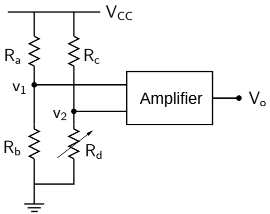
EE101: Op Amp circuits (Part 2)

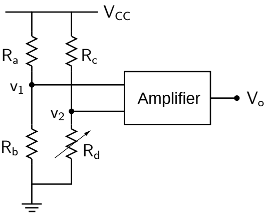
M. B. Patil
mbpatil@ee.iitb.ac.in
www.ee.iitb.ac.in/~sequel

Department of Electrical Engineering
Indian Institute of Technology Bombay

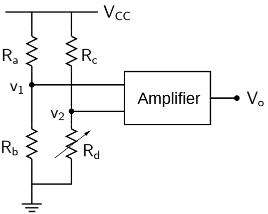
Common-mode and differential-mode voltages



Common-mode and differential-mode voltages



Consider a bridge circuit for sensing temperature, pressure, etc., with $R_a = R_b = R_c = R$.
$R_d = R + \Delta R$ varies with the quantity to be measured. Typically, ΔR is a small fraction of R.

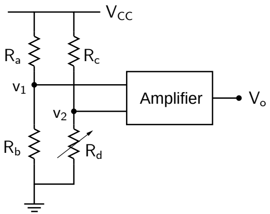


Consider a bridge circuit for sensing temperature, pressure, etc., with $R_a = R_b = R_c = R$.

$R_d = R + \Delta R$ varies with the quantity to be measured. Typically, ΔR is a small fraction of R.

The bridge converts ΔR to a signal voltage which can then be suitably amplified and used for display or control.

Common-mode and differential-mode voltages



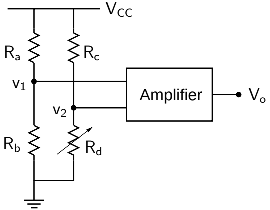
Consider a bridge circuit for sensing temperature, pressure, etc., with $R_a = R_b = R_c = R$.

$R_d = R + \Delta R$ varies with the quantity to be measured. Typically, ΔR is a small fraction of R.

The bridge converts ΔR to a signal voltage which can then be suitably amplified and used for display or control.

Assuming that the amplifier has a large input resistance,

Common-mode and differential-mode voltages



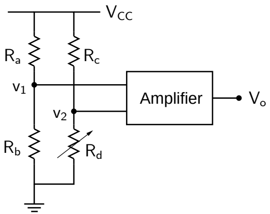
Consider a bridge circuit for sensing temperature, pressure, etc., with $R_a = R_b = R_c = R$.

$R_d = R + \Delta R$ varies with the quantity to be measured. Typically, ΔR is a small fraction of R.

The bridge converts ΔR to a signal voltage which can then be suitably amplified and used for display or control.

Assuming that the amplifier has a large input resistance,

$$v_1 = \frac{R}{R+R}\, V_{CC} = \frac{1}{2}\, V_{CC} \, .$$



Consider a bridge circuit for sensing temperature, pressure, etc., with $R_a = R_b = R_c = R$.

$R_d = R + \Delta R$ varies with the quantity to be measured. Typically, ΔR is a small fraction of R.

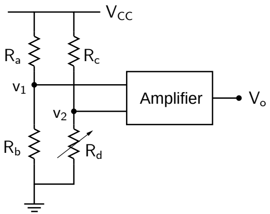
The bridge converts ΔR to a signal voltage which can then be suitably amplified and used for display or control.

Assuming that the amplifier has a large input resistance,

$$v_1 = \frac{R}{R+R}\,V_{CC} = \frac{1}{2}\,V_{CC}\,.$$

$$v_2 = \frac{(R+\Delta R)}{R+(R+\Delta R)}\,V_{CC} = \frac{1}{2}\,\frac{1+x}{1+x/2}\,V_{CC} \approx \frac{1}{2}\,(1+x)\,(1-x/2)\,V_{CC} = \frac{1}{2}\,(1+x/2)\,V_{CC}\,,$$

where $x = \Delta R/R$.



Consider a bridge circuit for sensing temperature, pressure, etc., with $R_a = R_b = R_c = R$.

$R_d = R + \Delta R$ varies with the quantity to be measured. Typically, ΔR is a small fraction of R.

The bridge converts ΔR to a signal voltage which can then be suitably amplified and used for display or control.

Assuming that the amplifier has a large input resistance,

$$v_1 = \frac{R}{R+R}\,V_{CC} = \frac{1}{2}\,V_{CC}\,.$$

$$v_2 = \frac{(R+\Delta R)}{R+(R+\Delta R)}\,V_{CC} = \frac{1}{2}\,\frac{1+x}{1+x/2}\,V_{CC} \approx \frac{1}{2}\,(1+x)\,(1-x/2)\,V_{CC} = \frac{1}{2}\,(1+x/2)\,V_{CC}\,,$$

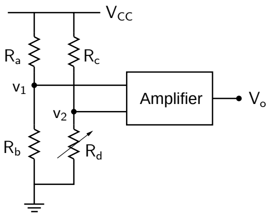
where $x = \Delta R/R$.

For example, with $V_{CC} = 15\,V$, $R = 1\,\mathrm{k}$, $\Delta R = 0.01\,\mathrm{k}$,

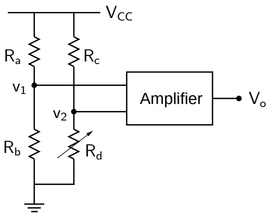
$v_1 = 7.5\,V$,

$v_2 = 7.5 + 0.0375\,V$.

Common-mode and differential-mode voltages



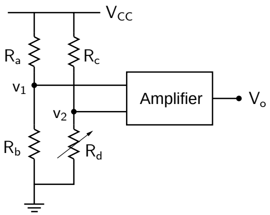
$v_1 = 7.5\ V\ ,\ \ v_2 = 7.5 + 0.0375\ V\ .$



$v_1 = 7.5\ V$, $v_2 = 7.5 + 0.0375\ V$.

The amplifier should only amplify $v_2 - v_1 = 0.0375\ V$ (since that is the signal arising from ΔR).

Common-mode and differential-mode voltages



$v_1 = 7.5\ V$, $v_2 = 7.5 + 0.0375\ V$.

The amplifier should only amplify $v_2 - v_1 = 0.0375\ V$ (since that is the signal arising from ΔR).

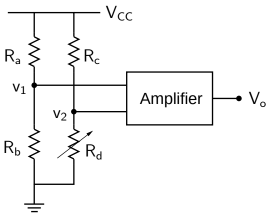
Definitions:

Given v_1 and v_2,

$v_c = \dfrac{1}{2}\,(v_1 + v_2)$ = common-mode voltage,

$v_d = (v_2 - v_1)$ = differential-mode voltage.

Common-mode and differential-mode voltages



$v_1 = 7.5\ V\ ,\ \ v_2 = 7.5 + 0.0375\ V\ .$

The amplifier should only amplify $v_2 - v_1 = 0.0375\ V$ (since that is the signal arising from ΔR).

Definitions:

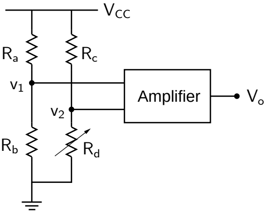
Given v_1 and v_2,

$v_c = \dfrac{1}{2}(v_1 + v_2) =$ common-mode voltage,

$v_d = (v_2 - v_1) =$ differential-mode voltage.

v_1 and v_2 can be rewritten as,

$v_1 = v_c - v_d/2\ ,\ \ v_2 = v_c + v_d/2\ .$



$v_1 = 7.5\ V\ ,\ \ v_2 = 7.5 + 0.0375\ V\ .$

The amplifier should only amplify $v_2 - v_1 = 0.0375\ V$ (since that is the signal arising from ΔR).

Definitions:

Given v_1 and v_2,

$v_c = \dfrac{1}{2}(v_1 + v_2) =$ common-mode voltage,

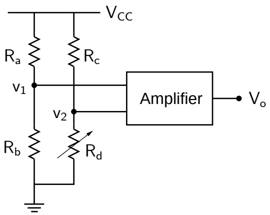
$v_d = (v_2 - v_1) =$ differential-mode voltage.

v_1 and v_2 can be rewritten as,

$v_1 = v_c - v_d/2\ ,\ \ v_2 = v_c + v_d/2\ .$

In the above example, $v_c \approx 7.5\ V\ ,\ \ v_d = 37.5\,\text{m}V\ .$

Common-mode and differential-mode voltages



$v_1 = 7.5\ V\ ,\ \ v_2 = 7.5 + 0.0375\ V\ .$

The amplifier should only amplify $v_2 - v_1 = 0.0375\ V$ (since that is the signal arising from ΔR).

Definitions:

Given v_1 and v_2,

$v_c = \dfrac{1}{2}\,(v_1 + v_2) =$ common-mode voltage,

$v_d = (v_2 - v_1) =$ differential-mode voltage.

v_1 and v_2 can be rewritten as,

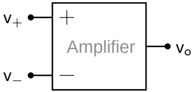
$v_1 = v_c - v_d/2\ ,\ \ v_2 = v_c + v_d/2\ .$

In the above example, $v_c \approx 7.5\ V,\ \ v_d = 37.5\,\text{m}V\ .$

Note that the common-mode voltage is quite large compared to the differential-mode voltage.

This is a common situation in transducer circuits.

Common-Mode Rejection Ratio



$$v_+ = v_c + v_d/2$$

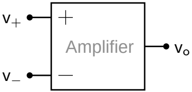
$$v_- = v_c - v_d/2$$

An ideal amplifier would only amplify the difference $(v_+ - v_-)$, giving

$v_o = A_d\,(v_+ - v_-) = A_d\,v_d$,

where A_d is called the "differential gain" or simply the gain (A_V).

Common-Mode Rejection Ratio



$$v_+ = v_c + v_d/2$$
$$v_- = v_c - v_d/2$$

An ideal amplifier would only amplify the difference $(v_+ - v_-)$, giving

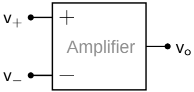
$v_o = A_d\,(v_+ - v_-) = A_d\,v_d\,,$

where A_d is called the "differential gain" or simply the gain (A_V).

In practice, the output can also have a common-mode component:

$v_o = A_d\,v_d + A_c\,v_c\,,$

where A_c is called the "common-mode gain".



$$\mathrm{v}_+ = \mathrm{v}_c + \mathrm{v}_d/2$$
$$\mathrm{v}_- = \mathrm{v}_c - \mathrm{v}_d/2$$

An ideal amplifier would only amplify the difference $(v_+ - v_-)$, giving

$v_o = A_d\,(v_+ - v_-) = A_d\, v_d$,

where A_d is called the "differential gain" or simply the gain (A_V).

