EE101: Op Amp circuits (Part 1)

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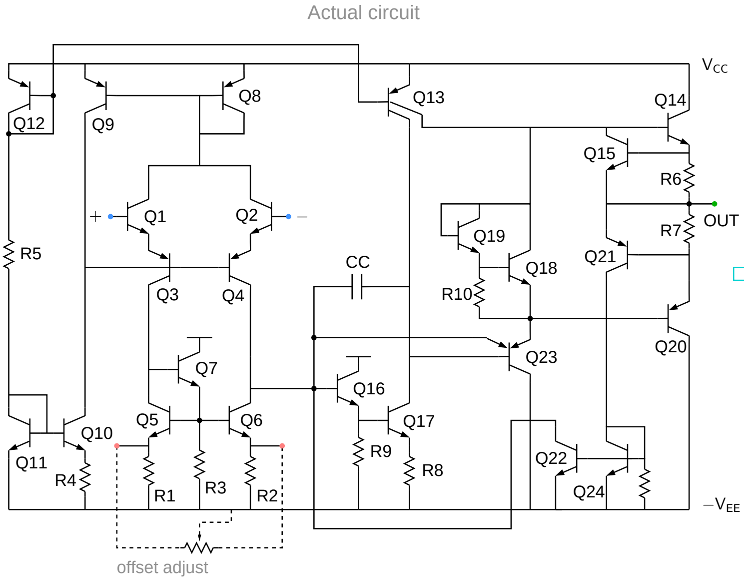
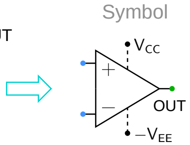
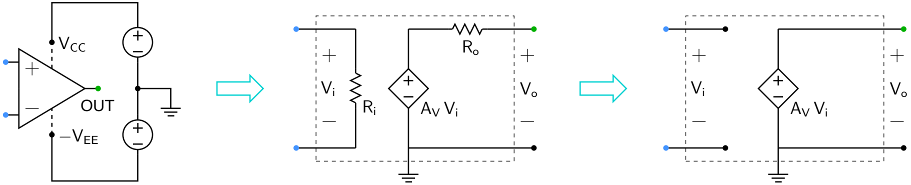
* Amplifiers built with Op Amps work with DC input voltages as well → useful in sensor applications (e.g., temperature, pressure)
* The user can generally carry out circuit design without a thorough knowledge of the intricate details (next slide) of an Op Amp. This makes the design process simple.
* However, as Einstein has said, we should "make everything as simple as possible, but not simpler." → need to know where the ideal world ends, and the real one begins.

Op Amp 741


Actual circuit
V_{CC}
Q12
Q9
Q8
Q13
Q14
Q15
R6
Q1
Q2
+
−
OUT
R7
Q19
R5
Q18
Q21
CC
Q3
Q4
R10
Q20
Q23
Q7
Q16
Q5
Q6
Q10
Q17
R9
Q22
Q11
R4
R8
R1
R3
R2
Q24
$-V_{EE}$
offset adjust


Symbol
V_{CC}
+
−
OUT
$-V_{EE}$

Op Amp: equivalent circuit



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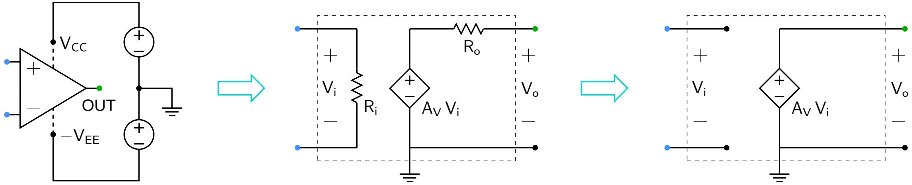
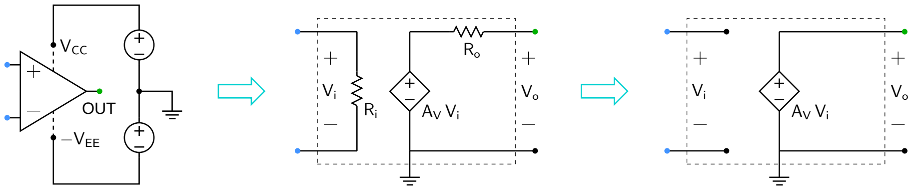


* The external resistances ($\sim$ a few kΩ) are generally much larger than R_o and much smaller than R_i $\rightarrow$ we can assume $R_i \rightarrow \infty$, $R_o \rightarrow 0$ without significantly affecting the analysis.



