EE101: Op Amp circuits (Part 1)

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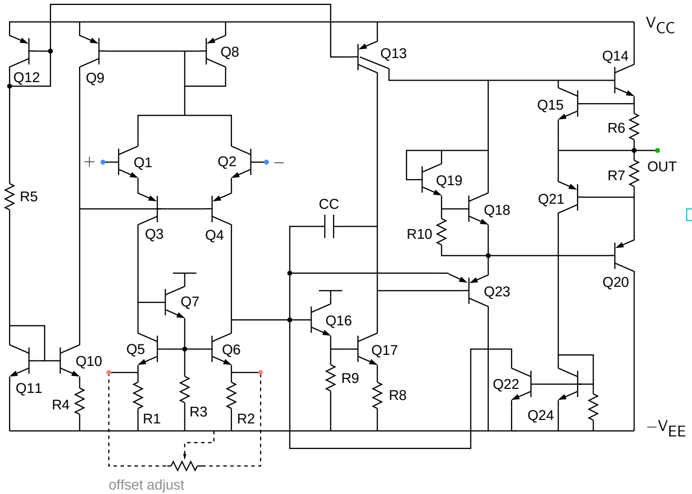
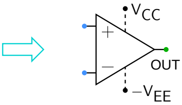
* The user can generally carry out circuit design without a thorough knowledge of the intricate details (next slide) of an Op Amp. This makes the design process simple.
* However, as Einstein has said, we should "make everything as simple as possible, but not simpler." $\rightarrow$ need to know where the ideal world ends, and the real one begins.

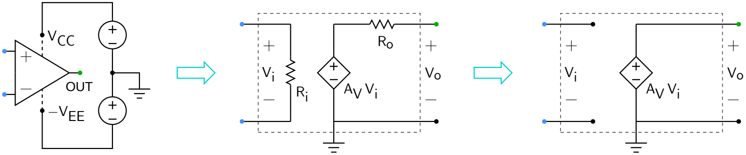
Op Amp 741

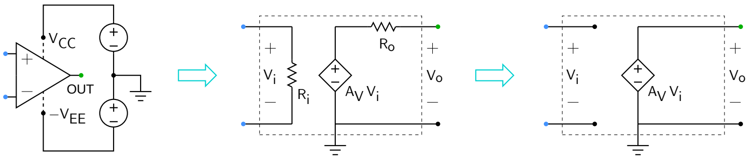
Actual circuit



Symbol




V_{CC}
OUT
$-V_{EE}$
V_i
R_i
$A_V V_i$
R_o
V_o



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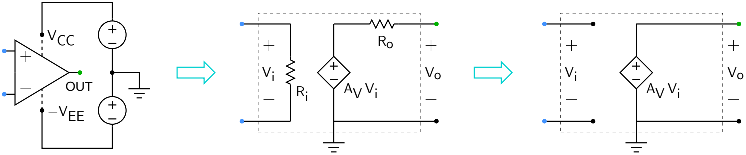

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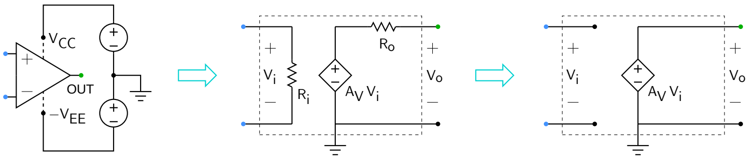
Op Amp: equivalent circuit



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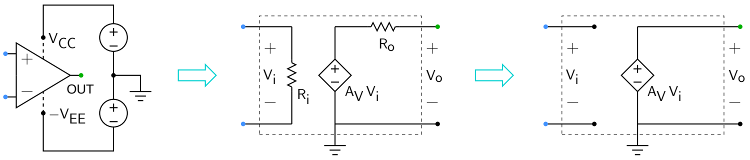

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Parameter	Ideal Op Amp	741
A_V	∞	10^5 (100 dB)
R_i	∞	2 MΩ
R_o	0	75 Ω

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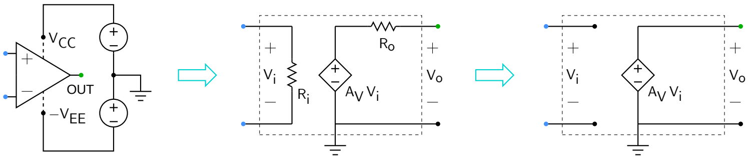

