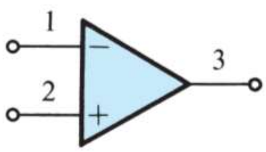
Chapter 2

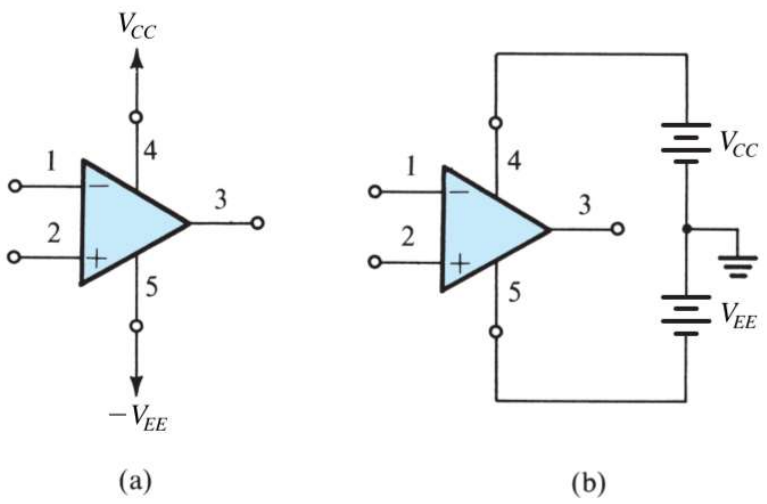
2-1 Ideal Op Amp

Models of Ideal Op Amp

From a signal point of view the op amp has three terminals: two inputs and one output terminal

Pin	Terminal
1	Negative Input
2	Positive Input
3	Output



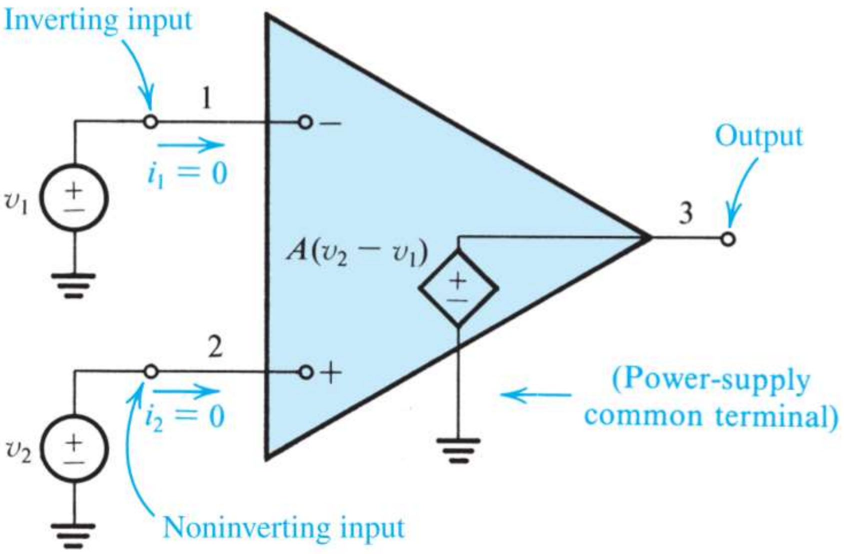


Most IC op amp have 5 terminals: two inputs, one output and two DC power terminals

Pin	Terminal
1	Negative Input
2	Positive Input
3	Output

Pin	Terminal
4	Positive Power
5	Negative Power

Function and Characteristics of the Ideal Op Amp



- Infinite input impedance
- Zero output impedance
- Zero common-mode gain
- Infinite open-loop gain A
- Infinite bandwidth

Differential and Common-Mode Signals

The differential input signal v_{Id} is simply the difference between the two input signals v_1 and v_2

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

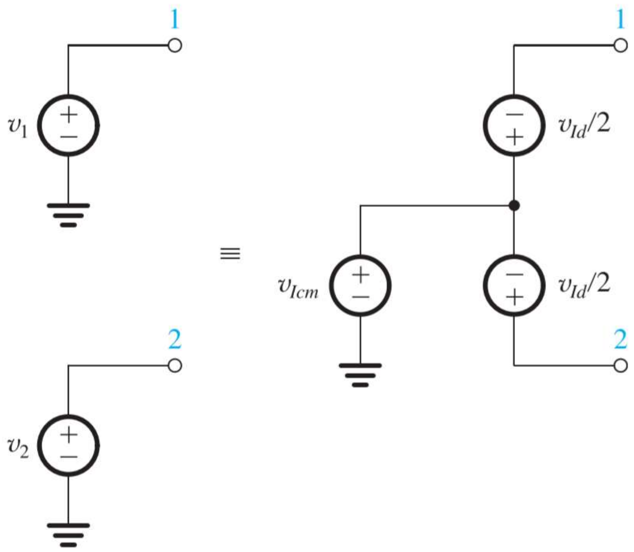
The common-mode input signal v_{Icm} is the average of the two input signals v_1 and v_2