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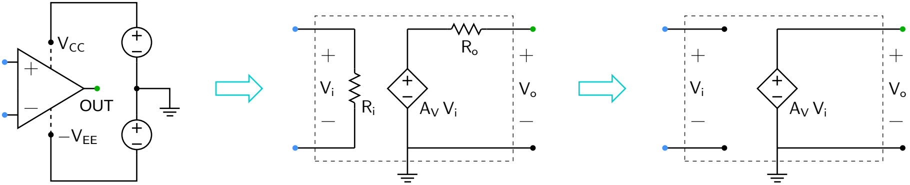
Op Amp: equivalent circuit



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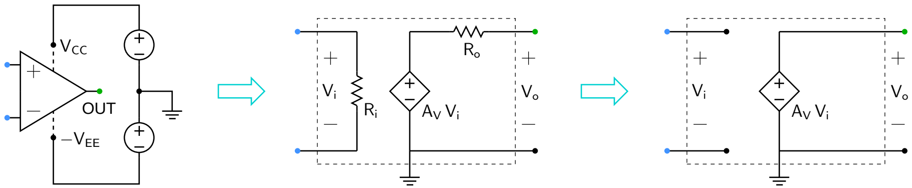

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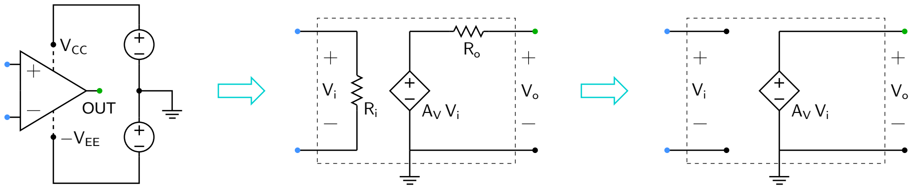
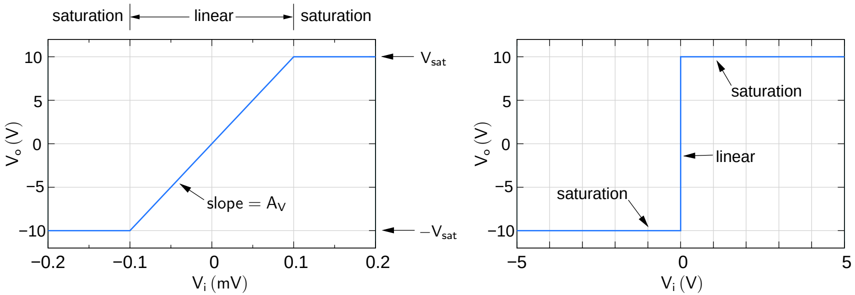
Parameter	Ideal Op Amp	741
A_V	∞	10^5 (100 dB)
R_i	∞	2 MΩ
R_o	0	75 Ω

Op Amp: equivalent circuit





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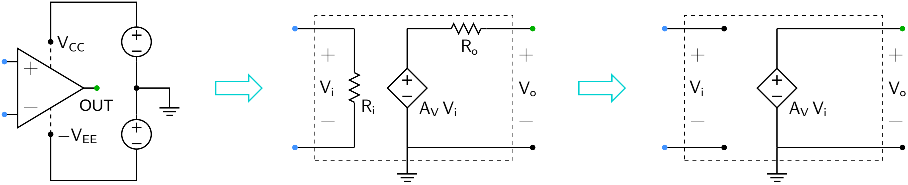
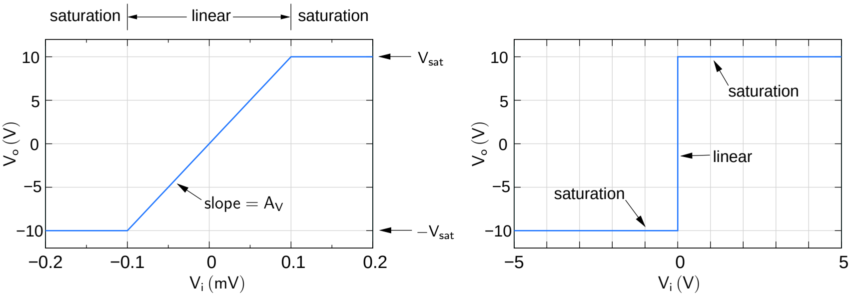
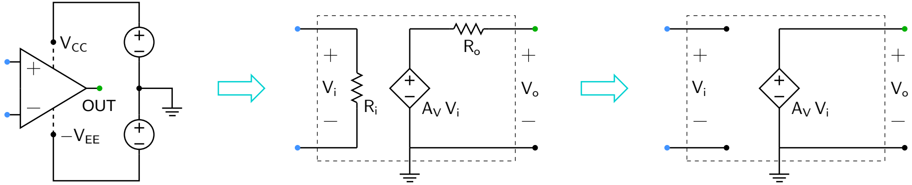
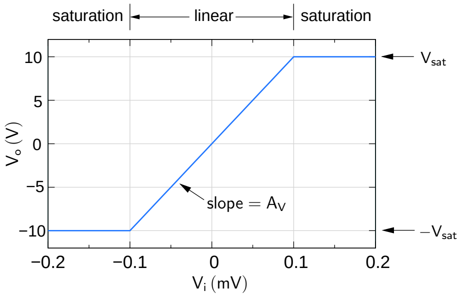


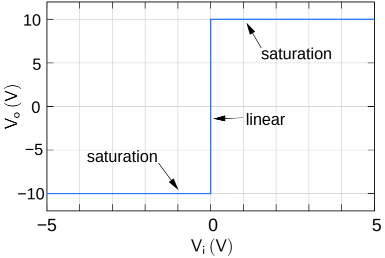


* The output voltage V_o is limited to $\pm V_{\rm sat}$, where $V_{\rm sat} \sim 1.5\ V$ less than V_{CC}.