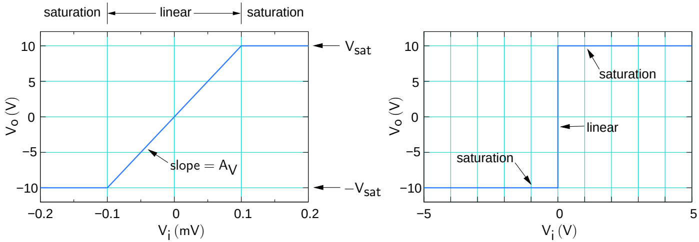

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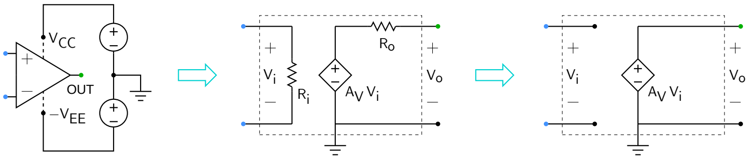
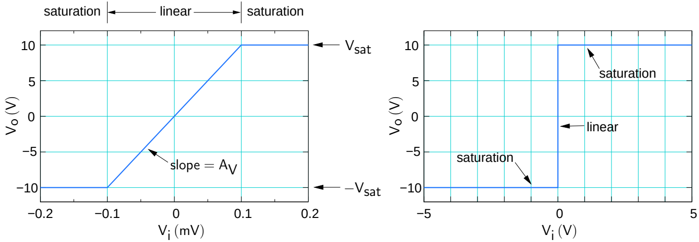
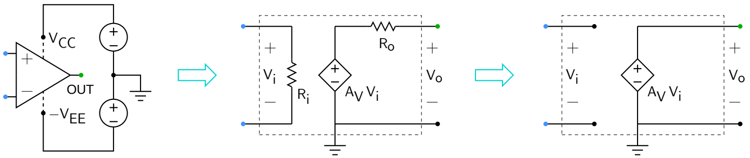
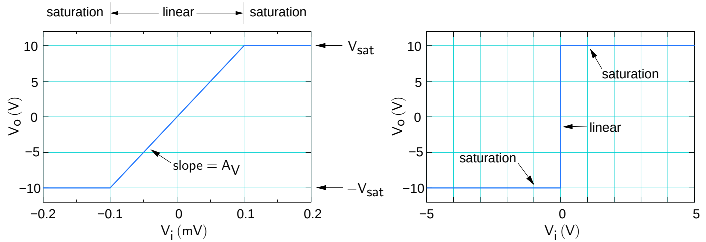




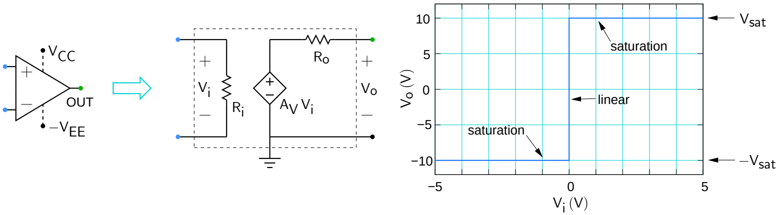
* The output voltage V_o is limited to $\pm V_{sat}$, where $V_{sat} \sim 1.5\ V$ less than V_{CC}.

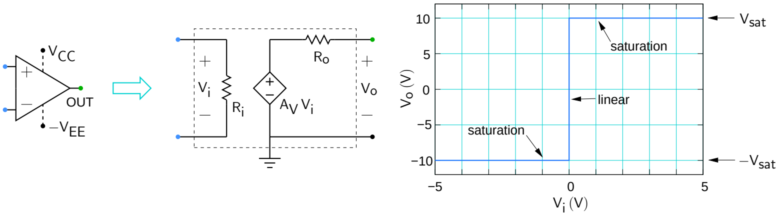




* The output voltage V_o is limited to $\pm V_{\rm sat}$, where $V_{\rm sat} \sim 1.5\ V$ less than V_{CC}.
* For $-V_{\rm sat} < V_o < V_{\rm sat}$, $V_i = V_+ - V_- = V_o/A_V$, which is very small $\rightarrow$ V_+ and V_- are *virtually* the same.

Op Amp circuits





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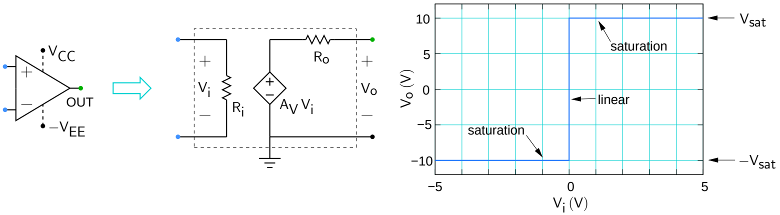

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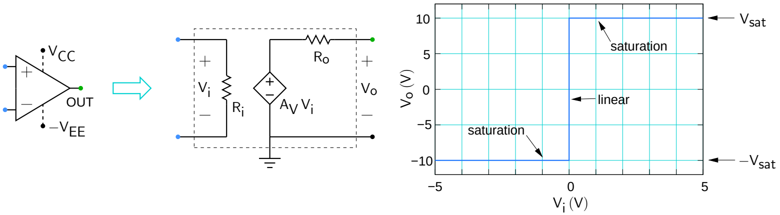

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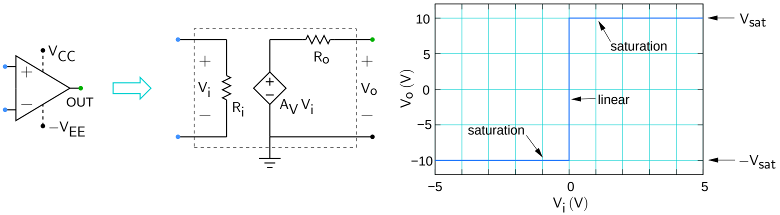