In practice, the output can also have a common-mode component:

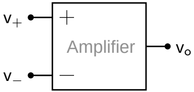
$v_o = A_d\, v_d + A_c\, v_c$,

where A_c is called the "common-mode gain".

The ability of an amplifier to *reject* the common-mode signal is given by the Common-Mode Rejection Ratio (CMRR):

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

Common-Mode Rejection Ratio



$$v_+ = v_c + v_d/2$$
$$v_- = v_c - v_d/2$$

An ideal amplifier would only amplify the difference $(v_+ - v_-)$, giving

$v_o = A_d\,(v_+ - v_-) = A_d\,v_d$,

where A_d is called the "differential gain" or simply the gain (A_V).

In practice, the output can also have a common-mode component:

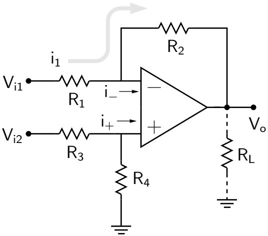
$v_o = A_d\,v_d + A_c\,v_c$,

where A_c is called the "common-mode gain".

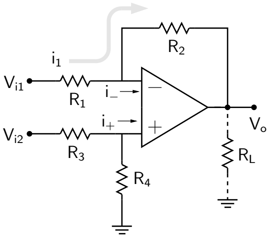
The ability of an amplifier to *reject* the common-mode signal is given by the Common-Mode Rejection Ratio (CMRR):

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

For the 741 Op Amp, the CMRR is 90 dB ($\simeq$ 30,000), which may be considered to be infinite in many applications. In such cases, mismatch between circuit components will determine the overall common-mode rejection performance of the circuit.

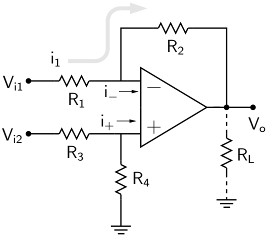


i1
Vi1
R1
R2
i−
i+
Vi2
R3
R4
Vo
RL



Method 1:

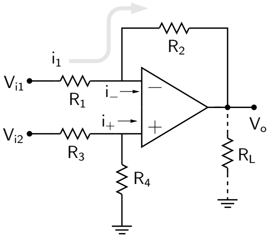
Large input resistance of Op Amp $\rightarrow i_+ = 0,\ V_+ = \dfrac{R_4}{R_3 + R_4}\, V_{i2}$.



Method 1:

Large input resistance of Op Amp $\rightarrow$ $i_+ = 0,\ V_+ = \dfrac{R_4}{R_3 + R_4}\, V_{i2}$.

Since $V_+ - V_- \approx 0,\ i_1 = \dfrac{1}{R_1}\,(V_{i1} - V_-) \approx \dfrac{1}{R_1}\,(V_{i1} - V_+)$.

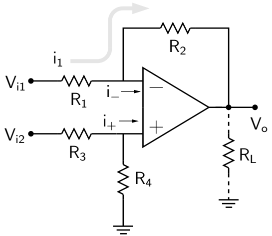


Method 1:

Large input resistance of Op Amp $\rightarrow i_+ = 0,\ V_+ = \dfrac{R_4}{R_3 + R_4}\, V_{i2}$.

Since $V_+ - V_- \approx 0,\ i_1 = \dfrac{1}{R_1}\,(V_{i1} - V_-) \approx \dfrac{1}{R_1}\,(V_{i1} - V_+)$.

$i_- \approx 0 \rightarrow V_o = V_- - i_1 R_2 \approx V_+ - \dfrac{R_2}{R_1}\,(V_{i1} - V_+)$.



Method 1:

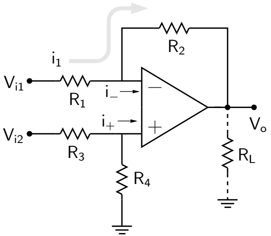
Large input resistance of Op Amp $\rightarrow i_+ = 0,\; V_+ = \dfrac{R_4}{R_3 + R_4}\, V_{i2}$.

Since $V_+ - V_- \approx 0,\; i_1 = \dfrac{1}{R_1}\,(V_{i1} - V_-) \approx \dfrac{1}{R_1}\,(V_{i1} - V_+)$.

$i_- \approx 0 \rightarrow V_o = V_- - i_1 R_2 \approx V_+ - \dfrac{R_2}{R_1}\,(V_{i1} - V_+)$.

Substituting for V_+ and selecting $R_3/R_4 = R_1/R_2$, we get (show this),

$$V_o = \frac{R_2}{R_1}\,(V_{i2} - V_{i1})\,.$$



Method 1:

Large input resistance of Op Amp $\rightarrow$ $i_+ = 0$, $V_+ = \dfrac{R_4}{R_3 + R_4} V_{i2}$.

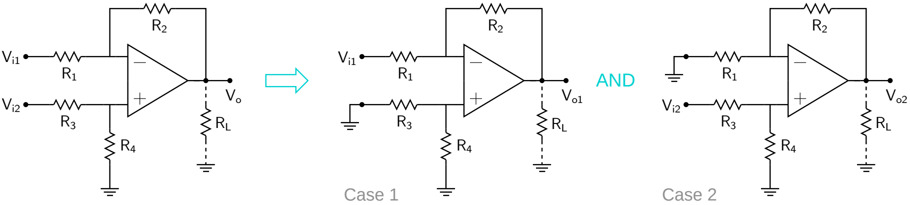
Since $V_+ - V_- \approx 0$, $i_1 = \dfrac{1}{R_1}(V_{i1} - V_-) \approx \dfrac{1}{R_1}(V_{i1} - V_+)$.

$i_- \approx 0 \rightarrow V_o = V_- - i_1 R_2 \approx V_+ - \dfrac{R_2}{R_1}(V_{i1} - V_+)$.

Substituting for V_+ and selecting $R_3/R_4 = R_1/R_2$, we get (show this),

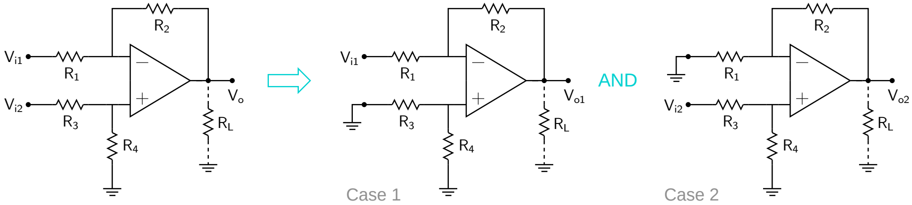
$V_o = \dfrac{R_2}{R_1}(V_{i2} - V_{i1})$.

The circuit is a "difference amplifier."



Method 2:

Since the Op Amp is operating in the linear region, we can use superposition:

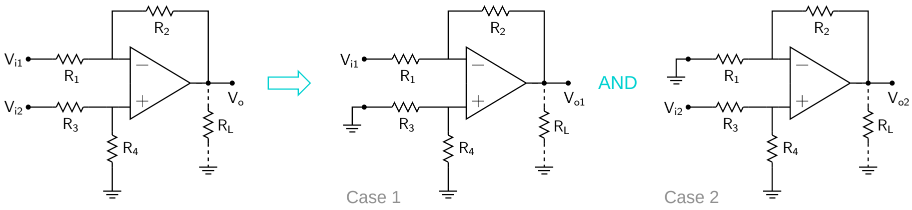


Method 2:

Since the Op Amp is operating in the linear region, we can use superposition:

Case 1: Inverting amplifier (note that $V_+ = 0\ V$).

$$\rightarrow V_{o1} = -\frac{R_2}{R_1}\, V_{i1}\,.$$



Method 2:

Since the Op Amp is operating in the linear region, we can use superposition:

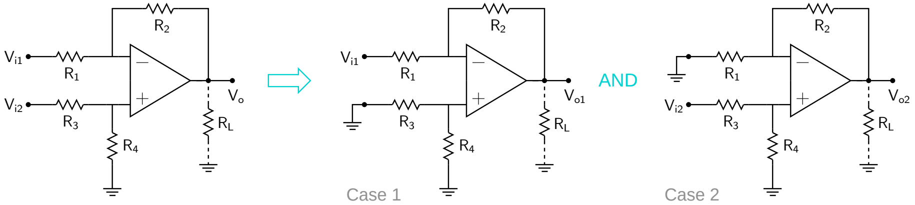
Case 1: Inverting amplifier (note that $V_+ = 0\ V$).

$$\rightarrow V_{o1} = -\frac{R_2}{R_1}\, V_{i1}\,.$$

Case 2: Non-inverting amplifier, with $V_i = \dfrac{R_4}{R_3 + R_4}\, V_{i2}\,.$

$$\rightarrow V_{o2} = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right)\, V_{i2}\,.$$

Difference amplifier



Method 2:

Since the Op Amp is operating in the linear region, we can use superposition:

Case 1: Inverting amplifier (note that $V_+ = 0\ V$).

$$\rightarrow V_{o1} = -\frac{R_2}{R_1} V_{i1}\,.$$

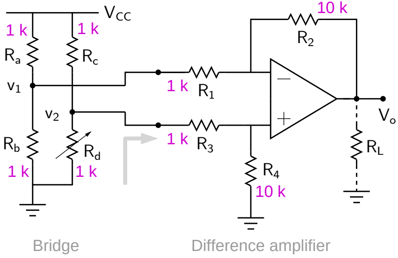
Case 2: Non-inverting amplifier, with $V_i = \dfrac{R_4}{R_3 + R_4} V_{i2}$.

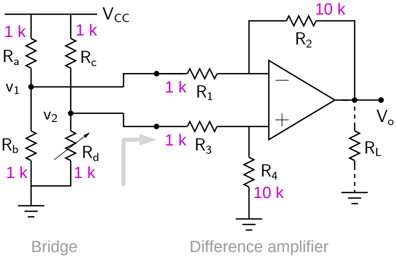
$$\rightarrow V_{o2} = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right) V_{i2}\,.$$

The net result is,

$$V_o = V_{o1} + V_{o2} = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right) V_{i2} - \frac{R_2}{R_1} V_{i1} = \frac{R_2}{R_1}\left(V_{i2} - V_{i1}\right), \text{ if } R_3/R_4 = R_1/R_2.$$

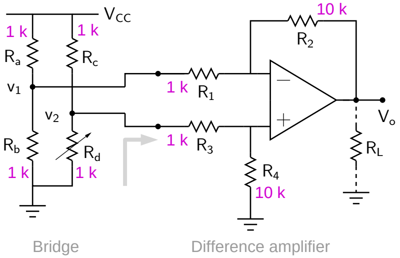
Difference amplifier





The resistance seen from v_2 is $(R_3 + R_4)$ which is small enough to cause v_2 to change.