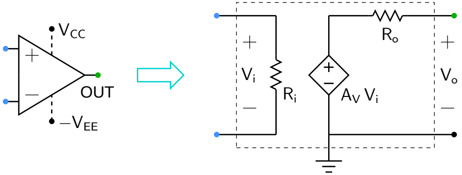
Op Amp: equivalent circuit

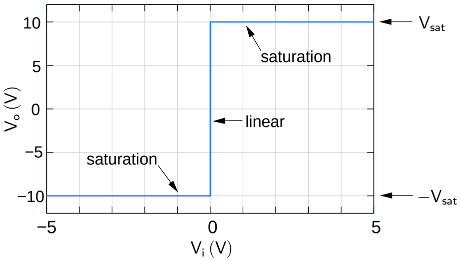




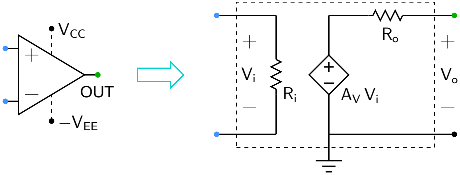


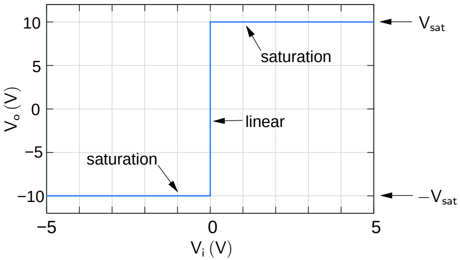
- ∗ The output voltage V_o is limited to $\pm V_{\mathrm{sat}}$, where $V_{\mathrm{sat}} \sim 1.5\ V$ less than V_{CC}.
- ∗ For $-V_{\mathrm{sat}} < V_o < V_{\mathrm{sat}}$, $V_i = V_+ - V_- = V_o/A_V$, which is very small
  $\rightarrow$ V_+ and V_- are *virtually* the same.


VCC
OUT
−VEE
Vi
Ri
Ro
AV Vi
Vo


10
5
0
−5
−10
−5
0
5
Vo (V)
Vi (V)
Vsat
−Vsat
saturation
linear
saturation

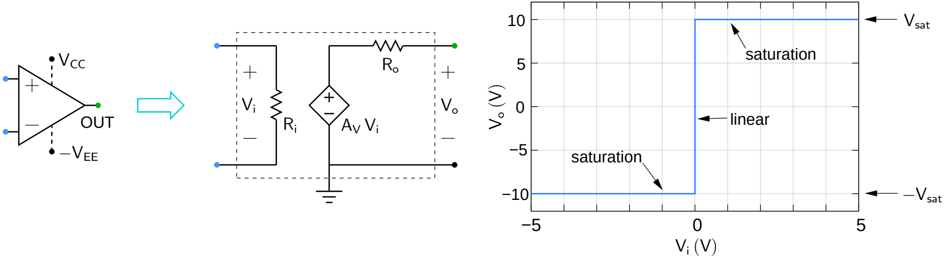
Op Amp circuits





* Broadly, Op Amp circuits can be divided into two categories:

Op Amp circuits



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  - Op Amp operating in the linear region

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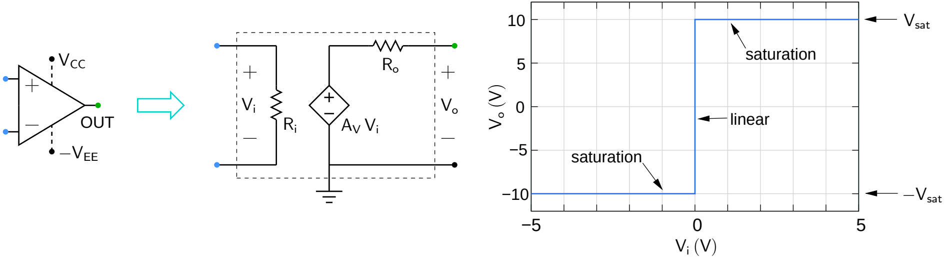
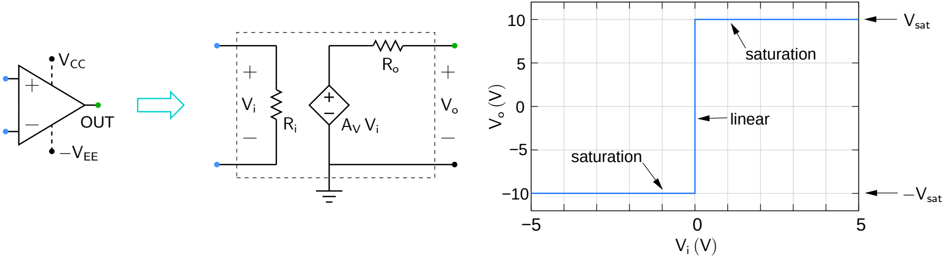