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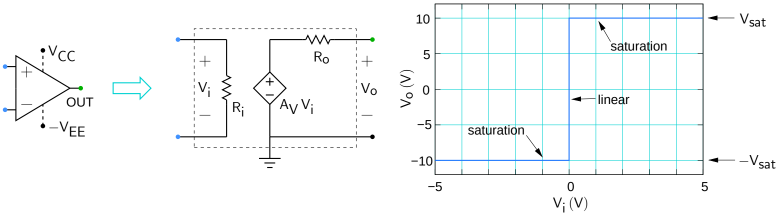

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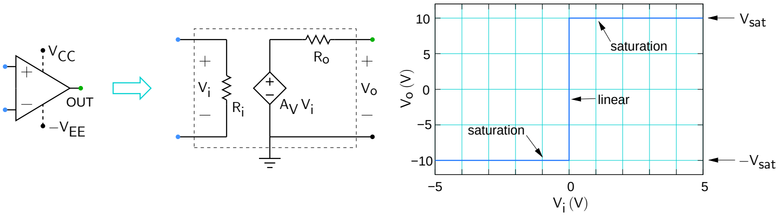

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  - Op Amp operating in the linear region
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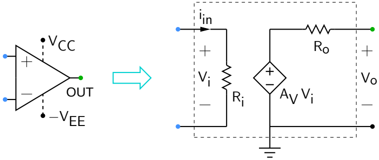
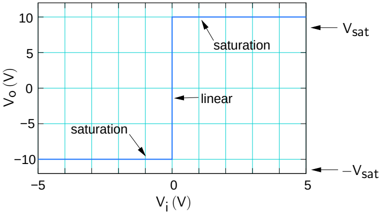
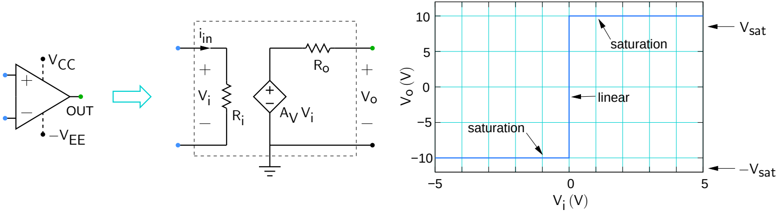
* Whether an Op Amp in a given circuit will operate in linear or saturation region depends on
  - input voltage magnitude
  - type of feedback (negative or positive)
    (We will take a qualitative look at feedback later.)

Op Amp circuits (linear region)



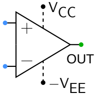


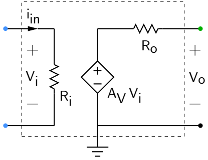


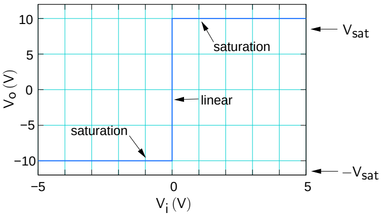
In the linear region,

* $V_+ - V_- = V_o/A_V$, which is very small

→ $\boxed{V_+ \approx V_-}$







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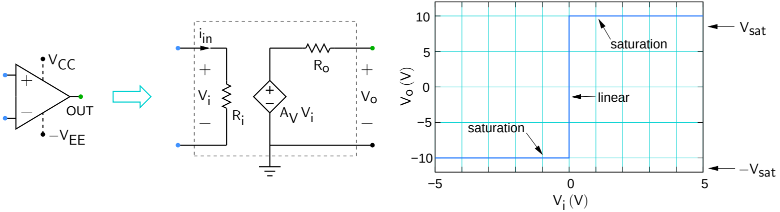

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These two "golden rules" enable us to understand several Op Amp circuits.

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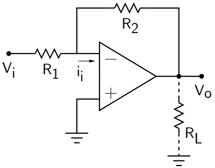

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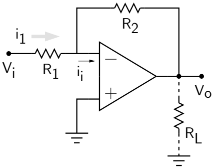

Since $V_+ \approx V_-$, $V_- \approx 0\,V \rightarrow i_1 = (V_i - 0)/R = V_i/R$.

