EE101: Op Amp circuits (Part 2)

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

The bridge converts $\Delta R$ 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, $v_1 = \frac{1}{2} V_{CC}$. $v_2 = \left(\frac{R + \Delta R}{R + (R + \Delta R)}\right) V_{CC} = \frac{1}{2} \left(1 + \frac{\Delta R}{R}\right) \left(1 - \frac{\Delta R}{2R}\right) V_{CC} \approx \frac{1}{2} \left(1 + \frac{\Delta R}{2R}\right) V_{CC}$, where $x = \frac{\Delta R}{R}$.

For example, with $V_{CC} = 15$ V, $R = 1 \, \text{k} \Omega$, $\Delta R = 0.01 \, \text{k} \Omega$, $v_1 = 7.5$ V, $v_2 = 7.5 + 0.0375$ V.
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For example, with $V_{CC} = 15\, V$, $R = 1\, k$, $\Delta R = 0.01\, k$, $v_1 = 7.5\, V$, $v_2 = 7.5 + 0.0375\, V$. 

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Common-mode and differential-mode voltages

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**Definitions:**

Given \( v_1 \) and \( v_2 \),

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v_c = \frac{1}{2} (v_1 + v_2) = \text{common-mode voltage},
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v_d = (v_2 - v_1) = \text{differential-mode voltage}.
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\( v_1 \) and \( v_2 \) can be rewritten as,

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In the above example, \( v_c \approx 7.5\, \text{V}, \quad v_d = 37.5\, \text{mV}. \)
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Note that the common-mode voltage is quite large compared to the differential-mode voltage.

This is a common situation in transducer circuits.

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Common-Mode Rejection Ratio

An ideal amplifier would only amplify the difference \(v_+ - v_-\), giving
\[v_o = A_d (v_+ - v_-) = A_d v_d,
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where \(A_d\) is called the “differential gain” or simply the gain \((A_V)\).
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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):
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For the 741 Op Amp, the CMRR is 90 dB \((\sim 30,000)\), 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.
Op Amp circuits (linear region)

Method 1:
Large input resistance of Op Amp → $i_+ = 0$, $V_+ = R_4/V_{i2}$.

Since $V_+ - V_- \approx 0$, $i_1 = 1/R_1 (V_{i1} - V_-) \approx 1/R_1 (V_{i1} - V_+)$. $i_- \approx 0 \rightarrow V_o = V_- - i_1 R_2 \approx V_+ - R_2/R_1 (V_{i1} - V_{i2})$.

Substituting for $V_+$ and selecting $R_3/R_4 = R_1/R_2$, we get (show this), $V_o = R_2/R_1 (V_{i2} - V_{i1})$.

The circuit is a "difference amplifier."
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Since the Op Amp is operating in the linear region, we can use superposition:
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\[ V_{o1} = -\frac{R_2}{R_1} V_{i1}. \]
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**Case 2:** Non-inverting amplifier, with \( V_i = \frac{R_4}{R_3 + R_4} V_{i2} \).

\[
V_{o2} = \left( 1 + \frac{R_2}{R_1} \right) \left( \frac{R_4}{R_3 + R_4} \right) V_{i2}.
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\rightarrow V_{o2} = \left(1 + \frac{R_2}{R_1}\right) \left(\frac{R_4}{R_3 + R_4}\right) V_{i2}.
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The net result is,

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

→ 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).
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Consider the difference amplifier with

\[ R_3 = R_1, \quad R_4 = R_2 \]

\[ R_L = R_2 \]

\[ v_{i1} = v_c - v_d/2 \]

\[ v_{i2} = v_c + v_d/2 \]

The output voltage depends only on the differential-mode signal \( v_i \), i.e.,

\[ A_c (\text{common-mode gain}) = 0. \]