∗ Broadly, Op Amp circuits can be divided into two categories:

- Op Amp operating in the linear region
- Op Amp operating in the saturation region

Op Amp circuits



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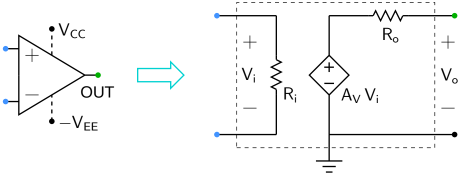
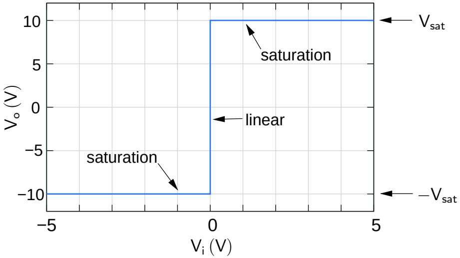
* Whether an Op Amp in a given circuit will operate in linear or saturation region depends on

Op Amp circuits





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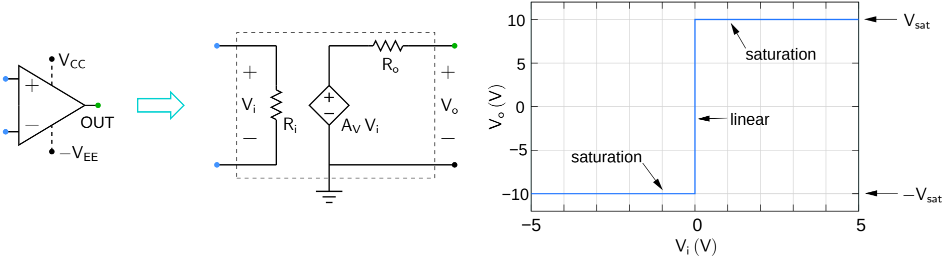

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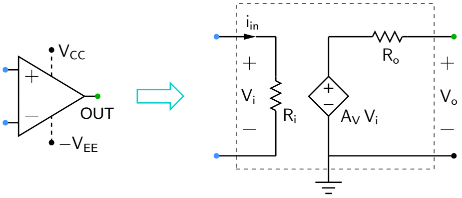
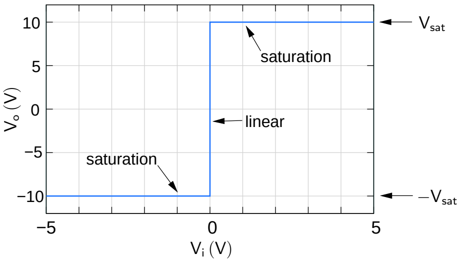
  - type of feedback (negative or positive)
    (We will take a qualitative look at feedback later.)

Op Amp circuits (linear region)





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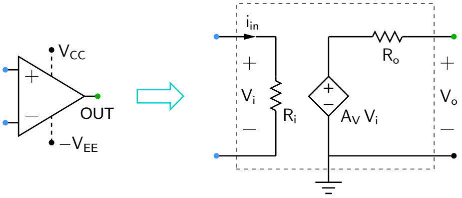

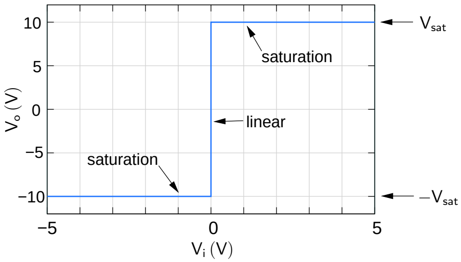

In the linear region,

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

$\rightarrow$ $\boxed{V_+ \approx V_-}$

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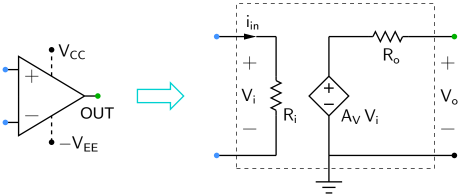

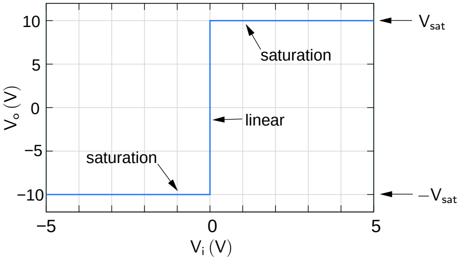

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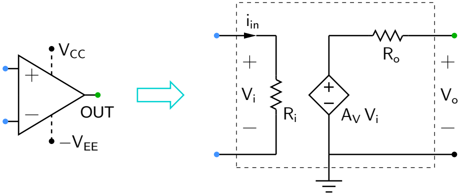