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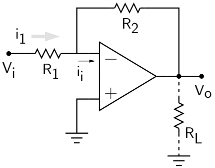

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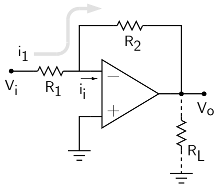

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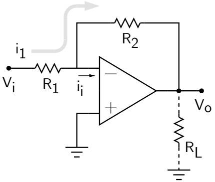

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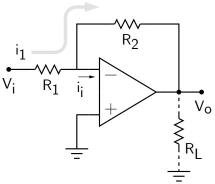

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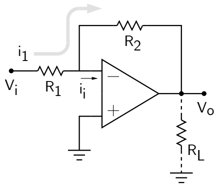

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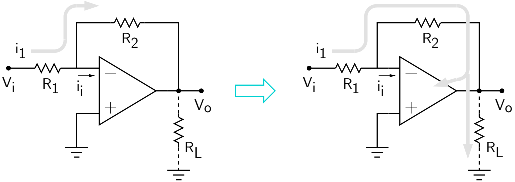

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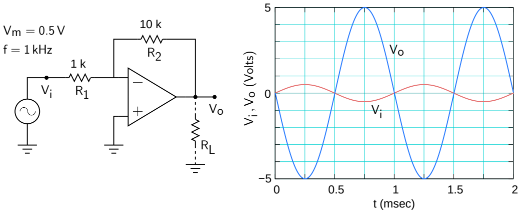
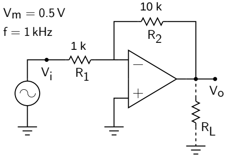
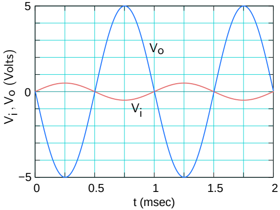


$V_m = 0.5\,V$
$f = 1\,kHz$
10 k
R_2
1 k
R_1
V_i
V_o
R_L
5
0
−5
0
0.5
1
1.5
2
t (msec)
V_i, V_o (Volts)
V_o
V_i





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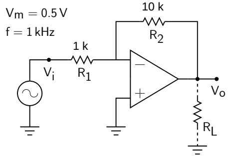

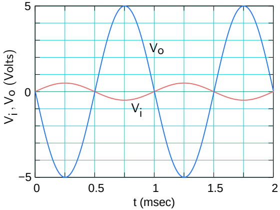

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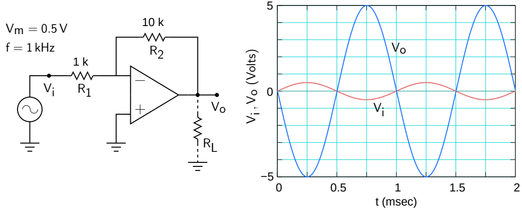

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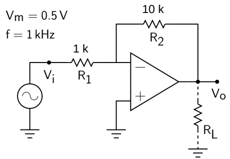

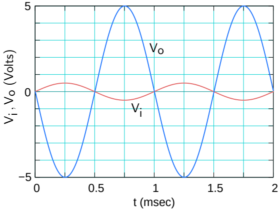

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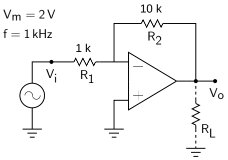
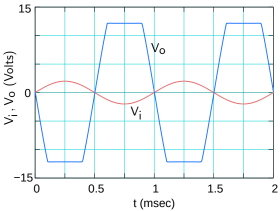
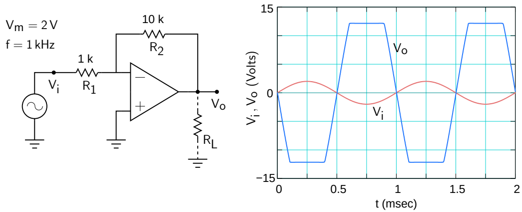
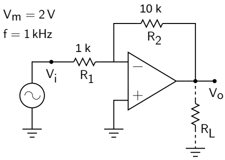
(SEQUEL file: `ee101_inv_amp_1.sqproj`)

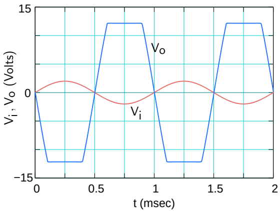

$V_m = 2\,V$
$f = 1\,kHz$
10 k
R_2
1 k
R_1
V_i
V_o
R_L


15
0
−15
0
0.5
1
1.5
2
t (msec)
V_i, V_o (Volts)
V_o
V_i



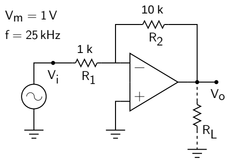
* The output voltage is limited to $\pm V_{sat}$.

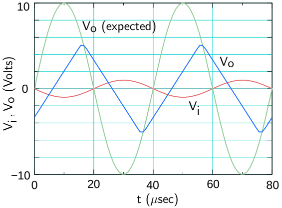




* The output voltage is limited to $\pm V_{\text{sat}}$.
* V_{sat} is $\sim 1.5\,\text{V}$ less than the supply voltage V_{CC}.

Op Amp circuits: inverting amplifier





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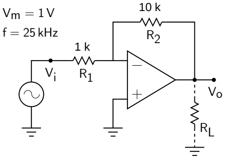
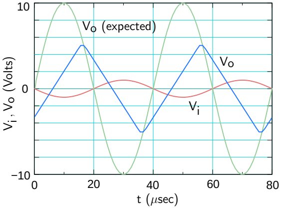
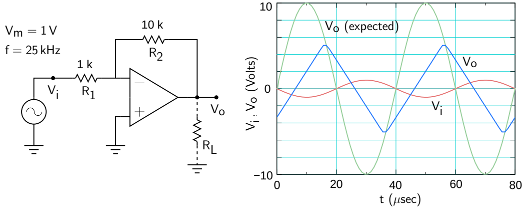




∗ If the signal frequency is too high, a practical Op Amp cannot keep up with the input due to its "slew rate" limitation.