$$v_{Icm} = \frac{1}{2}(v_1 + v_2)$$

Made the equation express v_1 and v_2 as

$$\begin{cases} v_1 = v_{Icm} - v_{Id}/2 \\ v_2 = v_{Icm} + v_{Id}/2 \end{cases}$$

which could turn the input terminals into another presentation

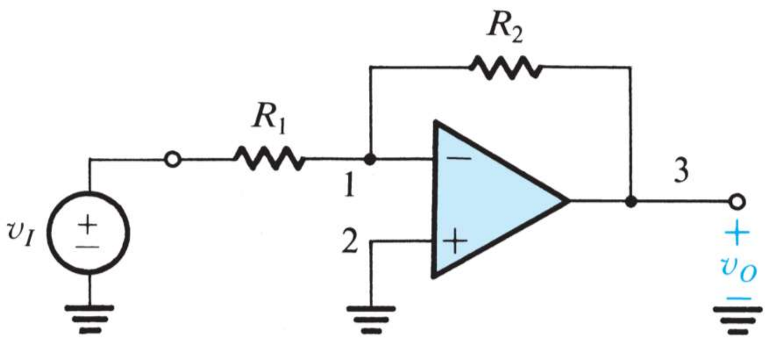


Analysis Method

There are tree rules to analyze the op amp circuit

- **virtual short**: $v_+ = v_-$
- **virtual open**: $i_+ = 0, i_- = 0$
- **zero output resistance**: $R_O = 0$

2-2 Inverting Amplifier



The **closed-loop gain** G could be determined as

$$G = \frac{v_O}{v_I}$$

Since $v_- = v_+ = 0$

$$i_1 = \frac{v_I - 0}{R_1} = \frac{v_I}{R_1} \quad i_2 = \frac{0 - v_O}{R_2} = -\frac{v_O}{R_2}$$