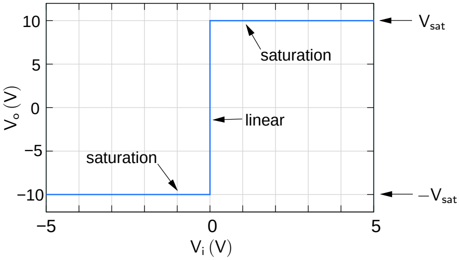

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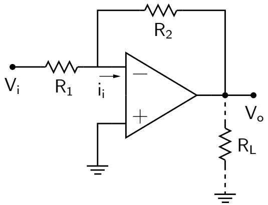
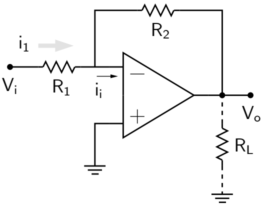
These two "golden rules" enable us to understand several Op Amp circuits.

Op Amp circuits (linear region)

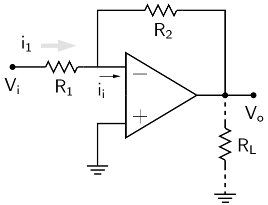




Since $V_+ \approx V_-$, $V_- \approx 0\ V \rightarrow i_1 = (V_i - 0)/R = V_i/R$.

(The non-inverting input is at *real* ground here, and the inverting input is at *virtual* ground.)

Op Amp circuits (linear region)



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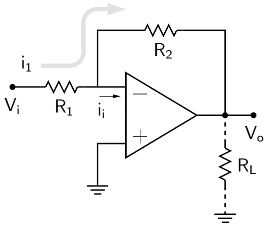

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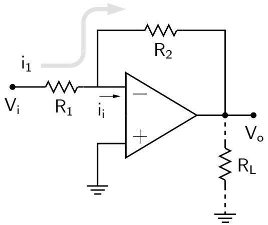

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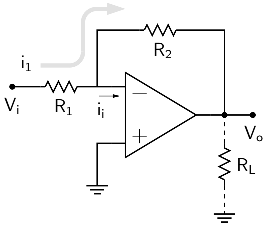
Op Amp circuits (linear region)



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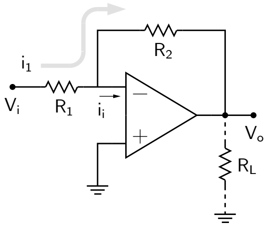
The circuit is called an "inverting amplifier."

Op Amp circuits (linear region)



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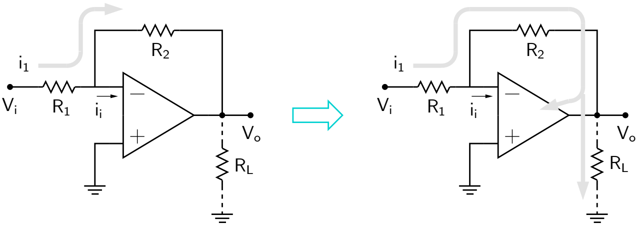
Where does the current go?



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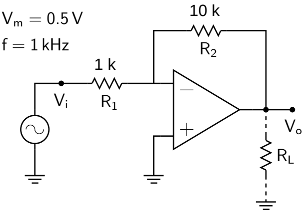
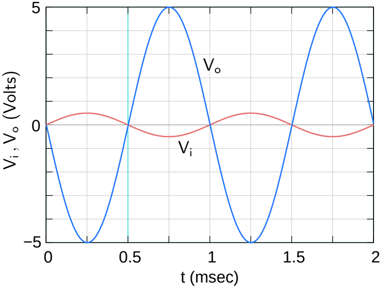
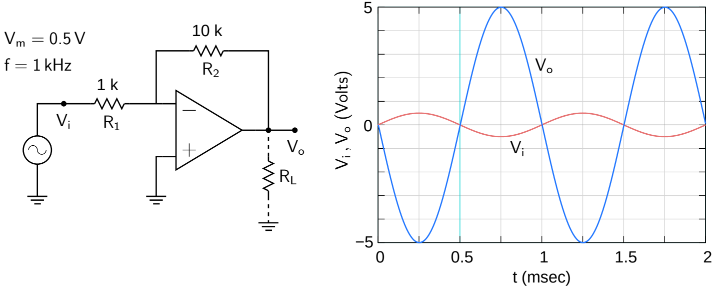


Vm = 0.5 V
f = 1 kHz
10 k
R2
1 k
Vi
R1
Vo
RL



5
0
−5
0
0.5
1
1.5
2
Vo
Vi
Vi , Vo (Volts)
t (msec)



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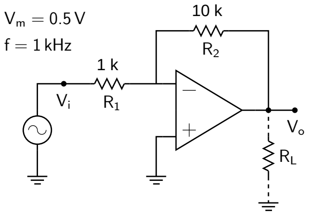