In practice, \( R_3 \) and \( R_1 \) may not be exactly equal. Let

\[ R_3 = R_1 + \Delta R \]

\[ v_o = \frac{R_L}{R_1} \left( v_{i2} - v_{i1} \right) + \frac{R_2}{R_1} \left( v_{i2} + v_{i1} \right) \]

\[ \approx \frac{R_2}{R_1} \left( v_d - x v_c \right) \]

with

\[ x = \frac{\Delta R}{R_1} + \frac{R_2}{R_1} \]

\[ |A_c| \approx x R_2 R_1 = 0.01 |A_d| = R_2 R_1. \]

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

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

The output voltage depends only on the differential-mode signal \( (v_{i2} - v_{i1}) \), i.e., \( A_c \) (common-mode gain) = 0.
Consider the difference amplifier with $R_3 = R_1$, $R_4 = R_2 \rightarrow V_o = \frac{R_2}{R_1} (v_{i2} - v_{i1})$.

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    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}
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    \simeq \frac{R_2}{R_1} (v_d - x \cdot v_c), \text{ with } x = \frac{\Delta R}{R_1 + R_2} \quad \text{(show this)}
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Consider the difference amplifier with $R_3 = R_1$, $R_4 = R_2 \rightarrow V_o = \frac{R_2}{R_1} (v_{i_2} - v_{i_1})$.

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

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Improved difference amplifier

The circuit shown is an improved difference amplifier. It consists of three operational amplifiers (A1, A2, and A3) connected in a specific configuration to achieve a high input impedance and amplify the difference between the two input voltages, $V_{i1}$ and $V_{i2}$.

The circuit can be described mathematically as follows:

1. The input voltages are $V_{i1}$ and $V_{i2}$.
2. Amplifiers A1 and A2 form a differential input stage.
3. Amplifier A3 serves as a follower stage.
4. The output voltage is $V_{o}$.

Mathematically:

- $V_{o1} = V_{i1}$, $V_{o2} = V_{i2}$
- $i_1 = \frac{V_{i1} - V_{i2}}{R_1}$
- $V_{o} = \frac{R_1}{R_2} \frac{V_{o1} - V_{o2}}{1 + \frac{2R_2}{R_1}}$ for $V_{o1} = V_{o2}$
- $V_{o} = \frac{R_3}{R_2} \frac{V_{o1} - V_{o2}}{1 + \frac{2R_2}{R_3}}$ for $V_{o1} \neq V_{o2}$

This circuit is known as the "instrumentation amplifier."
Improved difference amplifier

\[ V_+ \approx V_- \rightarrow V_A = V_{i1}, \quad V_B = V_{i2}, \rightarrow i_1 = \frac{1}{R_1} (V_{i1} - V_{i2}). \]
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Large input resistance of A1 and A2 \( \Rightarrow \) the current through the two resistors marked \( R_2 \) is also equal to \( i_1 \).
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\[ V_{o1} - V_{o2} = i_1(R_1 + 2R_2) = \frac{1}{R_1} (V_{i1} - V_{i2})(R_1 + 2R_2) = (V_{i1} - V_{i2}) \left(1 + \frac{2R_2}{R_1}\right). \]
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Finally, \(V_o = \frac{R_4}{R_3} (V_{o2} - V_{o1}) = \frac{R_4}{R_3} \left(1 + \frac{2R_2}{R_1}\right) (V_{i2} - V_{i1}).\)
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Finally, \( V_o = \frac{R_4}{R_3} (V_{o2} - V_{o1}) = \frac{R_4}{R_3} \left(1 + \frac{2 R_2}{R_1}\right) (V_{i2} - V_{i1}). \)

This circuit is known as the “instrumentation amplifier.”
The input resistance seen from $V_{i1}$ or $V_{i2}$ is large (since an Op Amp has a large input resistance). → 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.

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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.
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 \( v_o \)?
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 $v_o$?

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

$\begin{align*}
    v_{i1} &= v_c - v_d/2 \\
    v_{i2} &= v_c + v_d/2
\end{align*}$
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$v_c$ has simply got cancelled! (And this holds even if $R_2$ and $R_2'$ are not exactly matched.)
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$v_c$ has simply got cancelled! (And this holds even if $R_2$ and $R'_2$ are not exactly matched.)  

