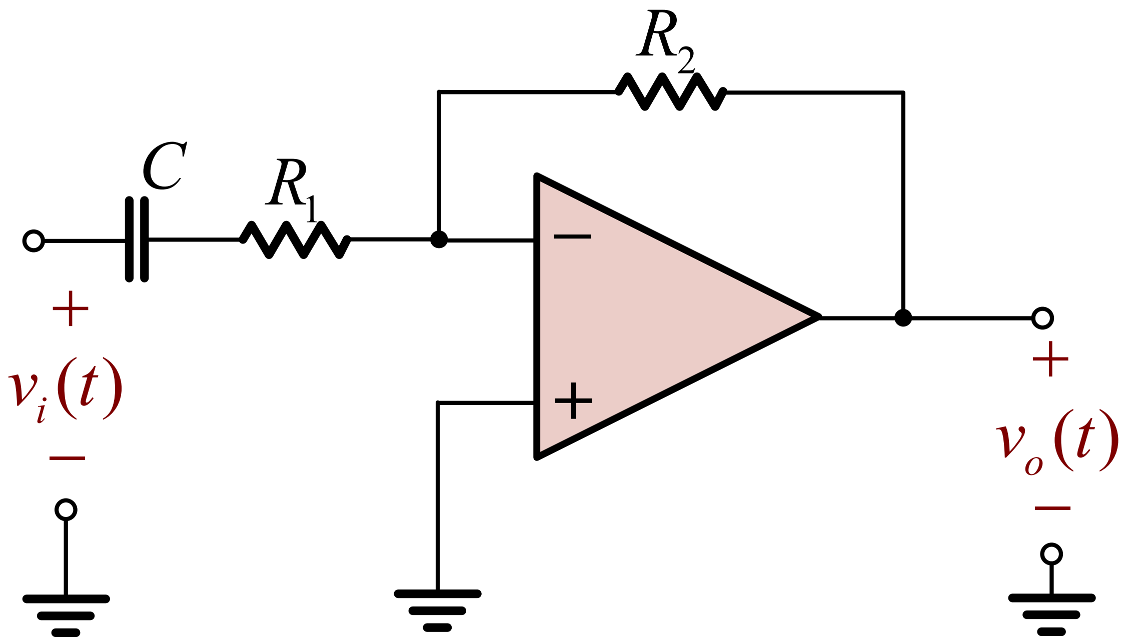
2.6 DC Imperfections

2.6.1 Offset Voltage

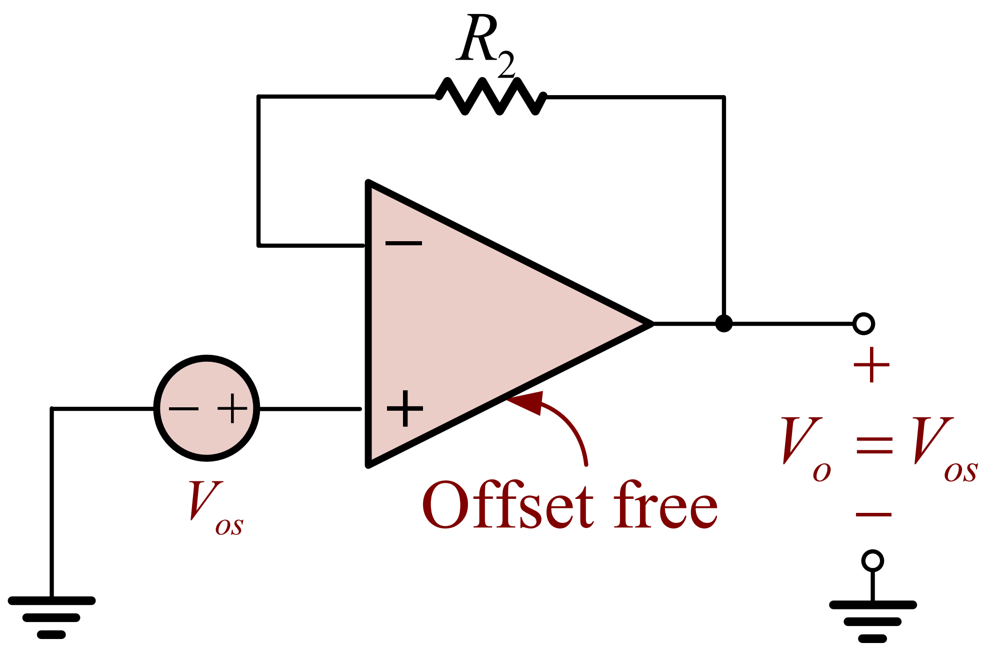