Op Amp circuits: inverting amplifier



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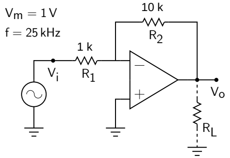
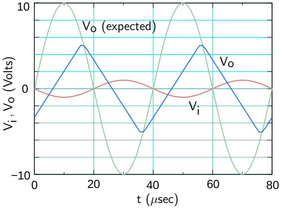
* The slew rate of an Op Amp is the maximum rate at which the Op Amp output can rise (or fall).





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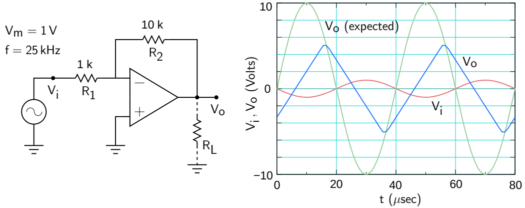
Op Amp circuits: inverting amplifier



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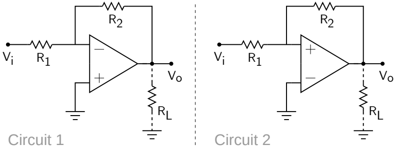
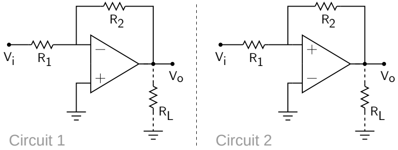
(SEQUEL file: `ee101_inv_amp_2.sqproj`)



What if the + (non-inverting) and − (inverting) inputs of the Op Amp are interchanged?



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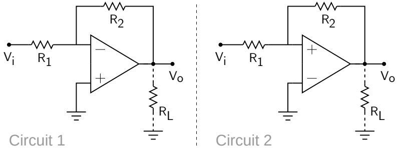

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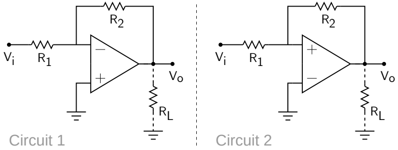
$\rightarrow$ Our assumption that the Op Amp is working in the linear region does not hold for Circuit 2, and $V_o = -\dfrac{R_2}{R_1}\, V_i$ does not apply any more.



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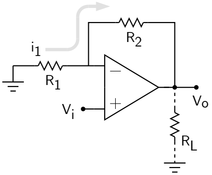
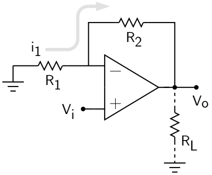
(Circuit 2 is also useful, and we will discuss it later.)



* $V_+ \approx V_- = V_i$



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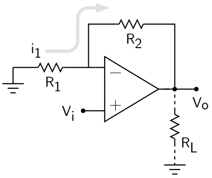

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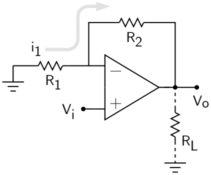

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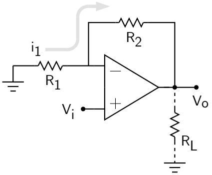

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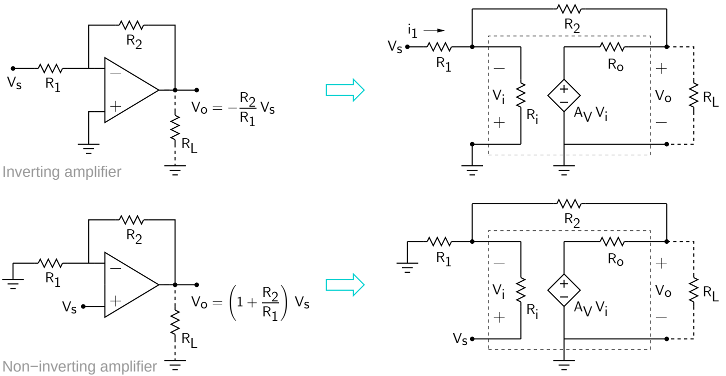
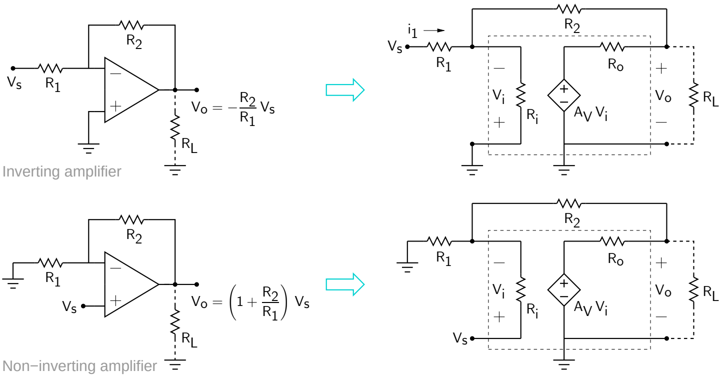
* This circuit is known as the "non-inverting amplifier."
* Again, interchanging + and − changes the nature of the feedback from negative to positive, and the circuit operation becomes completely different.