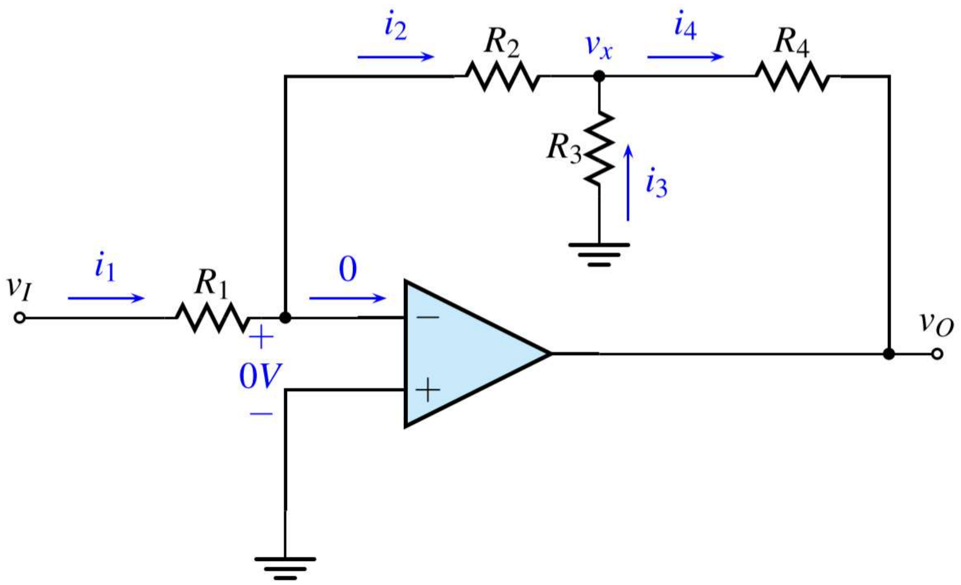
And we have $i_1 = i_2$

$$\frac{v_I}{R_1} = -\frac{v_O}{R_2}$$

$$\frac{v_O}{v_I} = -\frac{R_2}{R_1}$$

- gain: R_2/R_1
- input resistance: R_1
- output resistance: $R_O = 0$

T-shape Feedback Network



Since $v_- = v_+ = 0$

$$i_1 = \frac{v_I - 0}{R_1} = \frac{v_I}{R_1}$$

And we have $i_1 = i_2$

$$v_x = i_2 R_2 = i_1 R_2 = \frac{R_2}{R_1} v_I$$

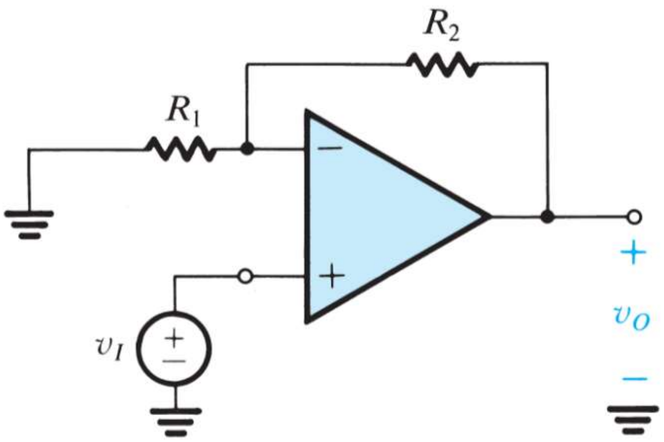
Therefore i_3 could be determined as

$$i_3 = \frac{v_x}{R_3} = \frac{R_2}{R_1} \cdot \frac{v_I}{R_3}$$

The output voltage could be calculated

$$
\begin{aligned}
v_o &= v_x + i_4 R_4 \\
&= \frac{R_2}{R_1} v_I + (i_2 + i_3) R_4 \\
&= \frac{R_2}{R_1} v_I + (i_1 + i_3) R_4 \\
&= \frac{R_2}{R_1} v_I + (\frac{1}{R_1} + \frac{R_2}{R_1} \cdot \frac{1}{R_3}) v_I R_4 \\
&= (\frac{R_2}{R_1} + \frac{R_4}{R_1} + \frac{R_2}{R_1} \frac{R_4}{R_3}) v_I
\end{aligned}
$$

2-3 Noninverting Amplifier



The **closed-loop gain** G could be determined as

$$G = \frac{v_O}{v_I}$$

Since $v_- = v_+ = v_1$

$$i_1 = \frac{v_I - 0}{R_1} = \frac{v_I}{R_1} \quad i_2 = \frac{v_O - v_I}{R_2}$$

And we have $i_1 = i_2$

$$\frac{v_I}{R_1} = \frac{v_O - v_I}{R_2}$$

$$(R_1 + R_2) v_I = R_1 v_O$$

$$\frac{v_O}{v_I} = (1 + \frac{R_2}{R_1})$$

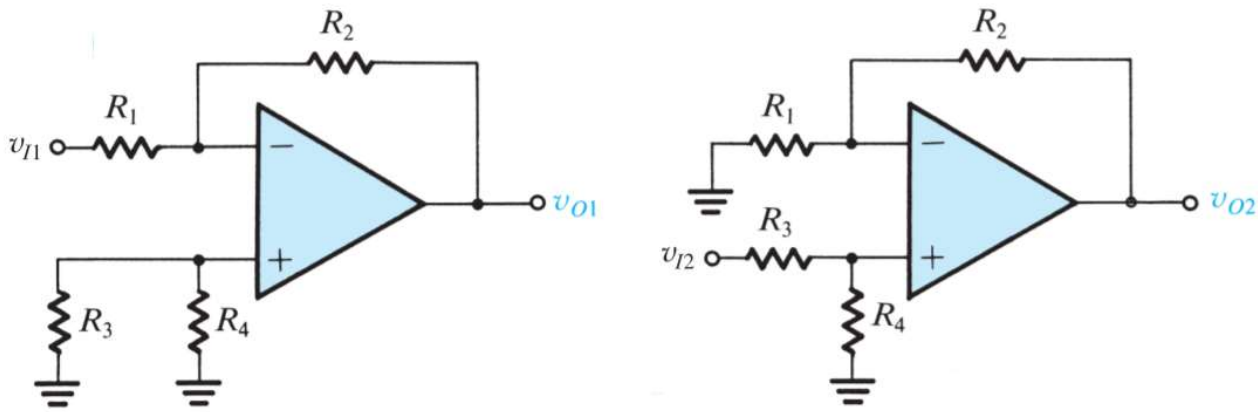
- gain: $1 + \frac{R_2}{R_1}$

- input resistance: $R_I = \infty$
- output resistance: $R_O = 0$

2-4 Difference Amplifier

A difference amplifier is one that responds to the difference between the two signals applied at its input and ideally rejects signals that are common to the two inputs.