$$V_o = V_{os}\left(1+\frac{R_2}{R_1}\right)$$

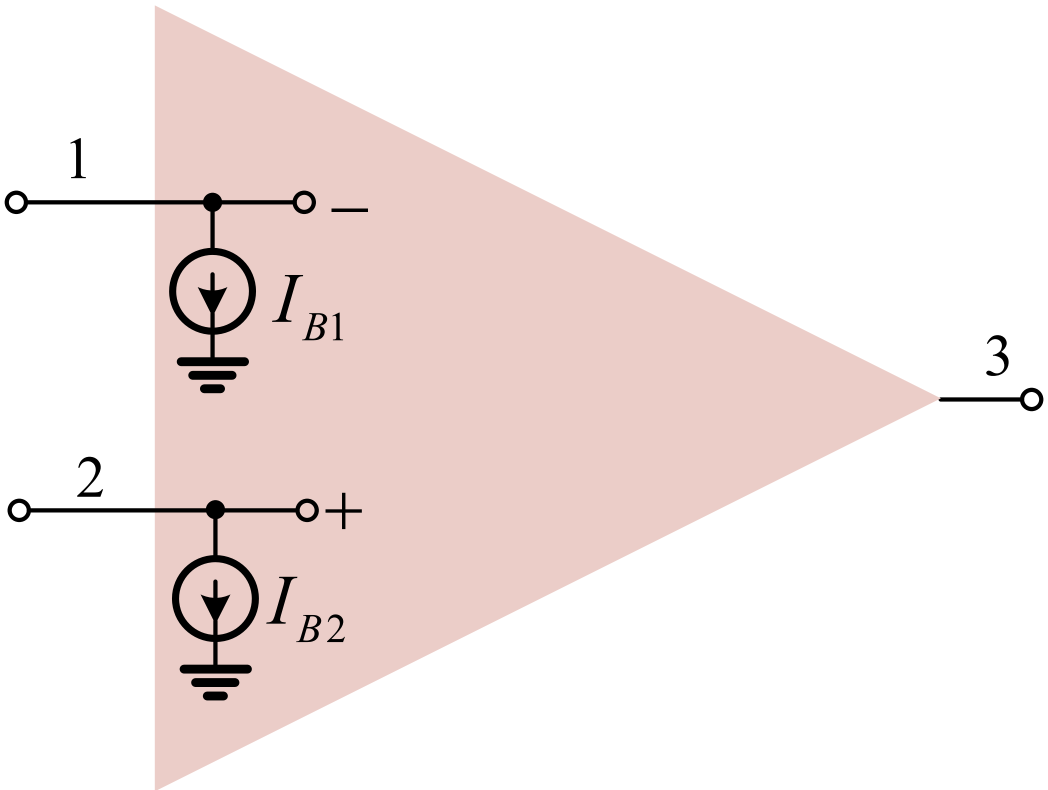


R_2
C
R_1