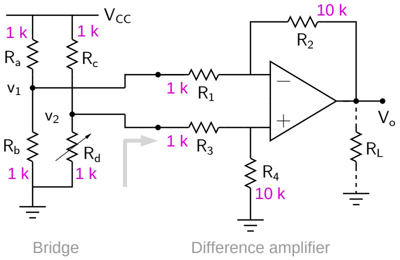
This is not desirable.



The resistance seen from v_2 is $(R_3 + R_4)$ which is small enough to cause v_2 to change. This is not desirable.

$\rightarrow$ need to improve the input resistance of the difference amplifier.

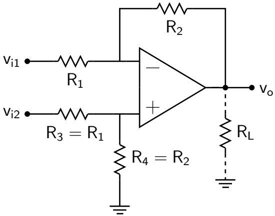
Difference amplifier



The resistance seen from v_2 is $(R_3 + R_4)$ which is small enough to cause v_2 to change. This is not desirable.

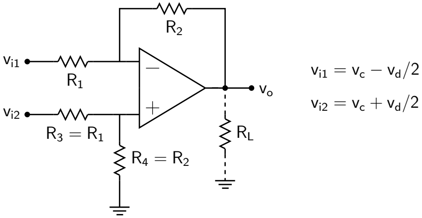
$\rightarrow$ need to improve the input resistance of the difference amplifier.

We will discuss an improved difference amplifier later. Before we do that, let us discuss another problem with the above difference amplifier which can be important for some applications (next slide).



$v_{i1} = v_c - v_d/2$

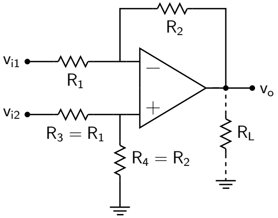
$v_{i2} = v_c + v_d/2$



Consider the difference amplifier with $R_3 = R_1$, $R_4 = R_2 \rightarrow V_o = \dfrac{R_2}{R_1}\,(v_{i2} - v_{i1})$.

The output voltage depends only on the differential-mode signal $(v_{i2} - v_{i1})$,

i.e., A_c (common-mode gain) $= 0$.



$v_{i1} = v_c - v_d/2$

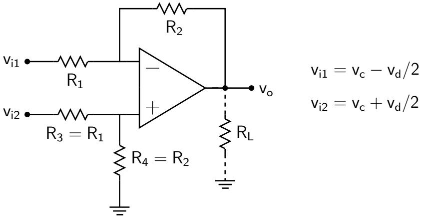
$v_{i2} = v_c + v_d/2$

Consider the difference amplifier with $R_3 = R_1$, $R_4 = R_2 \rightarrow V_o = \dfrac{R_2}{R_1}\,(v_{i2} - v_{i1})$.

The output voltage depends only on the differential-mode signal $(v_{i2} - v_{i1})$,

i.e., A_c (common-mode gain) $= 0$.

In practice, R_3 and R_1 may not be exactly equal. Let $R_3 = R_1 + \Delta R$.



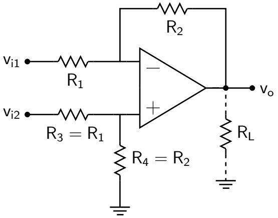
Consider the difference amplifier with $R_3 = R_1$, $R_4 = R_2 \rightarrow V_o = \dfrac{R_2}{R_1}\,(v_{i2} - v_{i1})$.

The output voltage depends only on the differential-mode signal $(v_{i2} - v_{i1})$,

i.e., A_c (common-mode gain) $= 0$.

In practice, R_3 and R_1 may not be exactly equal. Let $R_3 = R_1 + \Delta R$.

$$\begin{aligned} v_o &= \frac{R_2}{R_1 + \Delta R + R_2}\left(1 + \frac{R_2}{R_1}\right) v_{i2} - \frac{R_2}{R_1}\, v_{i1} \\ &\simeq \frac{R_2}{R_1}(v_d - x\, v_c)\,, \text{with } x = \frac{\Delta R}{R_1 + R_2} \qquad \text{(show this)} \end{aligned}$$



$v_{i1} = v_c - v_d/2$

$v_{i2} = v_c + v_d/2$

Consider the difference amplifier with $R_3 = R_1$, $R_4 = R_2 \rightarrow V_o = \dfrac{R_2}{R_1}\,(v_{i2} - v_{i1})$.

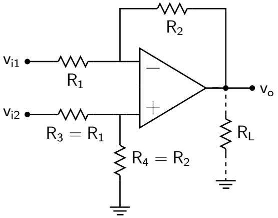
The output voltage depends only on the differential-mode signal $(v_{i2} - v_{i1})$,

i.e., A_c (common-mode gain) $= 0$.

In practice, R_3 and R_1 may not be exactly equal. Let $R_3 = R_1 + \Delta R$.

$$
\begin{aligned}
v_o &= \frac{R_2}{R_1 + \Delta R + R_2}\left(1 + \frac{R_2}{R_1}\right) v_{i2} - \frac{R_2}{R_1}\, v_{i1} \\
&\simeq \frac{R_2}{R_1}(v_d - x\, v_c)\,, \text{with } x = \frac{\Delta R}{R_1 + R_2} \qquad \text{(show this)}
\end{aligned}
$$

$|A_c| = x\,\dfrac{R_2}{R_1} \ll |A_d| = \dfrac{R_2}{R_1}$.



$\mathrm{v_{i1}} = \mathrm{v_c} - \mathrm{v_d}/2$

$\mathrm{v_{i2}} = \mathrm{v_c} + \mathrm{v_d}/2$

Consider the difference amplifier with $R_3 = R_1$, $R_4 = R_2 \rightarrow V_o = \dfrac{R_2}{R_1}\,(v_{i2} - v_{i1})$.

The output voltage depends only on the differential-mode signal $(v_{i2} - v_{i1})$,

i.e., A_c (common-mode gain) $= 0$.

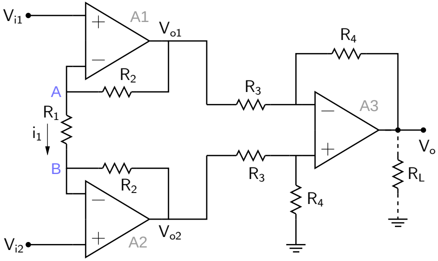
In practice, R_3 and R_1 may not be exactly equal. Let $R_3 = R_1 + \Delta R$.

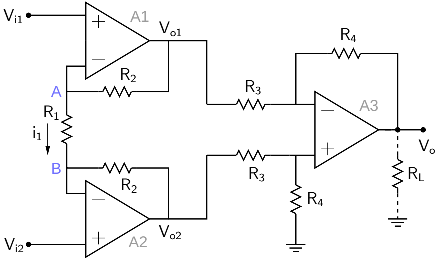
$$\begin{aligned} v_o &= \frac{R_2}{R_1 + \Delta R + R_2}\left(1 + \frac{R_2}{R_1}\right) v_{i2} - \frac{R_2}{R_1}\, v_{i1} \\ &\simeq \frac{R_2}{R_1}(v_d - x\, v_c)\,,\ \text{with } x = \frac{\Delta R}{R_1 + R_2} \quad \text{(show this)} \end{aligned}$$

$$|A_c| = x\,\frac{R_2}{R_1} \ll |A_d| = \frac{R_2}{R_1}.$$

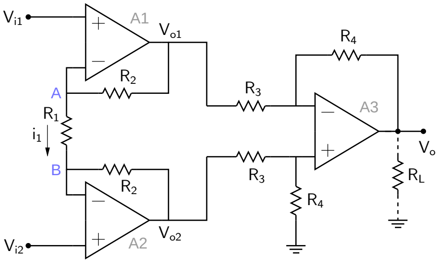
However, since v_c can be large compared to v_d, the effect of A_c cannot be ignored.

Improved difference amplifier



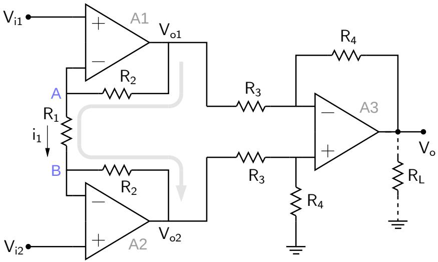


$$V_+ \approx V_- \rightarrow V_A = V_{i1}\,,\;\; V_B = V_{i2}\,, \rightarrow i_1 = \frac{1}{R_1}\,(V_{i1} - V_{i2})\,.$$



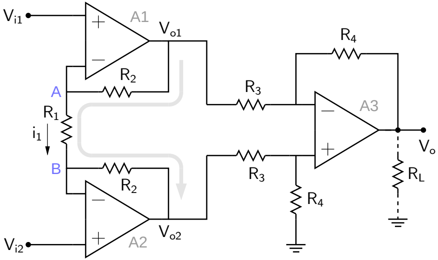
$$V_+ \approx V_- \rightarrow V_A = V_{i1}\,,\ \ V_B = V_{i2}\,, \rightarrow i_1 = \frac{1}{R_1}\,(V_{i1} - V_{i2})\,.$$

Large input resistance of A1 and A2 $\Rightarrow$ the current through the two resistors marked R_2 is also equal to i_1.



$$V_+ \approx V_- \;\rightarrow\; V_A = V_{i1}\;,\;\; V_B = V_{i2}\;, \rightarrow\; i_1 = \frac{1}{R_1}\left(V_{i1} - V_{i2}\right).$$

Large input resistance of A1 and A2 $\Rightarrow$ the current through the two resistors marked R_2 is also equal to i_1.

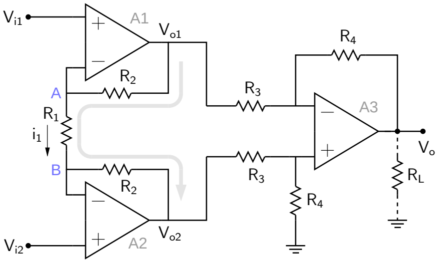


$V_+ \approx V_- \rightarrow V_A = V_{i1}\,,\;\; V_B = V_{i2}\,, \rightarrow i_1 = \dfrac{1}{R_1}\,(V_{i1} - V_{i2})\,.$

Large input resistance of A1 and A2 $\Rightarrow$ the current through the two resistors marked R_2 is also equal to i_1.

$$V_{o1} - V_{o2} = i_1(R_1 + 2\,R_2) = \frac{1}{R_1}\,(V_{i1} - V_{i2})\,(R_1 + 2\,R_2) = (V_{i1} - V_{i2})\left(1 + \frac{2\,R_2}{R_1}\right).$$

Improved difference amplifier

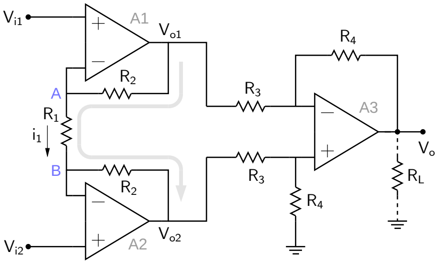


$V_+ \approx V_- \rightarrow V_A = V_{i1}\,,\;\; V_B = V_{i2}\,, \rightarrow i_1 = \dfrac{1}{R_1}\,(V_{i1} - V_{i2})\,.$

Large input resistance of A1 and A2 $\Rightarrow$ the current through the two resistors marked R_2 is also equal to i_1.