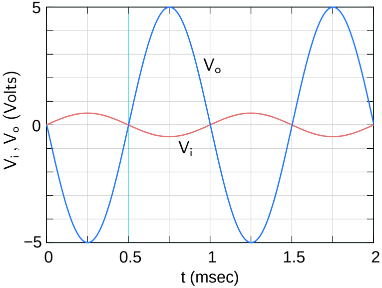

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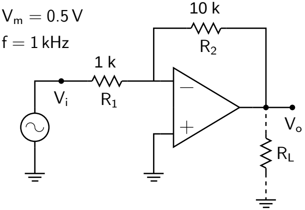
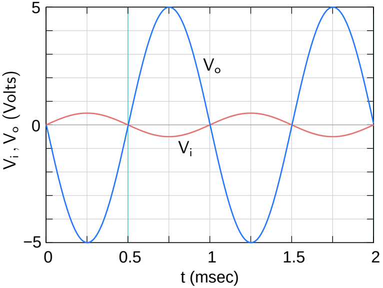
* The gain can be adjusted simply by changing R_1 or R_2 !





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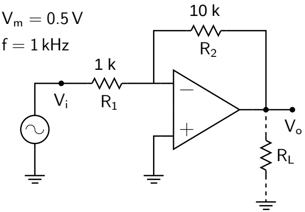

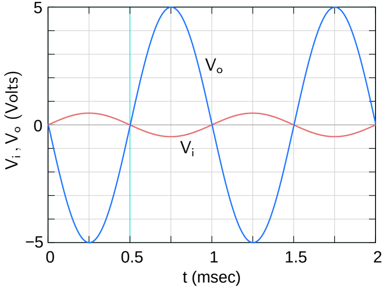

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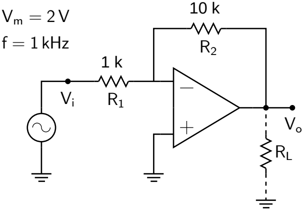
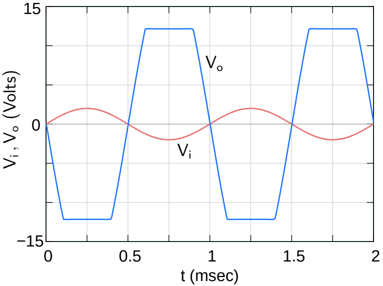
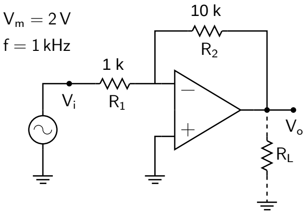
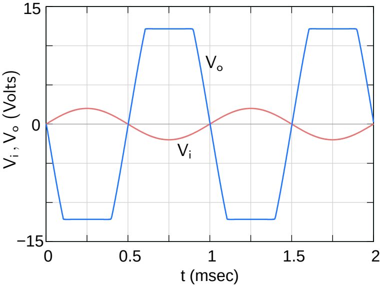
(SEQUEL file: `ee101_inv_amp_1.sqproj`)

Op Amp circuits: inverting amplifier

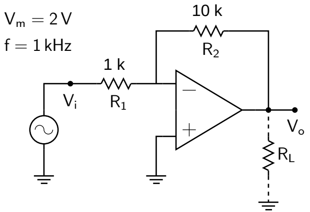


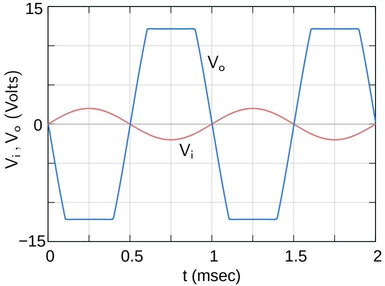




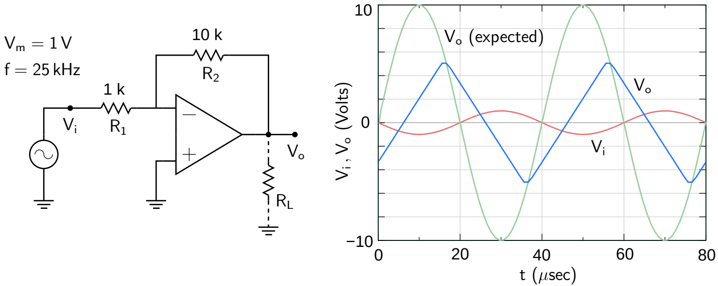


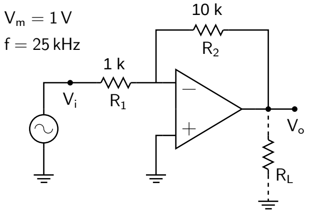
* The output voltage is limited to $\pm V_{sat}$.

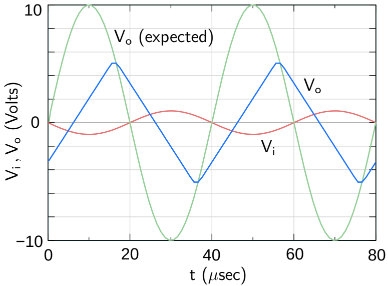




* The output voltage is limited to $\pm V_{\rm sat}$.
* $V_{\rm sat}$ is $\sim 1.5\,$V less than the supply voltage V_{CC}.