+
$v_i(t)$
−
+
$v_o(t)$
−



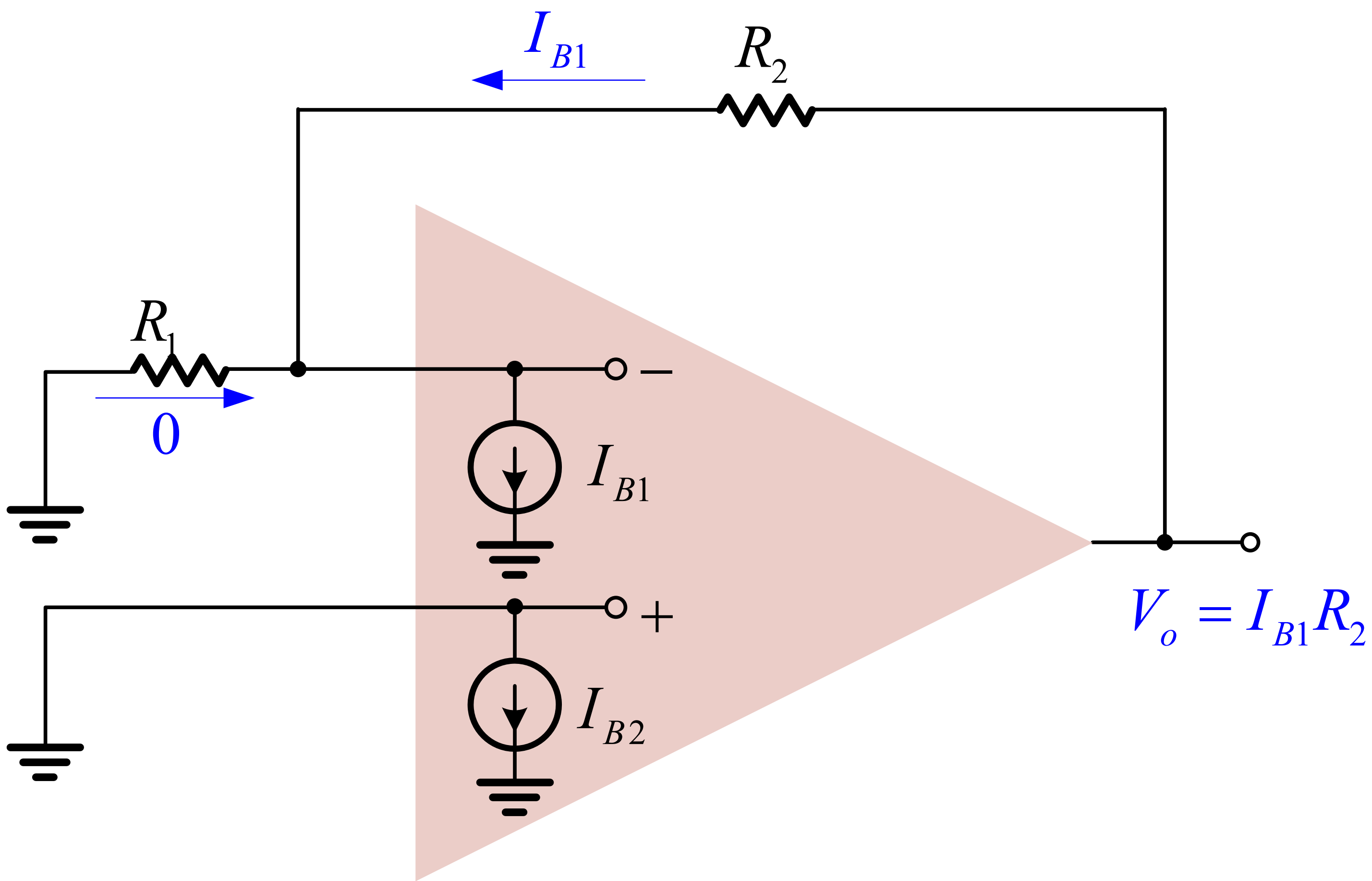
R_2
V_{os}
Offset free
+
$V_o = V_{os}$
−