Take the following two amplifiers into consideration



$$v_{O1} = -\frac{R_2}{R_1}v_{I1} \qquad v_{O2} = (1+\frac{R_2}{R_1})\frac{R_4}{R_3+R_4}v_{I2}$$

To produce no response to the common part, which means $v_{I1} = v_{I2}$

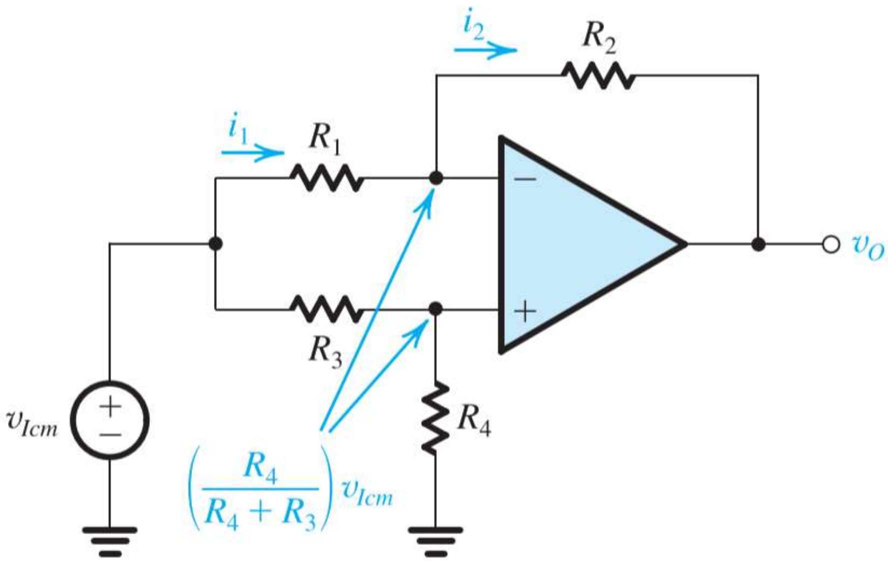
$$v_{O1} + v_{O2} = 0$$

$$\frac{R_2}{R_1}v_{I1} = (1+\frac{R_2}{R_1})\frac{R_4}{R_3+R_4}v_{I2}$$

$$\frac{R_2}{R_1}\cdot\frac{R_1}{R_1+R_2} = \frac{R_4}{R_3+R_4}$$

$$\frac{R_4}{R_2} = \frac{R_3}{R_1}$$

Now the common difference amplifier could be analyzed in the same way



The voltage on the input terminals could be determined as

$$\frac{R_4}{R_3+R_4}v_{Icm}$$

The current on R_1 is

$$i_1=\frac{R_3}{R_1}\frac{1}{R_3+R_4}v_{Icm}$$

And we know $i_1=i_2$

$$\begin{aligned}
v_O &= \frac{R_4}{R_3+R_4}v_{Icm}-\frac{R_3}{R_1}\frac{R_2}{R_3+R_4}v_{Icm}\\
&= \frac{v_{Icm}}{R_3+R_4}(R_4-\frac{R_3}{R_1}R_2)\\
\frac{v_O}{v_{Icm}} &= \frac{R_4}{R_3+R_4}(1-\frac{R_2}{R_1}\frac{R_3}{R_4})=0
\end{aligned}$$