Inverting or non-inverting?



* If the sign of the output voltage is not a concern, which configuration should be preferred?



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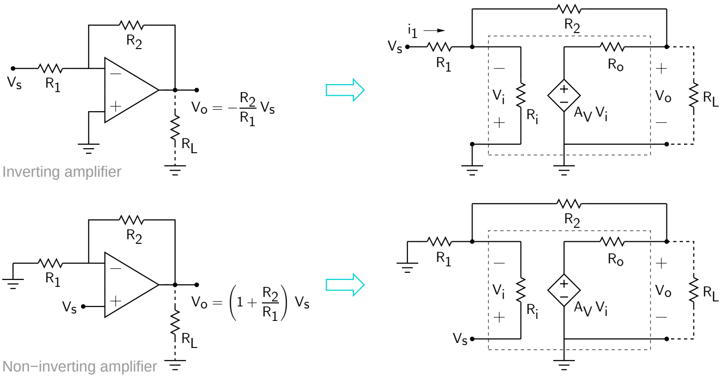

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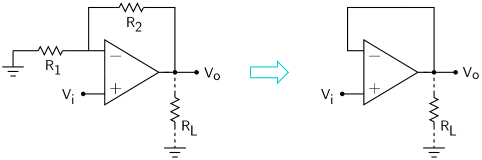
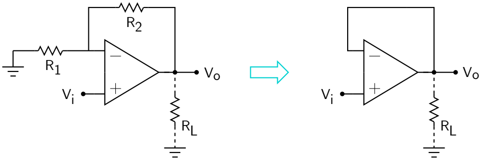
* For the inverting amplifier, since $V_- \approx 0\,V$, $i_1 = V_s/R_1 \rightarrow R_{\text{in}} = V_s/i_1 = R_1$.
* For the non-inverting amplifier, $R_{\text{in}} \sim R_i$ of the Op Amp, which is a few MΩ.

  $\rightarrow$ Non-inverting amplifier is better if a large R_{in} is required.

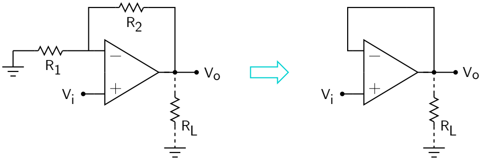


Consider $R_1 \rightarrow \infty\,,\;\; R_2 \rightarrow 0\,.$



Consider $R_1 \rightarrow \infty$, $R_2 \rightarrow 0$.

$$\frac{V_o}{V_i} \rightarrow 1 + \frac{R_2}{R_1} \rightarrow 1 \text{ , i.e., } V_o = V_i \text{ .}$$



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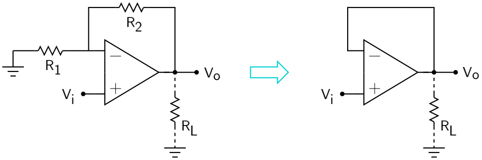
This circuit is known as unity-gain amplifier/voltage follower/buffer.



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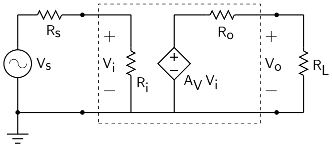
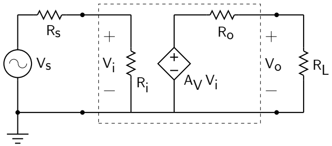
What has been achieved?



Consider an amplifier of gain A_V. We would like to have $V_o = A_V\, V_s$.



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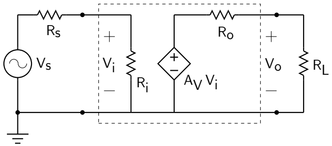
However, the actual output voltage is,

$$V_o = \frac{R_L}{R_o + R_L} \times A_V\, V_i = A_V \times \frac{R_L}{R_o + R_L} \times \frac{R_i}{R_i + R_s}\, V_s \, .$$



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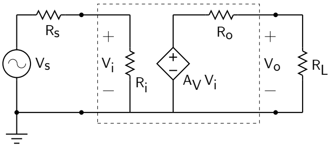
To obtain the desired V_o, we need $R_i \rightarrow \infty$ and $R_o \rightarrow 0$.



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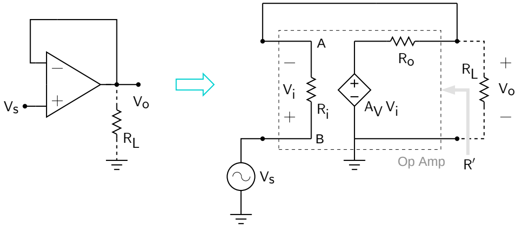
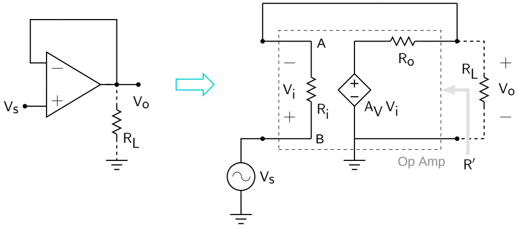
The buffer (voltage follower) provides this feature (next slide).