2.6.2 Input Bais and Offset Currents

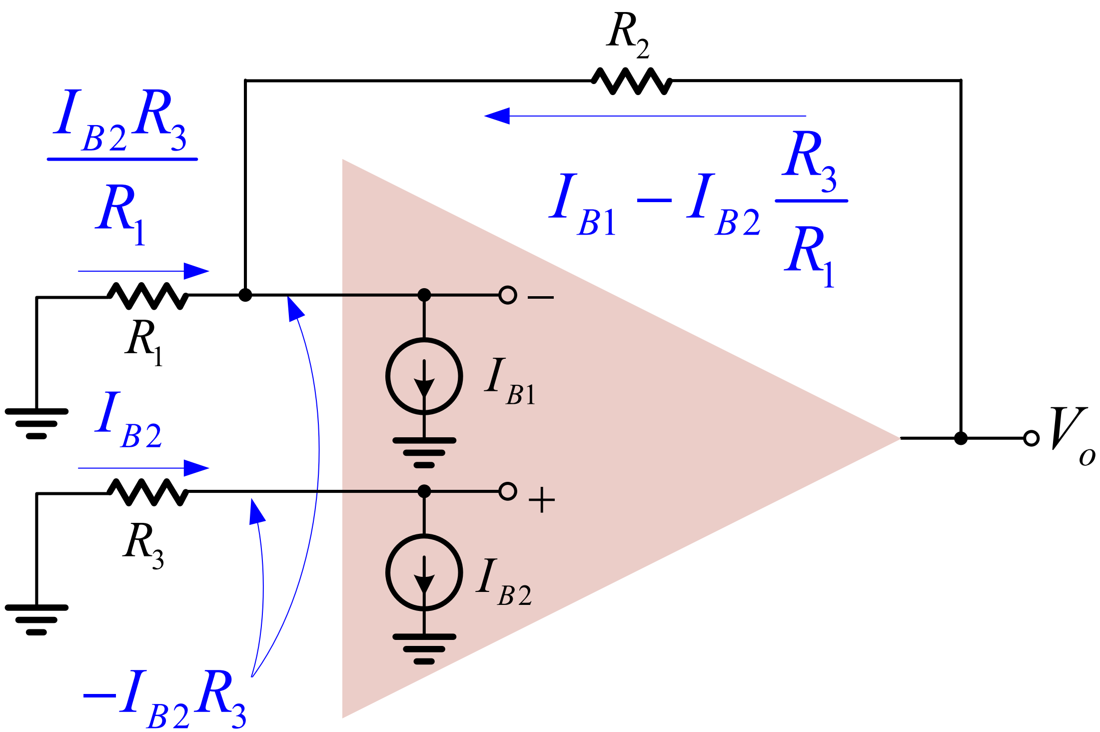


$$I_B = \frac{I_{B1} + I_{B2}}{2}$$

$$I_{OS} = \left| I_{B1} - I_{B2} \right|$$



$$V_O = I_{B1}R_2 \simeq I_B R_2$$



$$V_O = -I_{B2}R_3 + R_2\left(I_{B1} - I_{B2}R_3 / R_1\right)$$

Consider first case $I_B = I_{B1} = I_{B2}$, which results in

$$V_O = I_B\left[R_2 - R_3\left(1 + R_2 / R_1\right)\right]$$

Thus we can reduce V_O to zero by selecting R_3 such that

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

2.7 Effect of Finite Open-Loop Gain and Bandwidth on Circuit Performance

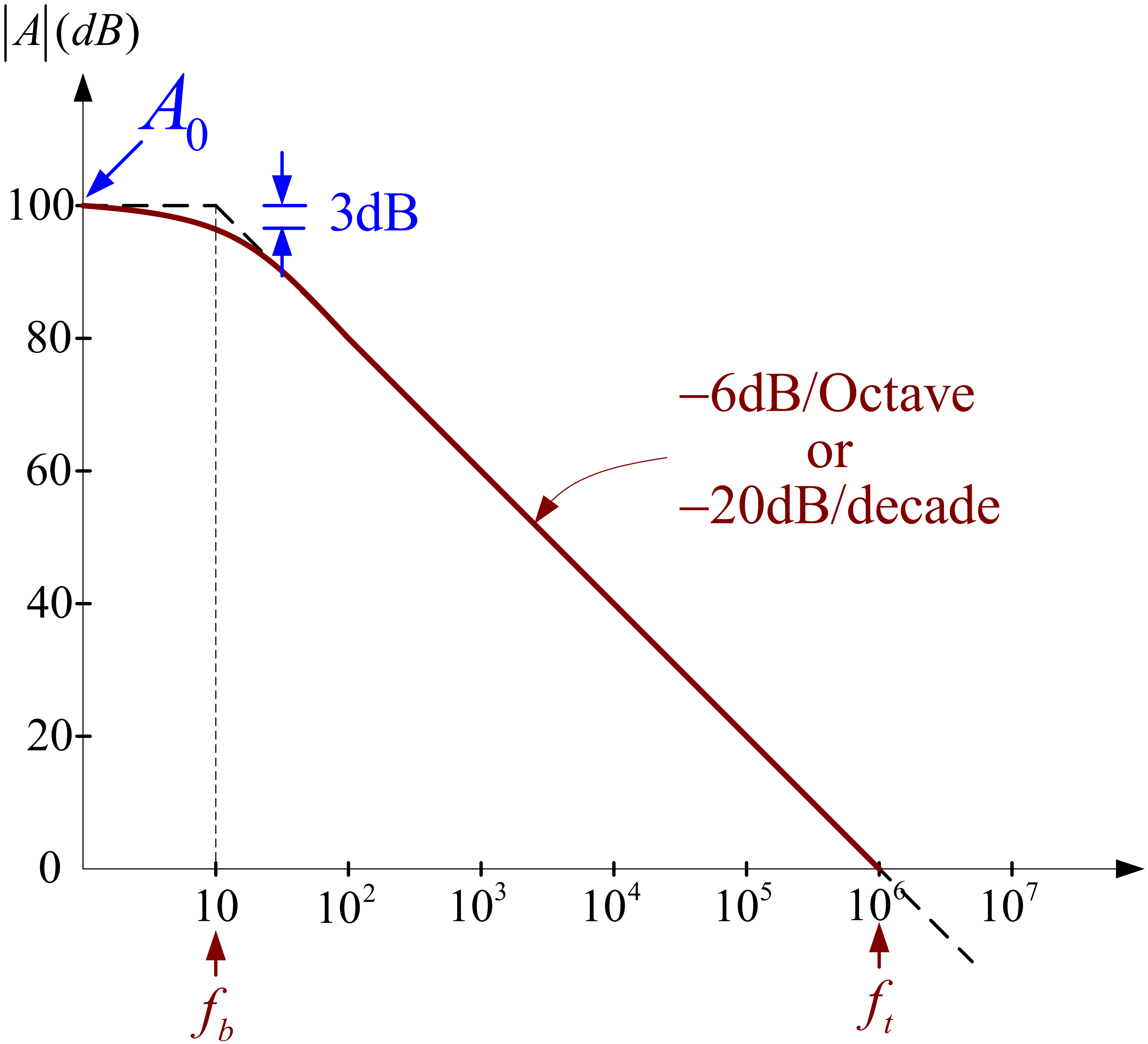
2.7.1 Frequency Dependence of the Open-loop Gain

$$A(s)=\frac{A_0}{1+\left(s/\omega_b\right)} \Rightarrow A(j\omega)=\frac{A_0}{1+\left(j\omega/\omega_b\right)} \simeq A(j\omega)=\frac{A_0\omega_b}{j\omega}$$

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

unity gain frequency $\omega_{\mathrm{t}}=A_0\omega_b$