$V_{o1} - V_{o2} = i_1(R_1 + 2\,R_2) = \dfrac{1}{R_1}\,(V_{i1} - V_{i2})\,(R_1 + 2\,R_2) = (V_{i1} - V_{i2})\left(1 + \dfrac{2\,R_2}{R_1}\right)\,.$

Finally, $V_o = \dfrac{R_4}{R_3}(V_{o2} - V_{o1}) = \dfrac{R_4}{R_3}\left(1 + \dfrac{2\,R_2}{R_1}\right)(V_{i2} - V_{i1})\,.$



$V_+ \approx V_- \rightarrow V_A = V_{i1}\,,\ V_B = V_{i2}\,, \rightarrow i_1 = \dfrac{1}{R_1}\,(V_{i1} - V_{i2})\,.$

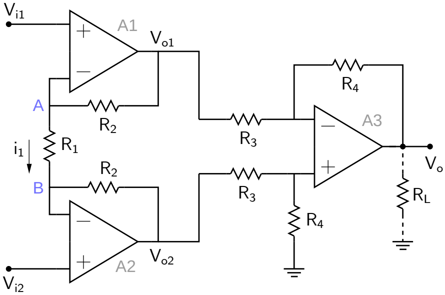
Large input resistance of A1 and A2 $\Rightarrow$ the current through the two resistors marked R_2 is also equal to i_1.

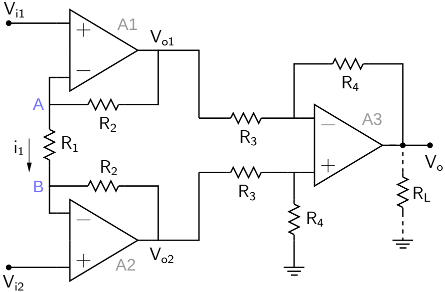
$$V_{o1} - V_{o2} = i_1(R_1 + 2\,R_2) = \frac{1}{R_1}\,(V_{i1} - V_{i2})\,(R_1 + 2\,R_2) = (V_{i1} - V_{i2})\left(1 + \frac{2\,R_2}{R_1}\right).$$

Finally, $V_o = \dfrac{R_4}{R_3}(V_{o2} - V_{o1}) = \dfrac{R_4}{R_3}\left(1 + \dfrac{2\,R_2}{R_1}\right)(V_{i2} - V_{i1})\,.$

This circuit is known as the “instrumentation amplifier.”

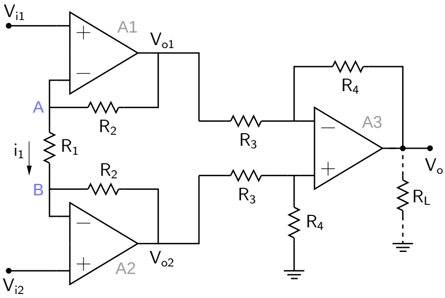
Instrumentation amplifier





The input resistance seen from V_{i1} or V_{i2} is large (since an Op Amp has a large input resistance).

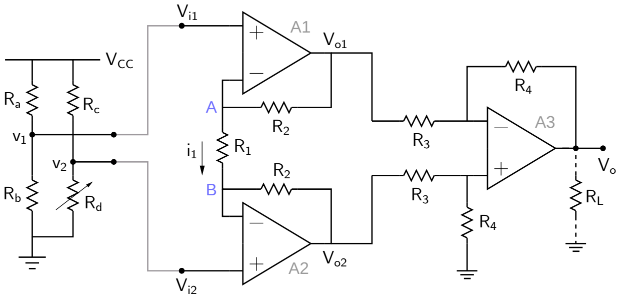
Instrumentation amplifier



The input resistance seen from V_{i1} or V_{i2} is large (since an Op Amp has a large input resistance).

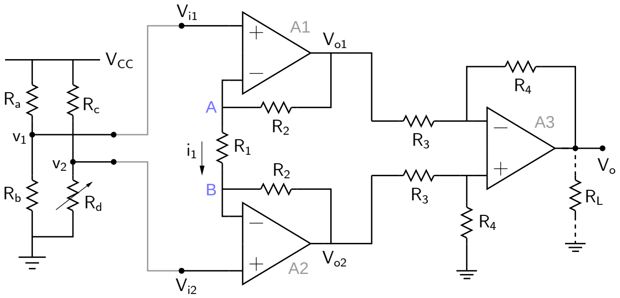
$\rightarrow$ the amplifier will not "load" the preceding stage, a desirable feature.

Instrumentation amplifier



The input resistance seen from V_{i1} or V_{i2} is large (since an Op Amp has a large input resistance).

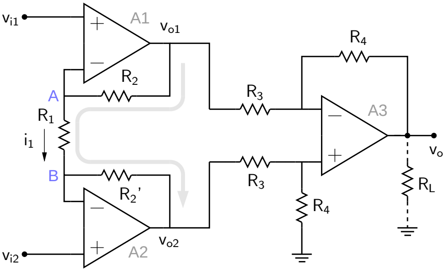
$\rightarrow$ the amplifier will not "load" the preceding stage, a desirable feature.



The input resistance seen from V_{i1} or V_{i2} is large (since an Op Amp has a large input resistance).

$\rightarrow$ the amplifier will not "load" the preceding stage, a desirable feature.

As a result, the voltages v_1 and v_2 in the bridge circuit will remain essentially the same when the bridge circuit is connected to the instrumentation amplifier.

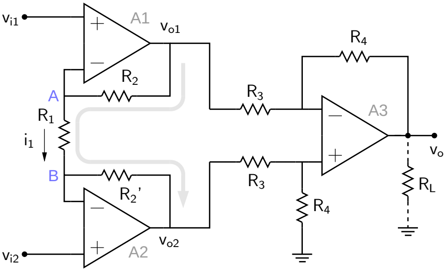


$v_{i1} = v_c - v_d/2$

$v_{i2} = v_c + v_d/2$

As we have seen earlier, v_{i1} and v_{i2} can have a large common-mode component (v_c).

What is the effect of v_c on the amplifier output v_o?



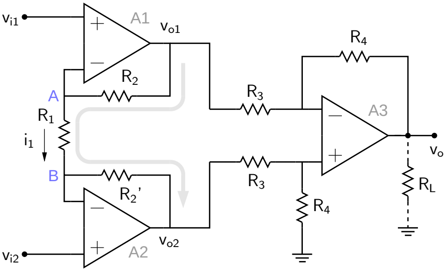
$v_{i1} = v_c - v_d/2$

$v_{i2} = v_c + v_d/2$

As we have seen earlier, v_{i1} and v_{i2} can have a large common-mode component (v_c).

What is the effect of v_c on the amplifier output v_o?

$v_+ \approx v_- \Rightarrow v_A = v_c - v_d/2\,,\;\; v_B = v_c + v_d/2\,.$



$v_{i1} = v_c - v_d/2$

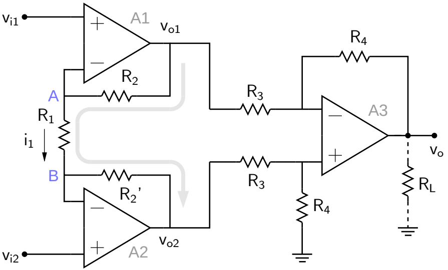
$v_{i2} = v_c + v_d/2$

As we have seen earlier, v_{i1} and v_{i2} can have a large common-mode component (v_c).

What is the effect of v_c on the amplifier output v_o?

$v_+ \approx v_- \Rightarrow v_A = v_c - v_d/2\,,\ v_B = v_c + v_d/2\,.$

$$i_1 = \frac{1}{R_1}(v_A - v_B) = \frac{1}{R_1}((v_c - v_d/2) - (v_c + v_d/2)) = -\frac{1}{R_1}v_d\,.$$



$v_{i1} = v_c - v_d/2$

$v_{i2} = v_c + v_d/2$

As we have seen earlier, v_{i1} and v_{i2} can have a large common-mode component (v_c).

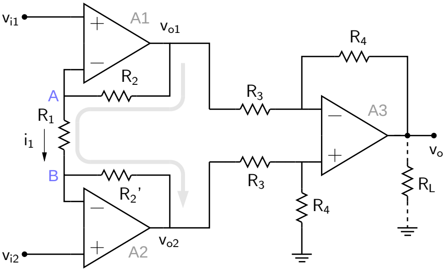
What is the effect of v_c on the amplifier output v_o?

$v_+ \approx v_- \Rightarrow v_A = v_c - v_d/2\,,\;\; v_B = v_c + v_d/2\,.$

$$i_1 = \frac{1}{R_1}(v_A - v_B) = \frac{1}{R_1}((v_c - v_d/2) - (v_c + v_d/2)) = -\frac{1}{R_1}v_d\,.$$

v_c has simply got cancelled! (And this holds even if R_2 and R_2' are not exactly matched.)

Instrumentation amplifier



$v_{i1} = v_c - v_d/2$

$v_{i2} = v_c + v_d/2$

As we have seen earlier, v_{i1} and v_{i2} can have a large common-mode component (v_c).

What is the effect of v_c on the amplifier output v_o?

$v_+ \approx v_- \Rightarrow v_A = v_c - v_d/2\,,\ v_B = v_c + v_d/2\,.$

$$i_1 = \frac{1}{R_1}(v_A - v_B) = \frac{1}{R_1}((v_c - v_d/2) - (v_c + v_d/2)) = -\frac{1}{R_1}v_d\,.$$

v_c has simply got cancelled! (And this holds even if R_2 and R_2' are not exactly matched.)

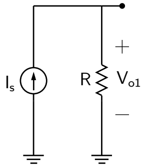
→ The instrumentation amplifier is very effective in minimising the effect of the common-mode signal. (Note that component mismatch in the second stage will cause a finite CMRR, but the first stage has effectively amplified only v_d while leaving v_c unchanged; so the overall CMRR has improved.)