* The current drawn from the source (V_s) is small (since R_i of the Op Amp is large) $\longrightarrow$ the buffer has a large input resistance.

Op Amp buffer



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* As we have seen earlier, A_V is large $\rightarrow$ $V_i \approx 0\ V$ $\rightarrow$ $V_A = V_B = V_s$.

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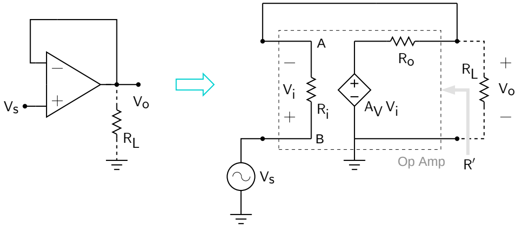

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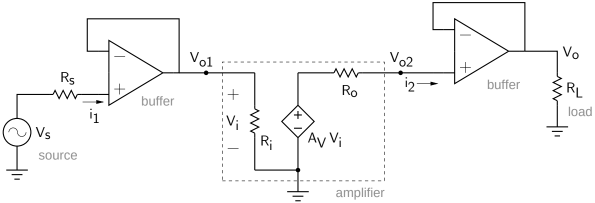
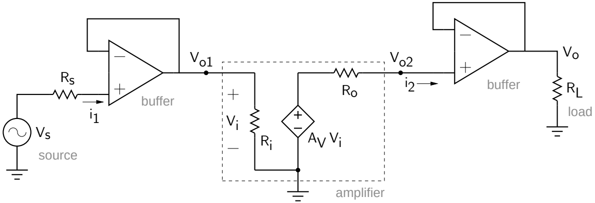
* As we have seen earlier, A_V is large $\rightarrow$ $V_i \approx 0\,V$ $\rightarrow$ $V_A = V_B = V_s$.
* The resistance seen by R_L is $R' \approx R_o$, which is small $\rightarrow$ the buffer has a small output resistance. (To find R', deactivate the input voltage source (V_s) $\rightarrow A_V V_i = 0\,V$.)

Op Amp buffer

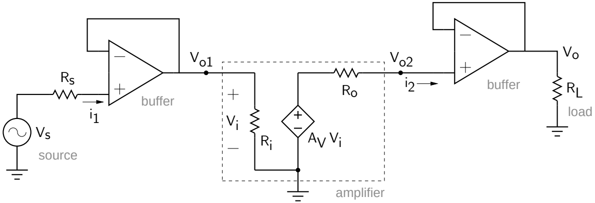




Since the buffer has a large input resistance, $i_1 \approx 0\,A$,

and V_+ (on the source side) $= V_s \rightarrow V_{o1} = V_s$.

Op Amp buffer



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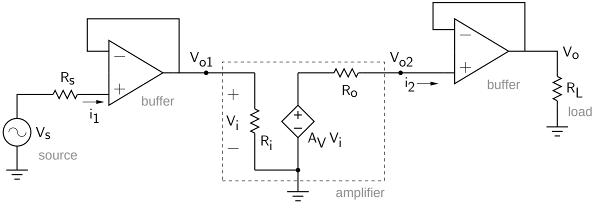

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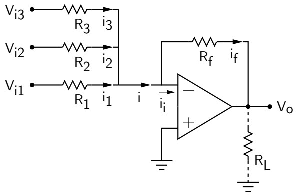
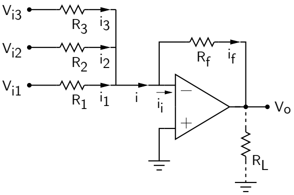
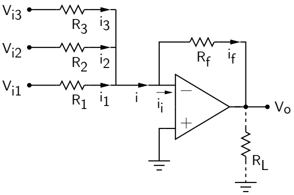
Finally, $V_o = V_{o2} = A_V\,V_s$, as desired, *irresepective* of R_S and R_L.

Op Amp circuits (linear region)





$V_- \approx V_+ = 0\,V \rightarrow i_1 = V_{i1}/R_1,\ i_1 = V_{i2}/R_2,\ i_1 = V_{i3}/R_3$.