$$\therefore A(j\omega)=\frac{\omega_{\mathrm{t}}}{j\omega} \Rightarrow \left|A(j\omega)\right|=\frac{\omega_{\mathrm{t}}}{\omega}=\frac{f_t}{f}$$


|A|(dB)
A_0
100
80
60
40
20
0
3dB
–6dB/Octave
or
–20dB/decade
10
10^2
10^3
10^4
10^5
10^6
10^7
f_b
f_t

2.7.2 Frequency Response of Closed-loop Amplifiers

The inverting amplifier transfer function

$$\frac{v_o}{v_i} = \frac{-R_f/R_1}{1+\dfrac{\left[1+(R_f/R_1)\right]}{A(s)}} \Rightarrow \frac{v_o(s)}{v_i(s)} = \frac{-R_f/R_1}{1+\dfrac{\left[1+(R_f/R_1)\right]}{A_0/\left[1+(s/\omega_b)\right]}}$$

$$= \frac{-R_f/R_1}{1+\dfrac{\left[1+(R_f/R_1)\right]\left[1+(s/\omega_b)\right]}{A_0}}$$

$$= \frac{-R_f/R_1}{1+\cancel{\dfrac{1+(R_f/R_1)}{A_0}}+\dfrac{(s/\omega_b)\left[1+(R_f/R_1)\right]}{A_0}}, \quad \text{where } A_0 \gg 1+\frac{R_f}{R_1}$$

$$\frac{v_o}{v_i} = \frac{-R_f / R_1}{1 + s\left(\frac{1+(R_f/R_1)}{A_0\omega_b}\right)} \Rightarrow \omega_{3\text{dB}} = \frac{\omega_t}{1+(R_f/R_1)}, \quad \omega_b = \frac{\omega_t}{A_0}$$