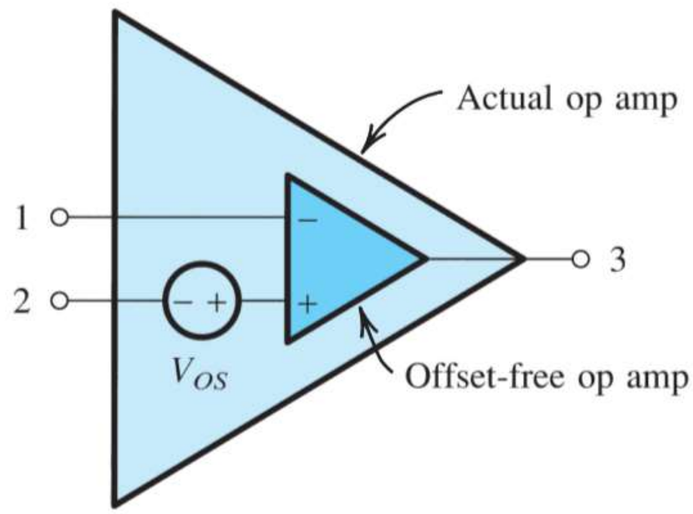
2-5 DC Imperfections

Offset Voltage

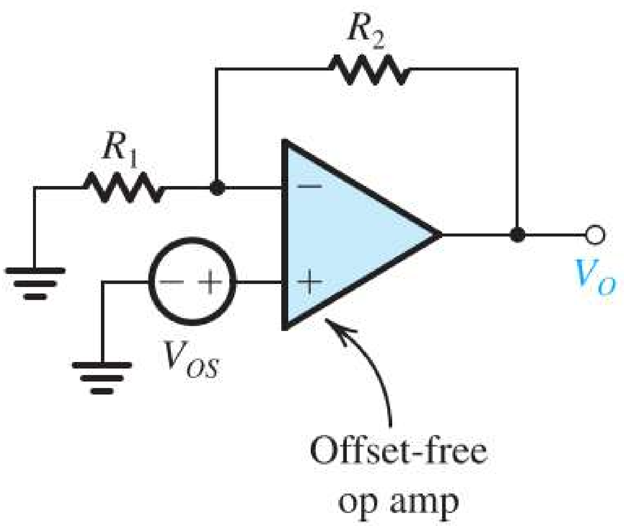
If the two input terminals of the op amp are tied together and connected to ground, it will be found that despite the fact thar $v_{Id}=0$, a finite dc voltage exists at the output.

The op-amp output can be brought back to its ideal value of $0\ V$ by connecting a dc voltage source of appropriate polarity and magnitude between the two input terminals of the op amp.

It follows that the **input offset voltage** V_{OS} must be of equal magnitude and of opposite polarity of the voltage



Based on the principle of superposition, we can find the both the inverting and the noninverting amplifier configurations result in the same circuit

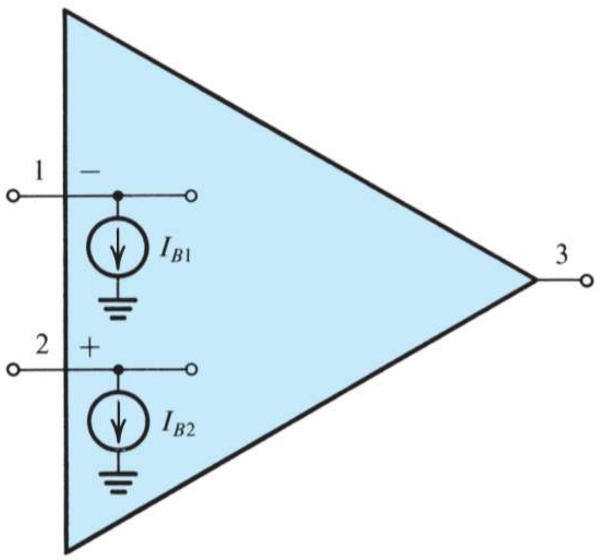


The output voltage due to V_{OS} is found to be

$$V_O = V_{OS}\left[1 + \frac{R_2}{R_1}\right]$$

Input Bias and Offset Currents

In order for the op amp to operate, its two input terminals have to be supplied with dc currents, termed the **input bias currents**, which are independent og the fact that a real op amp has finite input resistance