Current-to-voltage conversion

Some circuits produce an output in the form of a current. It is convenient to convert this current into a voltage for further processing.

Some circuits produce an output in the form of a current. It is convenient to convert this current into a voltage for further processing.

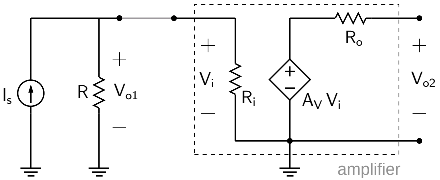
Current-to-voltage conversion can be achieved by simply passing the current through a resistor: $V_{o1} = I_s\,R$.



Current-to-voltage conversion

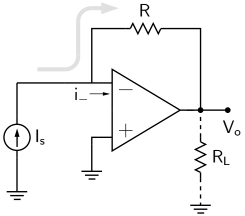
Some circuits produce an output in the form of a current. It is convenient to convert this current into a voltage for further processing.

Current-to-voltage conversion can be achieved by simply passing the current through a resistor: $V_{o1} = I_s\, R$.

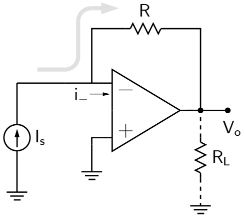


However, this simple approach will not work if the next stage in the circuit (such as an amplifier) has a finite R_i, since it will modify V_{o1} to $V_{o1} = I_s\,(R_i \parallel R)$, which is not desirable.

Current-to-voltage conversion

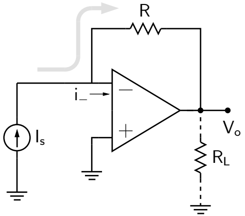


Current-to-voltage conversion



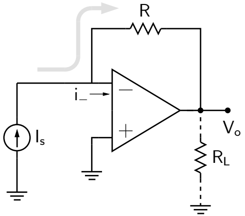
$V_- \approx V_+$, and $i_- \approx 0 \Rightarrow V_o = V_- - I_s R = -I_s R$.

Current-to-voltage conversion



$V_- \approx V_+$, and $i_- \approx 0 \Rightarrow V_o = V_- - I_s\,R = -I_s\,R\,.$

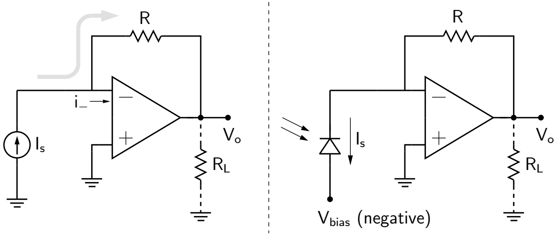
The output voltage is proportional to the source current, *irrespective* of the value of R_L, i.e., irrespective of the next stage.



$V_- \approx V_+$, and $i_- \approx 0 \Rightarrow V_o = V_- - I_s\, R = -I_s\, R$.

The output voltage is proportional to the source current, *irrespective* of the value of R_L, i.e., irrespective of the next stage.

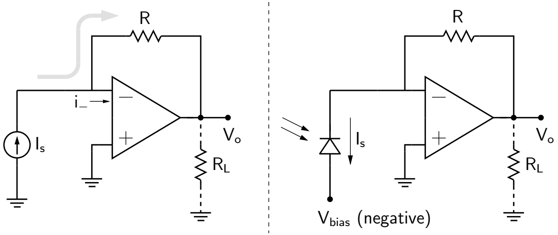
Example: a photocurrent detector.



$V_- \approx V_+$, and $i_- \approx 0 \Rightarrow V_o = V_- - I_s\,R = -I_s\,R$.

The output voltage is proportional to the source current, *irrespective* of the value of R_L, i.e., irrespective of the next stage.

Example: a photocurrent detector.

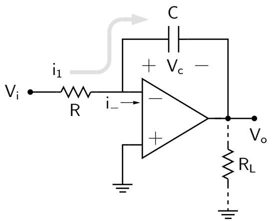


$V_- \approx V_+$, and $i_- \approx 0 \Rightarrow V_o = V_- - I_s\,R = -I_s\,R$.

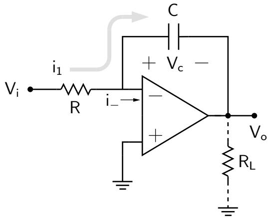
The output voltage is proportional to the source current, *irrespective* of the value of R_L, i.e., irrespective of the next stage.

Example: a photocurrent detector.

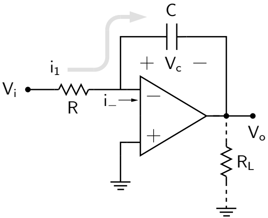
$V_o = I_s\,R$. The diode is under a reverse bias, with $V_n = 0\,V$ and $V_p = V_{\text{bias}}$.


C
i_1
$+$ V_c $-$
V_i
R
i_-
V_o
R_L

Op Amp circuits (linear region)



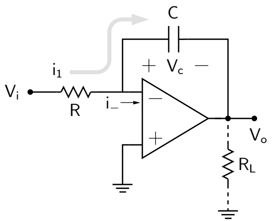
$V_- \approx V_+ = 0\,V \rightarrow i_1 = V_i/R\,.$



$V_- \approx V_+ = 0\,V \rightarrow i_1 = V_i/R$.

Since $i_- \approx 0$, the current through the capacitor is i_1 .

$\Rightarrow C\,\dfrac{dV_c}{dt} = i_1 = \dfrac{V_i}{R}$.

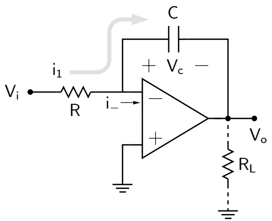


$V_- \approx V_+ = 0\,V \rightarrow i_1 = V_i/R$.

Since $i_- \approx 0$, the current through the capacitor is i_1 .

$\Rightarrow C\,\dfrac{dV_c}{dt} = i_1 = \dfrac{V_i}{R}$.

$V_c = V_- - V_o = 0 - V_o = -V_o \rightarrow C\left(-\dfrac{dV_o}{dt}\right) = \dfrac{V_i}{R}$



$V_- \approx V_+ = 0\,V \rightarrow i_1 = V_i/R\,.$

Since $i_- \approx 0$, the current through the capacitor is i_1.

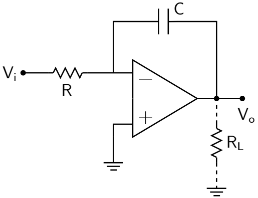
$\Rightarrow C\,\dfrac{dV_c}{dt} = i_1 = \dfrac{V_i}{R}\,.$

$V_c = V_- - V_o = 0 - V_o = -V_o \rightarrow C\left(-\dfrac{dV_o}{dt}\right) = \dfrac{V_i}{R}$

$$\boxed{V_o = -\frac{1}{RC}\int V_i\,dt}$$

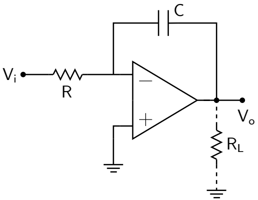
The circuit works as an integrator.

Integrator



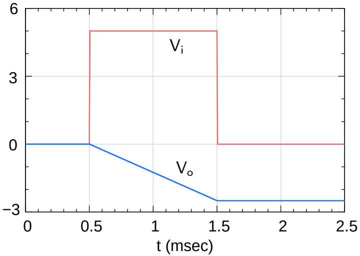
$R = 1\,\mathrm{k}\Omega\,,\;\; C = 0.2\,\mu F$

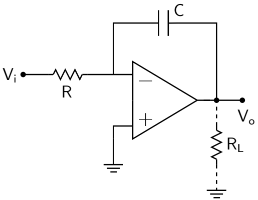
$$V_o = -\frac{1}{RC}\int V_i\,dt$$



$$R = 1\,\mathrm{k}\Omega\,,\;\; C = 0.2\,\mu F$$

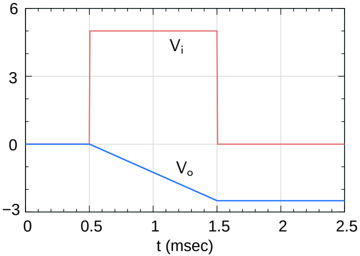
$$V_o = -\frac{1}{RC}\int V_i\,dt$$

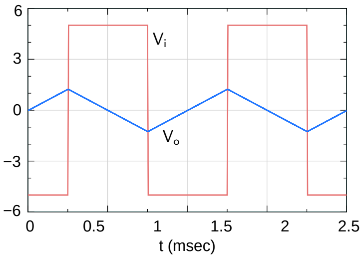




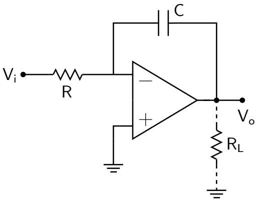
$R = 1\,\mathrm{k}\Omega\,,\ C = 0.2\,\mu F$

$$V_o = -\frac{1}{RC}\int V_i\,dt$$



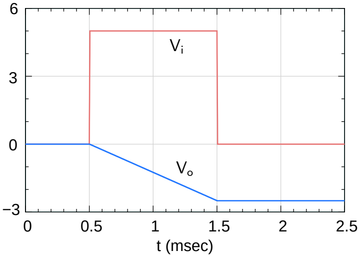


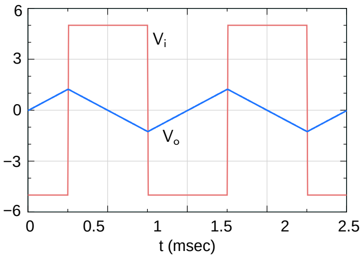
Integrator



$R = 1\,\mathrm{k}\Omega\,,\;\; C = 0.2\,\mu F$

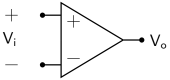
$$V_o = -\frac{1}{RC}\int V_i\, dt$$

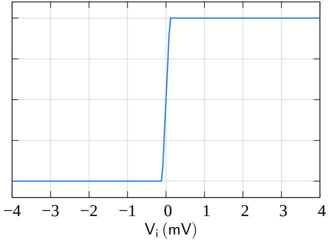




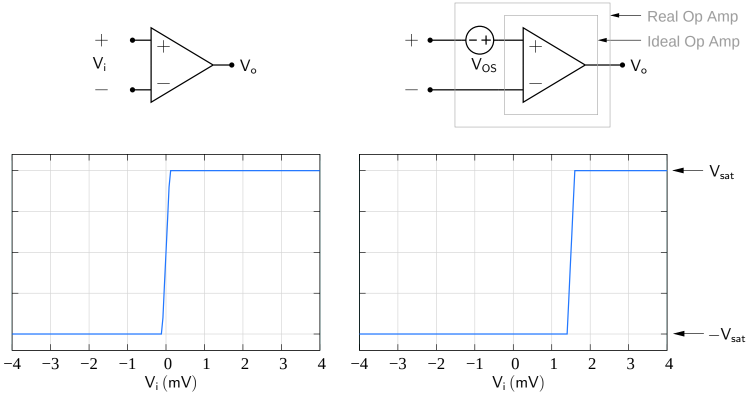
SEQUEL files: `ee101_integrator_1.sqproj`, `ee101_integrator_2.sqproj`