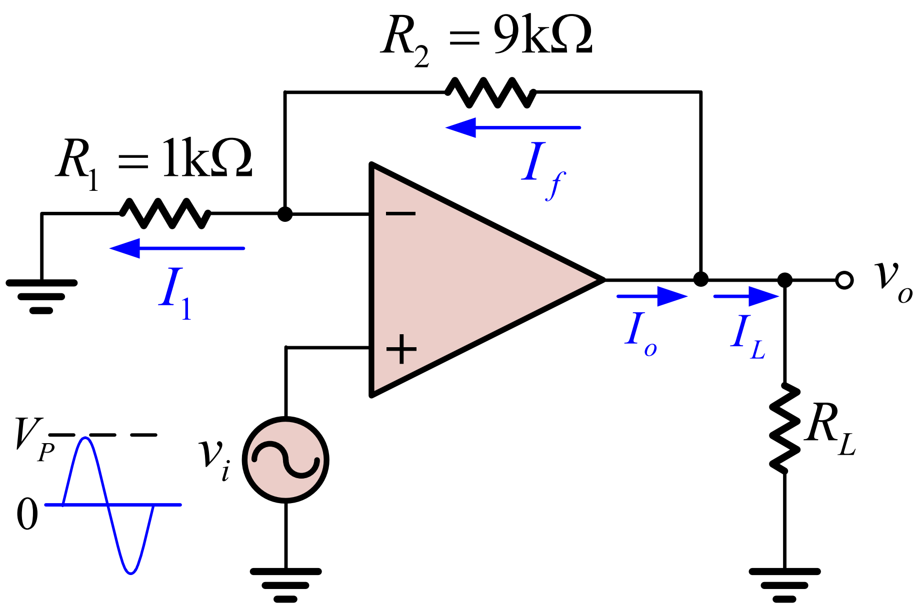
Similarly, the noninverting amplifier transfer function:

$$\frac{v_o}{v_i} = \frac{1+\left(R_f/R_1\right)}{1+\frac{\left(1+\left(R_f/R_1\right)\right)}{A(s)}}$$

$$\frac{v_o(s)}{v_i(s)} = \frac{1+\left(R_f/R_1\right)}{1+\frac{s}{\left(\frac{\omega_t}{1+\left(R_f/R_1\right)}\right)}} \Rightarrow \omega_{3\text{dB}} = \frac{\omega_t}{1+\left(R_f/R_1\right)}$$

2.8 Large-Signal Operation of Op Amp

Example 2.7: Consider the noninverting amplifier circuit shown in Fig. below. The op amp is specified to have output saturation voltages of ±13V, And output current limits of ±20mA.



(a) Find V_P=1V and R_L=1kΩ, specify the signal resulting at the output of the amplifier.

Sol:

$$G = 1 + \frac{R_2}{R_1} = 10$$

$$i_L = \frac{10\text{V}}{1\text{k}\Omega} = 10\text{mA}$$

the feedback current will be

$$i_F = \frac{10\text{V}}{(9+1)\text{k}\Omega} = 1\text{mA}$$

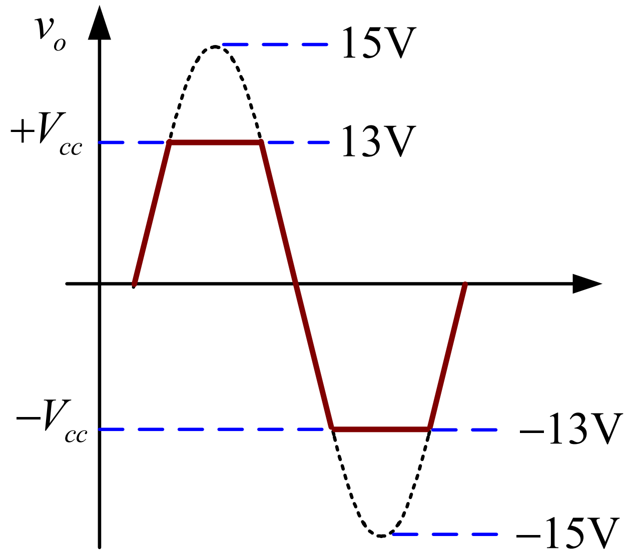
the total output current is 11mA, well under its limit of 20 mA.