The average value I_B is called the **input bias current**

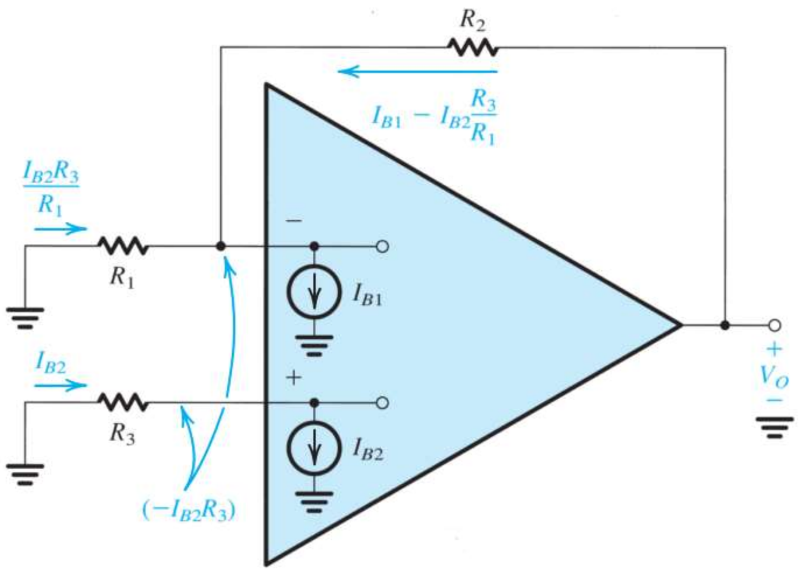
$$I_B = \frac{I_{B1} + I_{B2}}{2}$$

and the difference is called the **input offset current** and is given by

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

> Typical values for general-purpose op amps are $I_B = 100\ nA$ and $I_{OS} = 10\ nA$

Now we can analyses the closed loop amplifier, taking into account the input bias currents



$$V_O = -I_{B2}R_3 + R_2(I_{B2} - I_{B2}R_3/R_1)$$

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

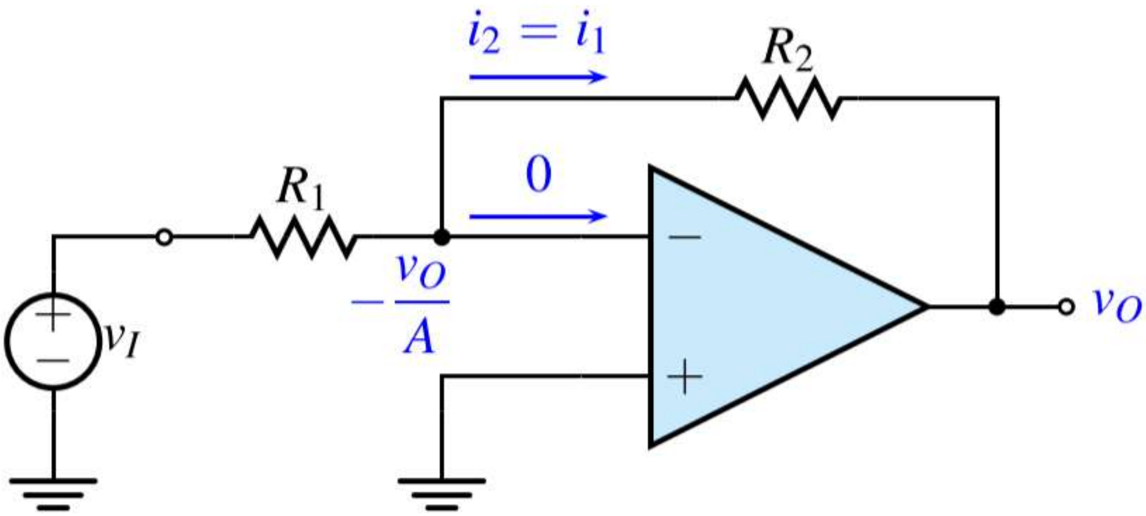
$$V_O = I_B[R_2 - R_3(1 + R_2/R_1)]$$

Thus output voltage could be zero when selecting R_3 equal to

$$R_3 = \frac{R_2}{1 + R_2/R_1} = \frac{R_1 R_2}{R_1 + R_2}$$

But in an **ac-coupled** amplifier the dc resistance seen by the inverting terminal is R_2, then R_3 is chosen equal to R_2

Effect of Finite Open-loop Gain



Since the op-amp open-loop gain A is finite

$$v_+ - v_- = \frac{v_O}{A} \Rightarrow v_- = -\frac{v_O}{A}$$

thus

$$i_1 = \frac{v_I - (-v_O/A)}{R_1} = \frac{v_I + v_O/A}{R_1}$$

Then the output voltage v_O becomes

$$v_O = -\frac{v_O}{A} - i_1 R_2 = -\frac{v_O}{A} - \left(\frac{v_I + v_O/A}{R_1}\right) R_2$$

where the the closed-loop gain is found as

$$G = \frac{v_O}{v_I} = -\frac{R_2/R_1}{1 + (1 + R_2/R_1)/A}$$

Similarly, we could get the closed-loop gain for the noninverting amplifier

$$G = \frac{v_O}{v_I} = \frac{1 + (R_2/R_1)}{1 + (1 + R_2/R_1)/A}$$