Offset voltage

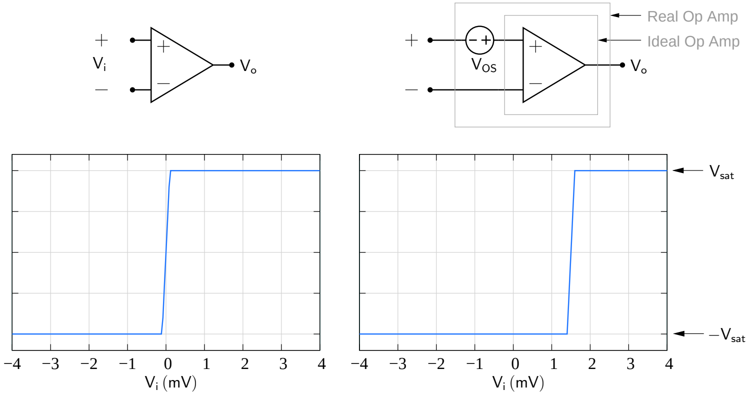




Offset voltage

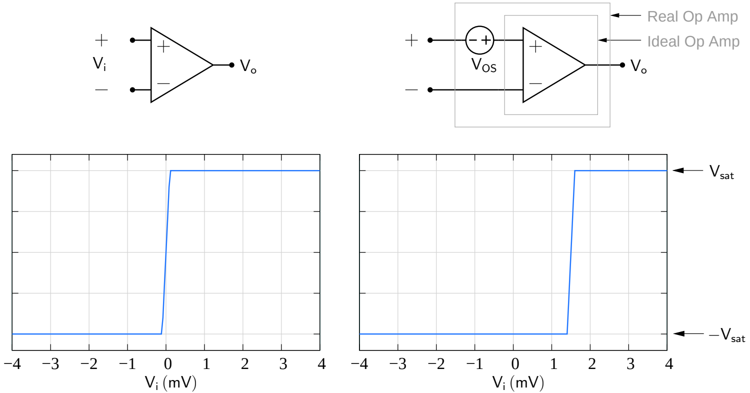


Offset voltage



For the real Op Amp, $V_o = A_V((V_+ + V_{OS}) - V_-)$.

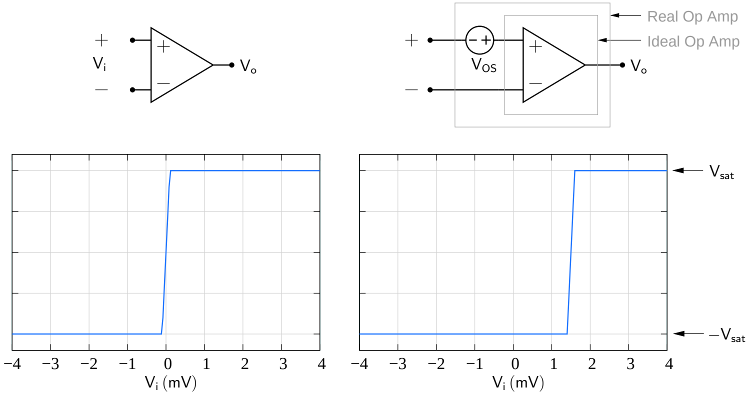
Offset voltage



For the real Op Amp, $V_o = A_V((V_+ + V_{OS}) - V_-)$.

For $V_o = 0\ V$, $V_+ + V_{OS} - V_- = 0 \rightarrow V_+ - V_- = -V_{OS}$.

Offset voltage

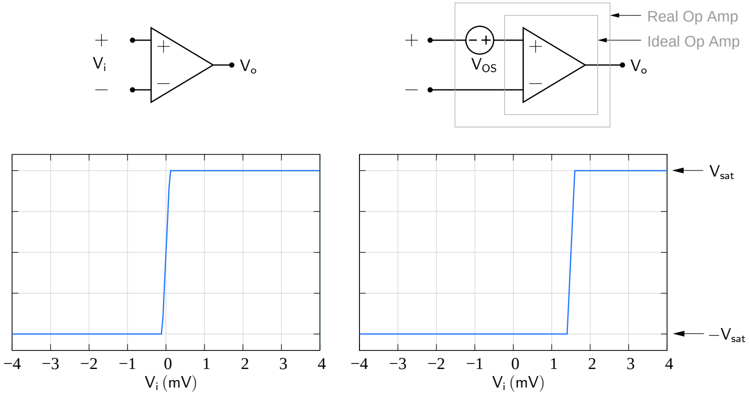


For the real Op Amp, $V_o = A_V((V_+ + V_{OS}) - V_-)$.

For $V_o = 0\,V$, $V_+ + V_{OS} - V_- = 0 \rightarrow V_+ - V_- = -V_{OS}$.

V_o versus V_i curve gets shifted.

Offset voltage



For the real Op Amp, $V_o = A_V((V_+ + V_{OS}) - V_-)$.

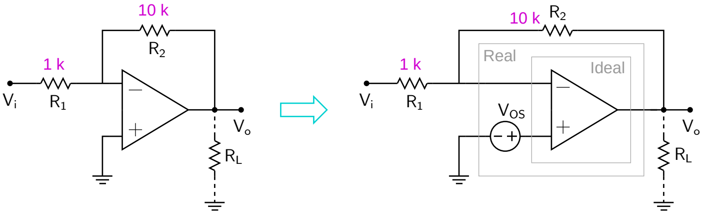
For $V_o = 0\,V$, $V_+ + V_{OS} - V_- = 0 \rightarrow V_+ - V_- = -V_{OS}$.

V_o versus V_i curve gets shifted.

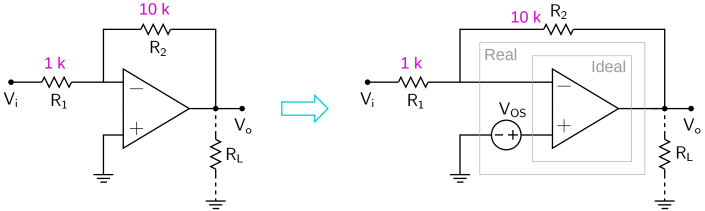
741: $-6\,\mathrm{m}V < V_{OS} < 6\,\mathrm{m}V$.

OP-77: $-50\,\mu V < V_{OS} < 50\,\mu V$.

Effect of V_{OS}

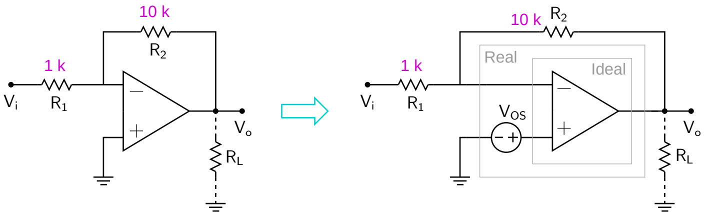


Effect of V_{OS}



By superposition, $V_o = -\dfrac{R_2}{R_1}\, V_i + V_{OS}\left(1 + \dfrac{R_2}{R_1}\right)$.

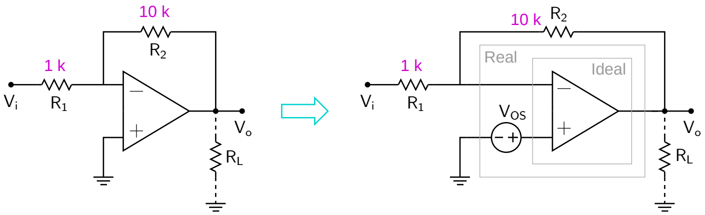
Effect of V_{OS}



By superposition, $V_o = -\dfrac{R_2}{R_1}\,V_i + V_{OS}\left(1+\dfrac{R_2}{R_1}\right)$.

For $V_{OS} = 2\,\mathrm{m}V$, the contribution from V_{OS} to V_o is $22\,\mathrm{m}V$,

Effect of V_{OS}

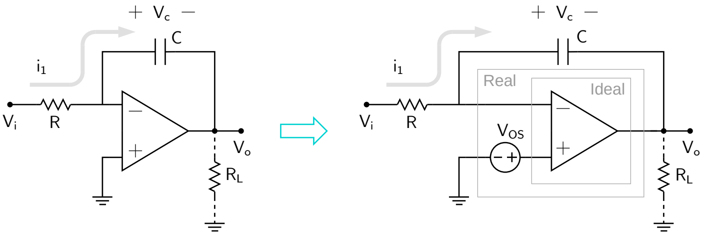


By superposition, $V_o = -\dfrac{R_2}{R_1}\,V_i + V_{OS}\left(1+\dfrac{R_2}{R_1}\right)$.

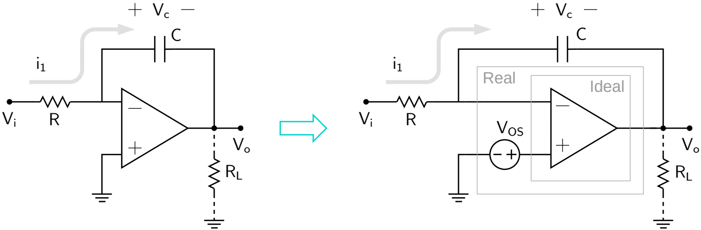
For $V_{OS} = 2\,\mathrm{m}V$, the contribution from V_{OS} to V_o is $22\,\mathrm{m}V$,

i.e., a DC shift of $22\,\mathrm{m}V$.