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

\[ V_o = i_s R \]

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 \( V_p = V_{bias} \).
Current-to-voltage conversion

\[ V_- \approx V_+ \text{, and } i_- \approx 0 \Rightarrow V_o = V_- - I_s R = -I_s R. \]
$V_- \approx V_+, \text{ and } i_- \approx 0 \Rightarrow V_o = V_- - I_s R = -I_s R.$

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Example: a photocurrent detector.

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Op Amp circuits (linear region)

\[ i - V_c \approx V_i + V_o = 0 \]

The circuit works as an integrator.

\[ V_{c} = V_{o} - V_{o} = 0 \rightarrow C \left( -\frac{dV_{o}}{dt} \right) = \frac{V_i}{R} \]

\[ V_{o} = -\frac{1}{RC} \int V_i \, dt \]

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

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\[ V_o = -\frac{1}{RC} \int V_i \ dt \]

The circuit works as an integrator.
Integrator

\[ R = 1 \, \text{k}\Omega, \quad C = 0.2 \, \text{\textmu F} \]

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R = 1 kΩ, C = 0.2 µF

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\[ V_i \]

\[ V_o \]

\[ t \text{ (msec)} \]
Integrator

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

SEQUEL files: ee101_integrator_1.sqproj, ee101_integrator_2.sqproj
Offset voltage

For the real Op Amp, \( V_o = A \cdot V_i \left( V_i + V_{OS} \right) - V_o \). For \( V_o = 0 \), \( V_i + V_{OS} = 0 \) → \( V_i - V_{OS} = -V_{OS} \). The \( V_o \) versus \( V_i \) curve gets shifted.

741: \(-6 \text{ mV} < V_{OS} < 6 \text{ mV}\).

OP-77: \(-50 \mu V < V_{OS} < 50 \mu V\).

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Offset voltage

For the real Op Amp, \( V_{o} = A \left( V_{+} + V_{OS} \right) - V_{-} \).

For \( V_{o} = 0 \), \( V_{+} + V_{OS} - V_{-} = 0 \) → \( V_{+} - V_{-} = -V_{OS} \).

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741: $-6 \, mV < V_{OS} < 6 \, mV$.
OP-77: $-50 \, \mu V < V_{OS} < 50 \, \mu V$. 
Effect of $V_{OS}$

By superposition, $V_o = -\frac{R_2}{R_1} V_i + V_{OS} \left(1 + \frac{R_2}{R_1}\right)$. For $V_{OS} = 2\text{ mV}$, the contribution from $V_{OS}$ to $V_o$ is $22\text{ mV}$, i.e., a DC shift of $22\text{ mV}$. 

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Effect of $V_{OS}$

$$i_1 = \frac{V_i - V_{OS}}{RC}$$

Even with $V_i = 0$, $V_c$ will keep rising or falling (depending on the sign of $V_{OS}$). Eventually, the Op Amp will be driven into saturation. → need to address this issue!
Effect of $V_{OS}$

$V_- \approx V_+ = V_{OS} \rightarrow i_1 = \frac{1}{R} (V_i - V_{OS}) = C \frac{dV_c}{dt}$.
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$\rightarrow$ need to address this issue!
Effect of $V_{OS}$

Integrator with $V_i = 0 V$:

(a) $i_1 = V_{OS}$

- $i_1 = V_{OS} \frac{1}{R} \frac{dV_c}{dt}$

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

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

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

$R'$ 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.