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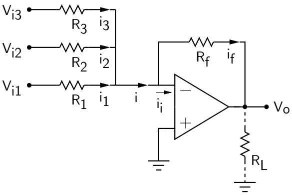
$i = i_1 + i_2 + i_3 = \left(\dfrac{V_{i1}}{R_1} + \dfrac{V_{i2}}{R_2} + \dfrac{V_{i3}}{R_3}\right).$



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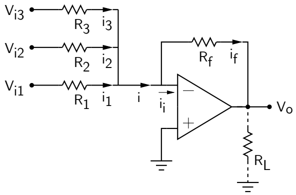

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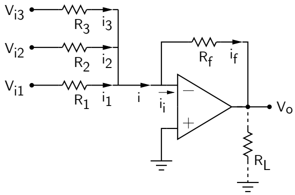
$$V_o = V_{-} - i_f\,R_f = 0 - \left(\frac{V_{i1}}{R_1} + \frac{V_{i2}}{R_2} + \frac{V_{i3}}{R_3}\right) R_f = -\left(\frac{R_f}{R_1}\,V_{i1} + \frac{R_f}{R_2}\,V_{i2} + \frac{R_f}{R_3}\,V_{i3}\right),$$

i.e., V_o is a *weighted sum* of V_{i1}, V_{i2}, V_{i3}.

Op Amp circuits (linear region)



$V_- \approx V_+ = 0\,V \rightarrow i_1 = V_{i1}/R_1,\ i_1 = V_{i2}/R_2,\ i_1 = V_{i3}/R_3\,.$

$i = i_1 + i_2 + i_3 = \left(\dfrac{V_{i1}}{R_1} + \dfrac{V_{i2}}{R_2} + \dfrac{V_{i3}}{R_3}\right).$

Because of the large input resistance of the Op Amp, $i_i \approx 0 \rightarrow i_f = i$, which gives,

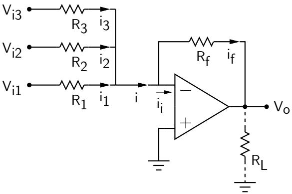
$V_o = V_- - i_f\,R_f = 0 - \left(\dfrac{V_{i1}}{R_1} + \dfrac{V_{i2}}{R_2} + \dfrac{V_{i3}}{R_3}\right) R_f = -\left(\dfrac{R_f}{R_1}\,V_{i1} + \dfrac{R_f}{R_2}\,V_{i2} + \dfrac{R_f}{R_3}\,V_{i3}\right),$

i.e., V_o is a *weighted sum* of V_{i1}, V_{i2}, V_{i3}.

If $R_1 = R_2 = R_3 = R$, the circuit acts as a summer, giving

$\boxed{V_o = -K\,(V_{i1} + V_{i2} + V_{i3})}$ with $K = R_f/R\,.$

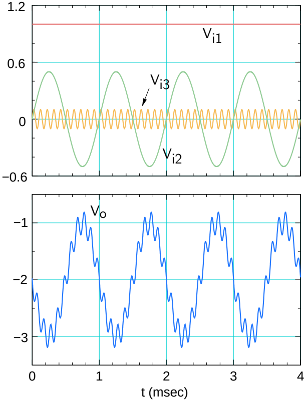
Summer example



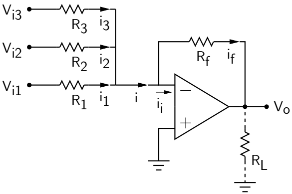
$R_1 = R_2 = R_3 = 1\ \text{k}\Omega$

$R_f = 2\ \text{k}\Omega$

$\rightarrow V_o = -2\,(V_{i1} + V_{i2} + V_{i3})$



Summer example



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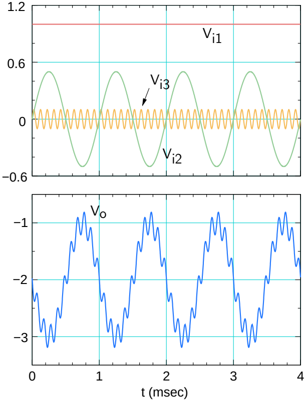
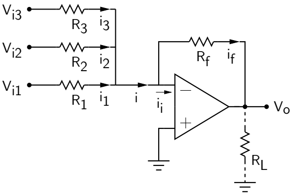


* Note that the summer also works with DC inputs. This is true about the inverting and non-inverting amplifiers as well.

Summer example



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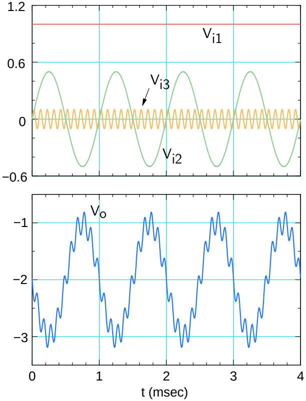

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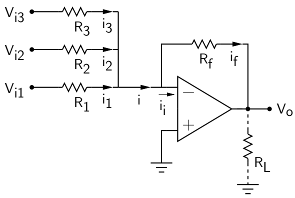
Summer example



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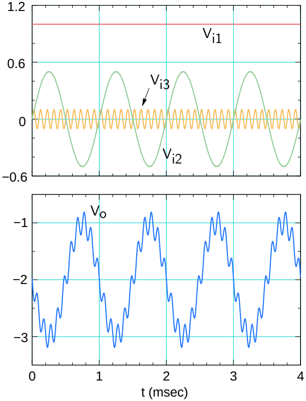

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(SEQUEL file: `ee101_summer.sqproj`)