Effect of V_{OS}

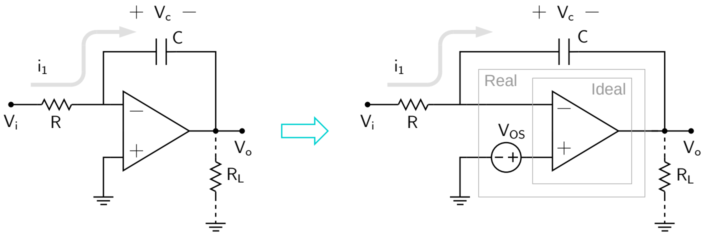


Effect of V_{OS}



$$V_- \approx V_+ = V_{OS} \rightarrow i_1 = \frac{1}{R}(V_i - V_{OS}) = C\,\frac{dV_c}{dt}\,.$$

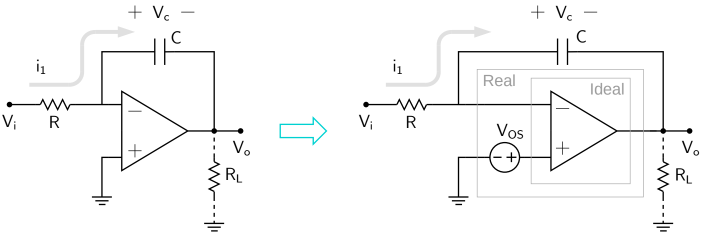
Effect of V_{OS}



$$V_- \approx V_+ = V_{OS} \rightarrow i_1 = \frac{1}{R}(V_i - V_{OS}) = C\,\frac{dV_c}{dt}\,.$$

i.e., $V_c = \dfrac{1}{RC}\displaystyle\int (V_i - V_{OS})\,dt\,.$

Effect of V_{OS}



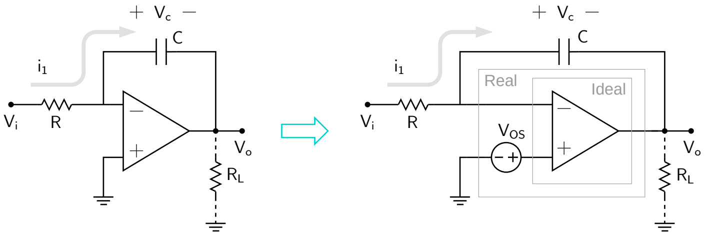
$$V_- \approx V_+ = V_{OS} \rightarrow i_1 = \frac{1}{R}(V_i - V_{OS}) = C\,\frac{dV_c}{dt}\,.$$

i.e., $V_c = \dfrac{1}{RC}\displaystyle\int (V_i - V_{OS})\,dt\,.$

Even with $V_i = 0\,V$, V_c will keep rising or falling (depending on the sign of V_{OS}).

Eventually, the Op Amp will be driven into saturation.

Effect of V_{OS}



$$V_- \approx V_+ = V_{OS} \rightarrow i_1 = \frac{1}{R}(V_i - V_{OS}) = C\,\frac{dV_c}{dt}\,.$$

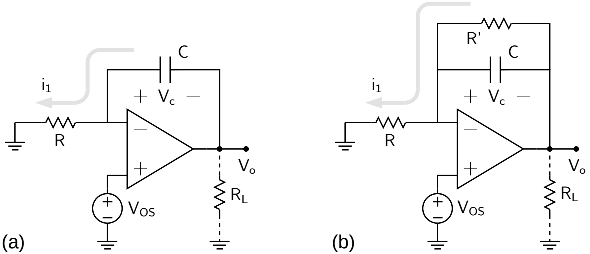
i.e., $V_c = \dfrac{1}{RC}\displaystyle\int (V_i - V_{OS})\,dt\,.$

Even with $V_i = 0\,V$, V_c will keep rising or falling (depending on the sign of V_{OS}).

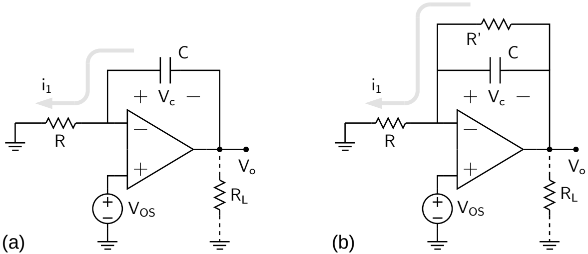
Eventually, the Op Amp will be driven into saturation.

$\rightarrow$ need to address this issue!

Integrator with $V_i = 0\ V$:



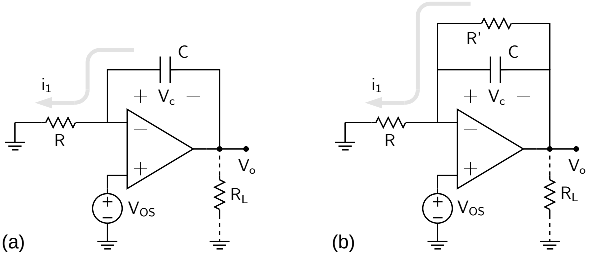
Integrator with $V_i = 0\ V$:



(a) $$i_1 = \frac{V_{OS}}{R} = -C\,\frac{dV_c}{dt}$$

$$V_c = -\frac{1}{RC}\int V_{OS}\,dt \rightarrow \text{Op Amp saturates.}$$

Integrator with $V_i = 0\ V$:



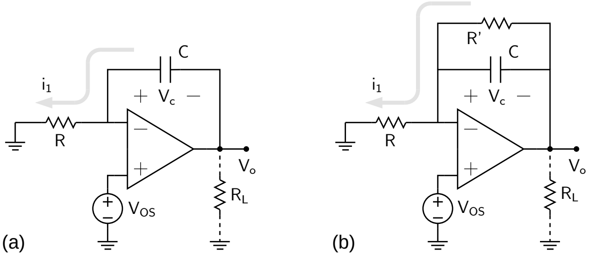
(a) $$i_1 = \frac{V_{OS}}{R} = -C\,\frac{dV_c}{dt}$$

$$V_c = -\frac{1}{RC}\int V_{OS}\,dt \rightarrow \text{Op Amp saturates.}$$

(b) There is a DC path for the current.

$$\rightarrow V_o = \left(1 + \frac{R'}{R}\right) V_{OS}\,.$$

Integrator with $V_i = 0\ V$:



(a) $$i_1 = \frac{V_{OS}}{R} = -C\,\frac{dV_c}{dt}$$

$$V_c = -\frac{1}{RC}\int V_{OS}\,dt \rightarrow \text{Op Amp saturates.}$$

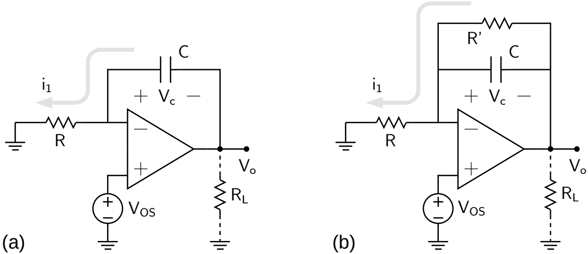
(b) There is a DC path for the current.

$$\rightarrow V_o = \left(1 + \frac{R'}{R}\right) V_{OS}\,.$$

R' should be small enough to have a negligible effect on V_o.

Effect of V_{OS}

Integrator with $V_i = 0\ V$:



(a) $\quad i_1 = \dfrac{V_{OS}}{R} = -C\,\dfrac{dV_c}{dt}$

$V_c = -\dfrac{1}{RC}\displaystyle\int V_{OS}\,dt \rightarrow$ Op Amp saturates.

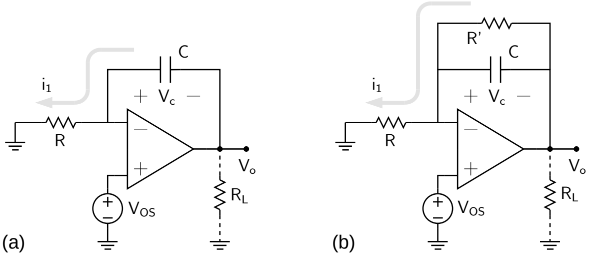
(b) $\quad$ There is a DC path for the current.

$$\rightarrow V_o = \left(1 + \frac{R'}{R}\right) V_{OS}\,.$$

R' should be small enough to have a negligible effect on V_o.

However, R' must be large enough to ensure that the circuit still functions as an integrator.

Integrator with $V_i = 0\ V$:



(a) $i_1 = \dfrac{V_{OS}}{R} = -C\,\dfrac{dV_c}{dt}$

$V_c = -\dfrac{1}{RC}\displaystyle\int V_{OS}\,dt$ → Op Amp saturates.

(b) There is a DC path for the current.

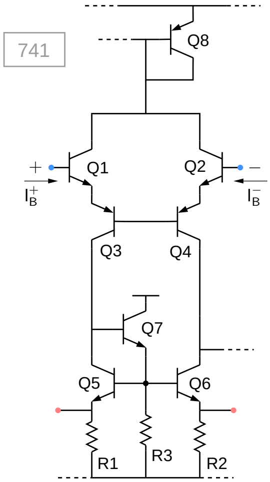
$$\rightarrow V_o = \left(1 + \frac{R'}{R}\right) V_{OS}\,.$$

R' should be small enough to have a negligible effect on V_o.

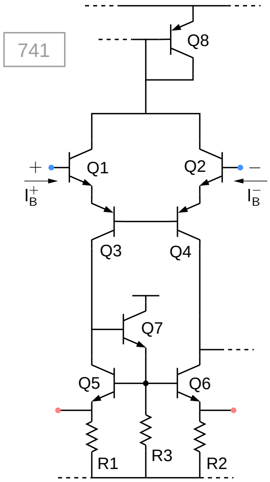
However, R' must be large enough to ensure that the circuit still functions as an integrator.

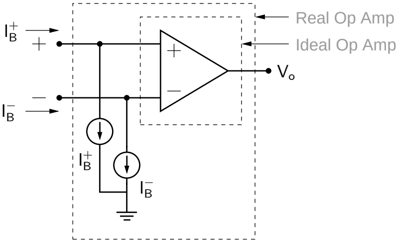
→ $R' \gg 1/\omega C$ at the frequency of interest.

Input bias currents

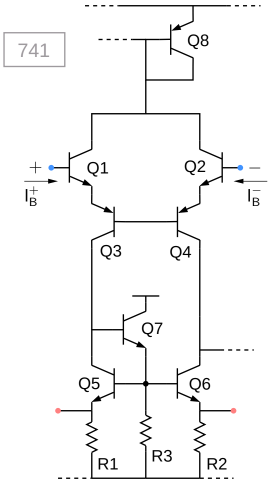


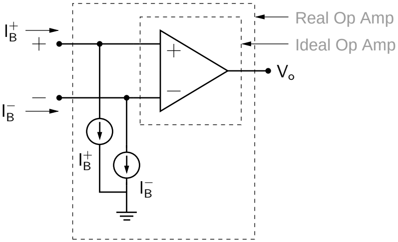
Input bias currents





Input bias currents

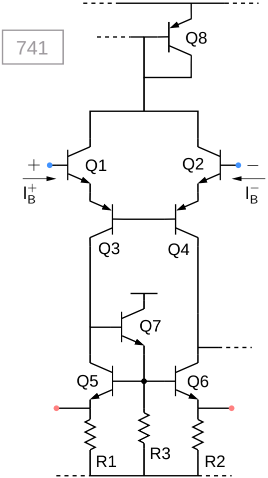


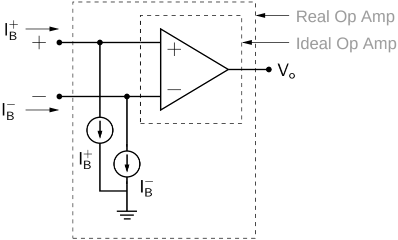


I_B^+ and I_B^- are generally not exactly equal.