(b) Find V_P=1.5V and R_L=1kΩ, specify the signal resulting at the output of the amplifier.

Sol: V_p is increased to 1.5V , V_o will saturate at $\pm 13\text{V}$

$$i_L = \frac{13\text{V}}{1\text{k}\Omega} = 13\text{mA}, \qquad i_F = \frac{13\text{V}}{(9+1)\text{k}\Omega} = 1.3\text{mA}$$

i_o = 14.3 mA, well under its limit of 20 mA. ▲



(c) Find R_L=1kΩ, what is the maximum value of V_P for which an undistorted sine-wave output is obtained？

Sol: The maximum value of V_P for undistoted sine-wave output 1.3V.

The output will be a 13-V peak sine-wave.

The op-amp output current at peak will be 14.3mA.

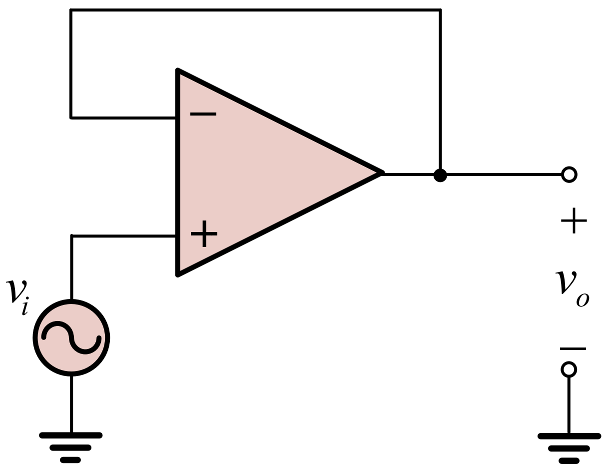
(d) Find V_p=1V, what is the lowest value of R_L for which an undistorted sine-wave output is obtained？

Sol: $V_p = 1.5\text{V}$,

$$i_{o(\max)} = 20\text{mA} = \frac{10\text{V}}{R_{L\min}} + \frac{10\text{V}}{9\text{k}\Omega + 1\text{k}\Omega}$$

$R_{L\min}$=526Ω.