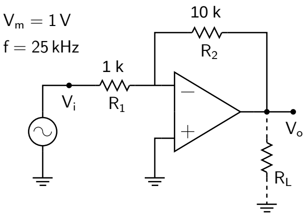

Vm = 1 V
f = 25 kHz
10 k
R2
1 k
Vi
R1
Vo
RL
10
0
−10
Vo (expected)
Vo
Vi
Vi , Vo (Volts)
0
20
40
60
80
t (μsec)

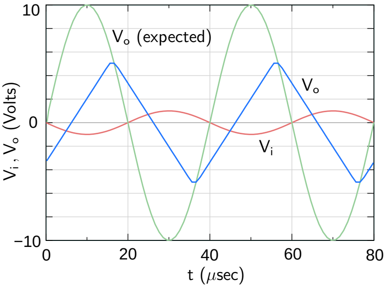




* If the signal frequency is too high, a practical Op Amp cannot keep up with the input due to its "slew rate" limitation.

Op Amp circuits: inverting amplifier





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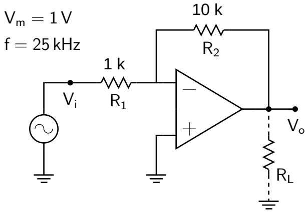
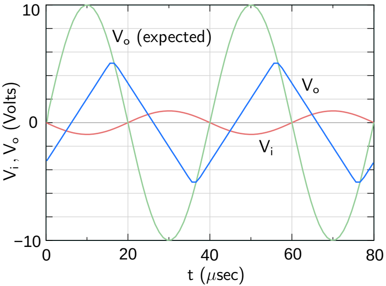
* The slew rate of an Op Amp is the maximum rate at which the Op Amp output can rise (or fall).





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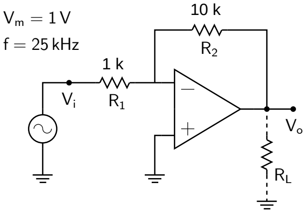
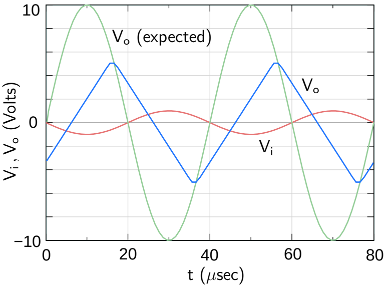
* For the 741, the slew rate is 0.5 V/μsec.

Op Amp circuits: inverting amplifier





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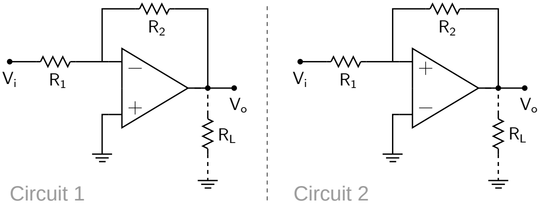
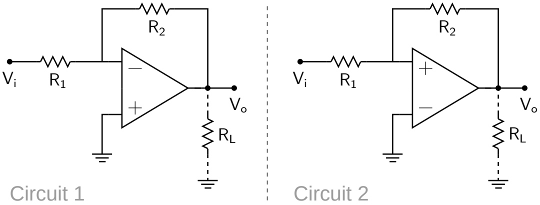
(SEQUEL file: `ee101_inv_amp_2.sqproj`)



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



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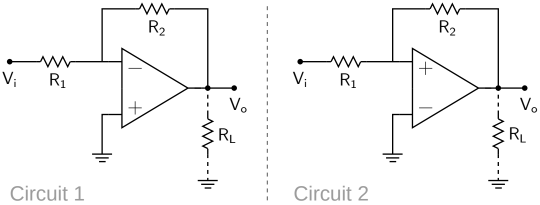
Our previous analysis would once again give us $V_o = -\dfrac{R_2}{R_1}\,V_i$.

Op Amp circuits: inverting amplifier



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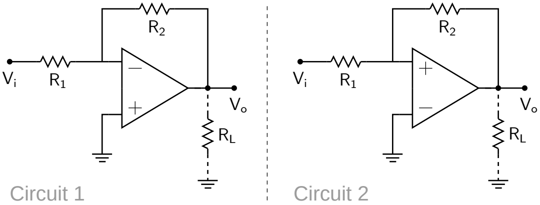
However, from Circuit 1 to Circuit 2, the nature of the feedback changes from negative to positive.

$\rightarrow$ 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.