$|I_B^+ - I_B^-|$: "offset current" (I_{OS})

$(I_B^+ + I_B^-)/2$: "bias current" (I_B).





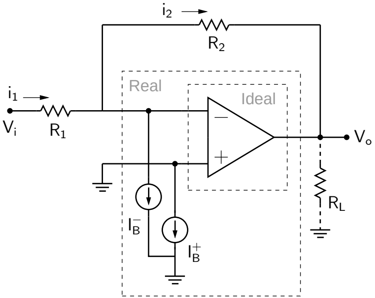
Op Amp	I_B	I_{OS}	V_{OS}	
741	80 nA	20 nA	1 mV	BJT input
OP77	1.2 nA	0.3 nA	10 μV	BJT input
411	50 pA	25 pA	0.8 mV	FET input

I_B^+ and I_B^- are generally not exactly equal.

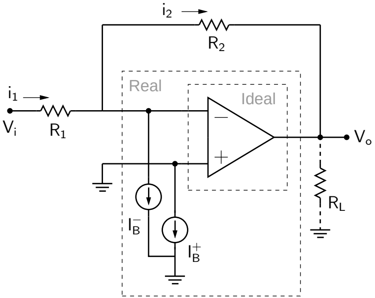
$|I_B^+ - I_B^-|$: "offset current" (I_{OS})

$(I_B^+ + I_B^-)/2$: "bias current" (I_B).

Inverting amplifier:

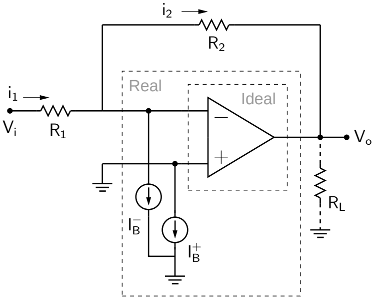


Inverting amplifier:



Assume that the Op Amp is ideal in other respects (i.e., $V_{OS} = 0\ V$, etc.).

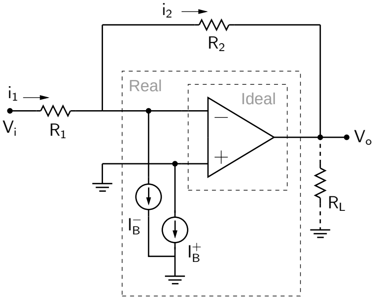
Inverting amplifier:



Assume that the Op Amp is ideal in other respects (i.e., $V_{OS} = 0\ V$, etc.).

$V_- \approx V_+ = 0\ V \rightarrow i_1 = V_i/R_1$.

Inverting amplifier:

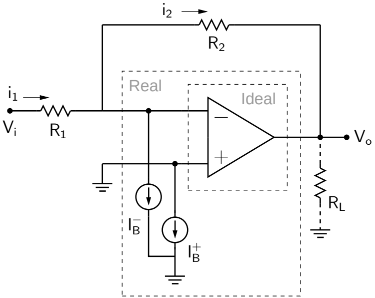


Assume that the Op Amp is ideal in other respects (i.e., $V_{OS} = 0\,V$, etc.).

$V_- \approx V_+ = 0\,V \rightarrow i_1 = V_i/R_1$.

$$i_2 = i_1 - I_B^- \rightarrow V_o = V_- - i_2\,R_2 = 0 - \left(\frac{V_i}{R_1} - I_B^-\right) R_2 = -\frac{R_2}{R_1}\,V_i + I_B^-\,R_2\ ,$$

Inverting amplifier:



Assume that the Op Amp is ideal in other respects (i.e., $V_{OS} = 0\,V$, etc.).

$V_- \approx V_+ = 0\,V \rightarrow i_1 = V_i/R_1$.

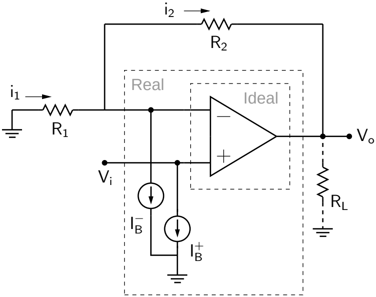
$i_2 = i_1 - I_B^- \rightarrow V_o = V_- - i_2\,R_2 = 0 - \left(\dfrac{V_i}{R_1} - I_B^-\right) R_2 = -\dfrac{R_2}{R_1}\,V_i + I_B^-\,R_2$,

i.e., the bias current causes a DC shift in V_o.

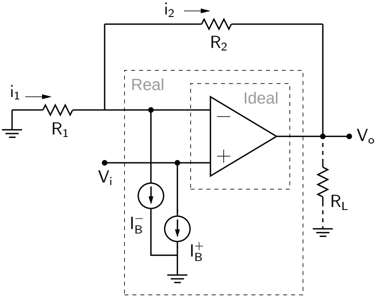
For $I_B^- = 80\,\mathrm{n}A$, $R_2 = 10\,\mathrm{k}$, $\Delta V_o = 0.8\,\mathrm{m}V$.

Effect of bias currents

Non-nverting amplifier:

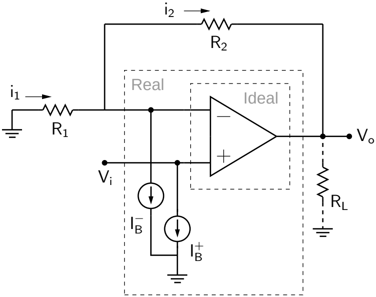


Non-nverting amplifier:



Assume that the Op Amp is ideal in other respects (i.e., $V_{OS} = 0\,V$, etc.).

Non-nverting amplifier:

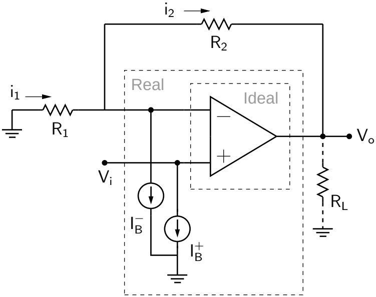


Assume that the Op Amp is ideal in other respects (i.e., $V_{OS} = 0\ V$, etc.).

$V_- \approx V_+ = V_i \rightarrow i_1 = -V_i/R_1$.

Effect of bias currents

Non-nverting amplifier:

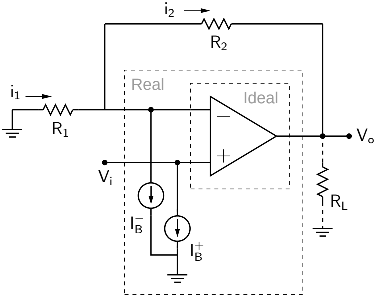


Assume that the Op Amp is ideal in other respects (i.e., $V_{OS} = 0\,V$, etc.).

$V_- \approx V_+ = V_i \rightarrow i_1 = -V_i/R_1$.

$$i_2 = i_1 - I_B^- = -\frac{V_i}{R_1} - I_B^- \; .$$

Non-nverting amplifier:



Assume that the Op Amp is ideal in other respects (i.e., $V_{OS} = 0\,V$, etc.).

$V_- \approx V_+ = V_i \rightarrow i_1 = -V_i/R_1$.

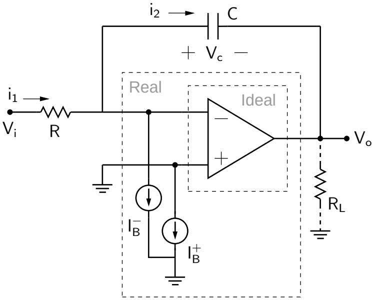
$i_2 = i_1 - I_B^- = -\dfrac{V_i}{R_1} - I_B^-$.

$V_o = V_i - i_2\,R_2 = V_i - \left(-\dfrac{V_i}{R_1} - I_B^-\right) R_2 = V_i \left(1 + \dfrac{R_2}{R_1}\right) + I_B^-\,R_2$.

$\rightarrow$ Again, a DC shift ΔV_o.

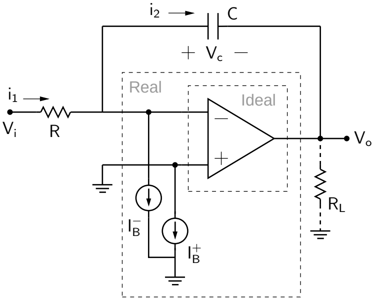
Effect of bias currents

Integrator:



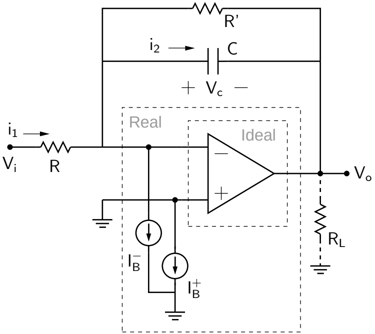
Effect of bias currents

Integrator:



Even with $V_i = 0\,V$, $V_c = \dfrac{1}{C}\displaystyle\int -I_B^-\,dt$ will drive the Op Amp into saturation.

Integrator:

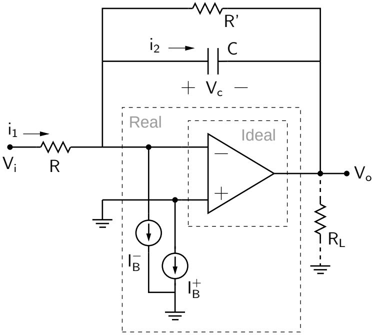


Even with $V_i = 0\,V$, $V_c = \dfrac{1}{C}\displaystyle\int -I_B^- \, dt$ will drive the Op Amp into saturation.

Connecting R' across C provides a DC path for the current, and results in a DC shift $\Delta V_o = I_B^- R'$ at the output.

Effect of bias currents

Integrator:



Even with $V_i = 0\,V$, $V_c = \dfrac{1}{C}\displaystyle\int -I_B^-\,dt$ will drive the Op Amp into saturation.

Connecting R' across C provides a DC path for the current, and results in a DC shift $\Delta V_o = I_B^- R'$ at the output.

As we have discussed earlier, R' should be small enough to have a negligible effect on V_o. However, R' must be large enough to ensure that the circuit still functions as an integrator.