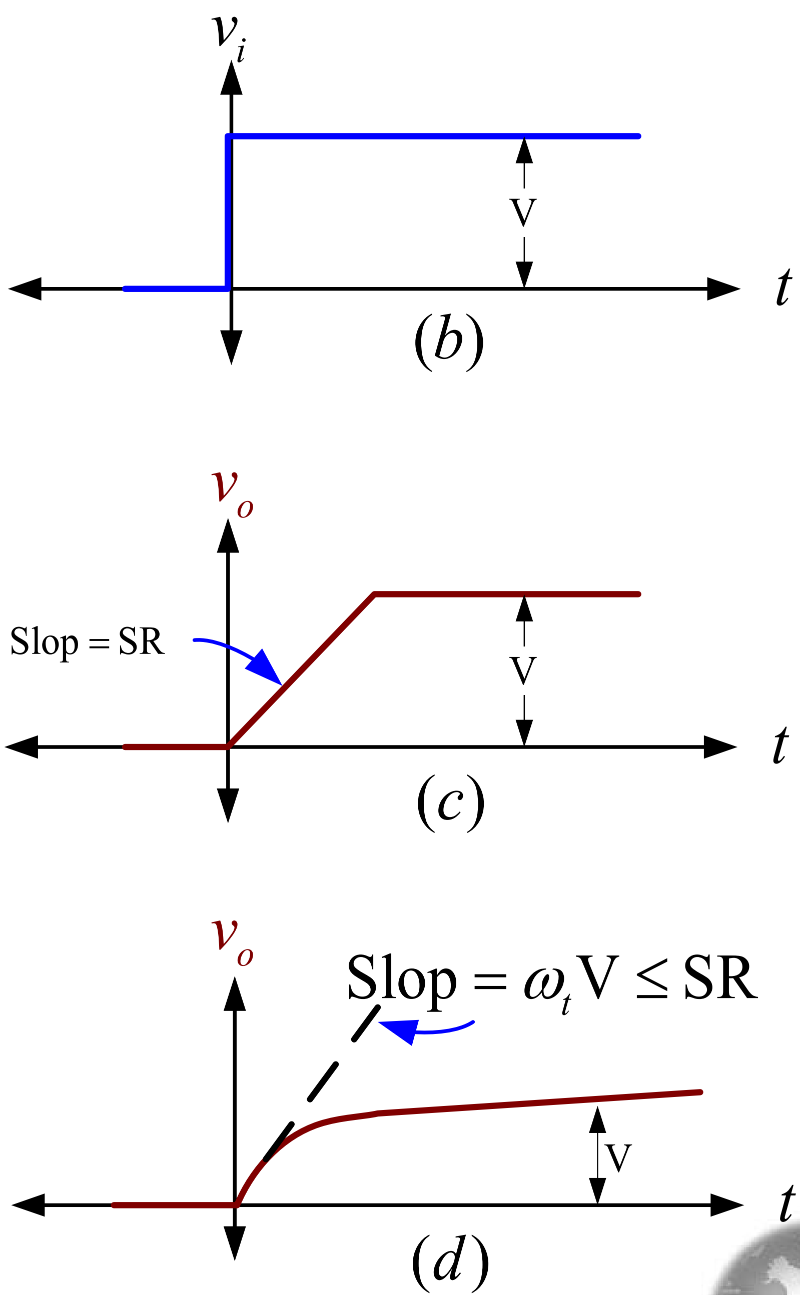
2.8.3 Slew Rate



$$SR = \left.\frac{dv_o}{dt}\right|_{\max}$$

$$\frac{v_o}{v_i} = \frac{1}{1 + s/\omega_t}$$

$$v_o(t) = V(1 - e^{-\omega_t t})$$



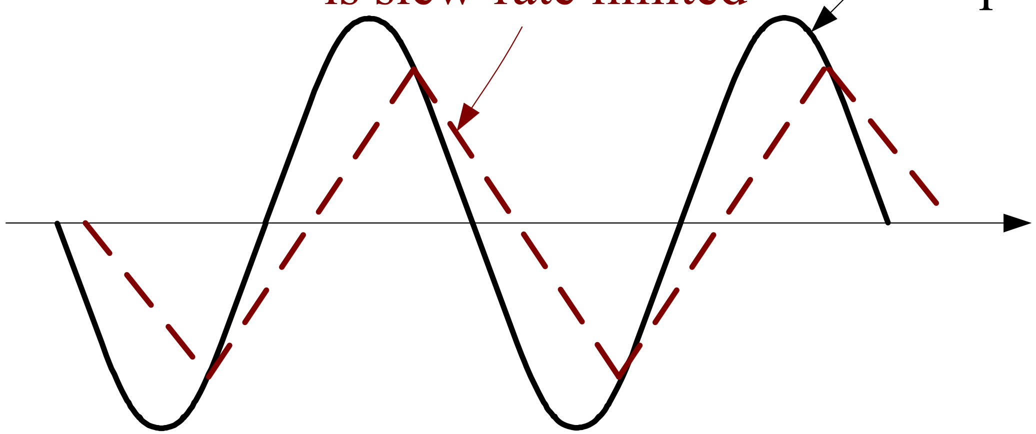
2.8.4 Full-Power Bandwidth

$$v_i = \hat{V}_i \sin \omega t$$

$$\frac{dv_i}{dt} = \omega \hat{V}_i \cos \omega t$$

$$SR = \omega_M V_{o_{max}}$$

$$f_M = \frac{SR}{2\pi V_{o_{max}}}$$



The Maximum amplitude of the undistorted output sinusoild is given by

$$V_o = V_{o_{max}} \left(\frac{\omega_M}{\omega} \right)$$

Thanks For Your Attention !

Q&A