- $R' \gg \frac{1}{\omega C}$ at the frequency of interest.
Effect of $V_{OS}$

Integrator with $V_i = 0$ V:

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

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However, $R'$ must be large enough to ensure that the circuit still functions as an integrator.
\[ \rightarrow R' \gg 1/\omega C \text{ at the frequency of interest}. \]
Input bias currents

\[ I^+ + B I^- = 0.8 \text{ mV} \]

\[ 25 \text{ pA} \]

\[ 411 \text{ FET input} \]

\[ 50 \text{ pA} \]

\[ 80 \text{ nA} \]

\[ 20 \text{ nA} \]

\[ 1 \text{ mV} \]

\[ 741 \text{ BJT input} \]

\[ \text{Op Amp} \]

\[ \text{BJT input OP77} \]

\[ 1.2 \text{ nA} \]

\[ 0.3 \text{ nA} \]

\[ I^+ \]

\[ I^- \]

\[ I^+ B I^- \]

\[ \text{offset current} (I_{OS}) \]

\[ (I^+ B I^- + I^- B I^+) / 2 : \text{bias current} (I_B) \]

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Input bias currents

\[ I^+ + I^- = 0 \]

Real Op Amp

Ideal Op Amp

\[ V_o \]

\[ \frac{I^+ + I^-}{2} : \text{bias current (I_B)} \]

\[ |I^+ + I^-| : \text{offset current (I_{OS})} \]

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

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

$(I_B^+ + I_B^-)/2$ : “bias current” ($I_B$).
$I_B^+$ and $I_B^-$ are generally not exactly equal.

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

$(I_B^+ + I_B^-)/2$ : “bias current” ($I_B$).
Effect of bias currents

Inverting amplifier:

\[ i_2 = i_1 - I_B \rightarrow V_o = V_i + \frac{I_B R_2}{R_1} \]

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

\[ V_i \approx V_o = 0 \]

\[ i_1 = \frac{V_i}{R_1} \]

\[ i_2 = i_1 - I_B \rightarrow V_o = \frac{V_i R_2}{R_1} - \frac{I_B R_2}{R_1} = -\frac{R_2}{R_1} V_i + \frac{I_B R_2}{R_1}, \]

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

For \( I_B = 80 \text{nA} \), \( R_2 = 10 \text{k} \), \( \Delta V_o = 0.8 \text{mV} \).

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Effect of bias currents

Inverting amplifier:

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

Inverting amplifier:

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

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

$\Delta V_o = I_{\text{bias}} R_2 = 80 \, \text{nA} \times 10 \, \text{k} = 800 \, \text{mV}$. 

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

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

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

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

For $I_B^- = 80$ nA, $R_2 = 10$ k, $\Delta V_o = 0.8$ mV.
Effect of bias currents

Non-inverting amplifier:

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

- $V_+ \approx V_- = V_i \rightarrow i_1 = -\frac{V_i}{R_1}$.
- $i_2 = i_1 - I_- = -\frac{V_i}{R_1} - I_-$.  
- $V_o = V_i - i_2 R_2 = V_i - \left(-\frac{V_i R_1}{R_2} - I_-\right) R_2 = V_i \left(1 + \frac{R_2}{R_1}\right) + I_- R_2$.

→ Again, a DC shift $\Delta V_o$.

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Effect of bias currents

Non-inverting amplifier:

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

Non-inverting amplifier:

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

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

$V_o = V_i - i_2 R_2 = V_i - (i_1 - I_i - B) R_2 = V_i \left(1 + \frac{R_2}{R_1}\right) + I_i R_2$. 

Again, a DC shift $\Delta V_o$. 

M. B. Patil, IIT Bombay
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Effect of bias currents

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$\rightarrow$ Again, a DC shift $\Delta V_o$. 

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Effect of bias currents

Integrator:

\[
V_c = \frac{1}{RC} \int (i_1 - B_i) dt
\]

Even with \( V_i = 0 \), \( V_c = 1 \) 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.

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Effect of bias currents

Even with $V_i = 0 \, V$, $V_c = \frac{1}{C} \int -I_B^- \, dt$ will drive the Op Amp into saturation.
Effect of bias currents

Integrator:

\[ V_c = \frac{1}{C} \int -I_B^- dt \]  

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

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Effect of bias currents

Even with $V_i = 0 \, V$, $V_c = \frac{1}{C} \int -I_B^- \, dt$ 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.