Op Amp circuits: inverting amplifier



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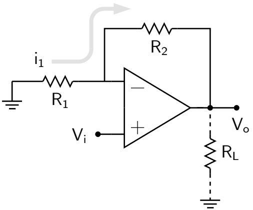
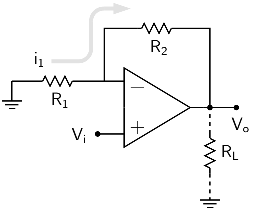
(Circuit 2 is also useful, and we will discuss it later.)

Op Amp circuits (linear region)

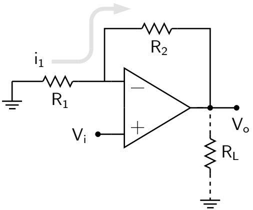


* $V_+ \approx V_- = V_i$



* $V_+ \approx V_- = V_i$
  $\rightarrow i_1 = (0 - V_i)/R_1 = -V_i/R_1$.

Op Amp circuits (linear region)



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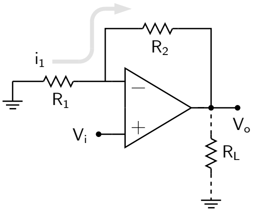
* $V_o = V_+ - i_1 \, R_2 = V_i - \left(-\dfrac{V_i}{R_1} \right) \, R_2 = V_i \, \left(1 + \dfrac{R_2}{R_1} \right)$.



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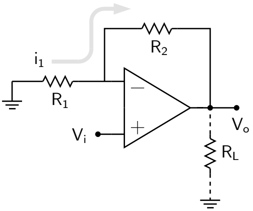
* This circuit is known as the “non-inverting amplifier.”



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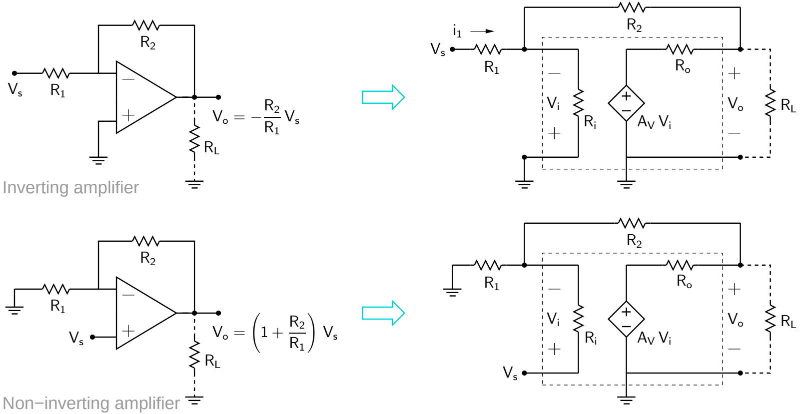
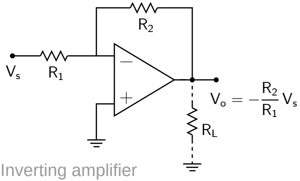
* Again, interchanging + and − changes the nature of the feedback from negative to positive, and the circuit operation becomes completely different.

Inverting or non-inverting?

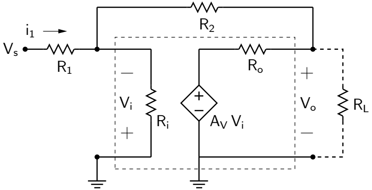


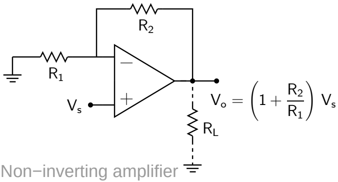
* If the sign of the output voltage is not a concern, which configuration should be preferred?

Inverting or non-inverting?

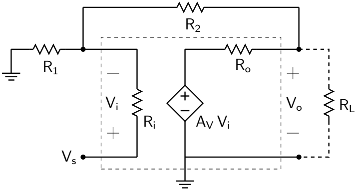


Inverting amplifier





Non−inverting amplifier



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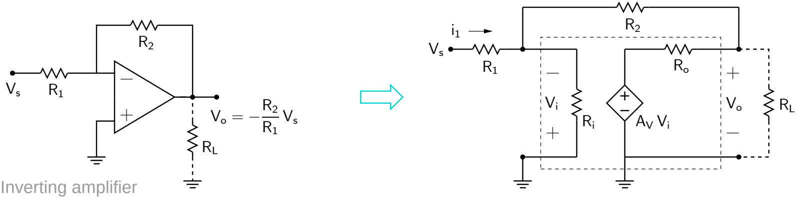
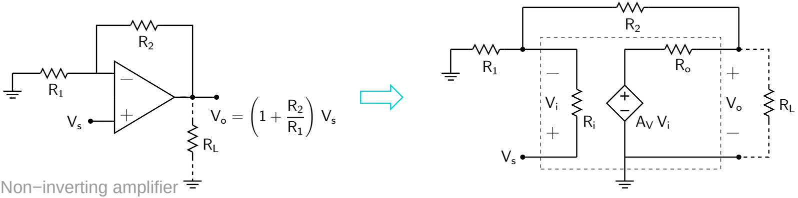
* For the inverting amplifier, since $V_- \approx 0\,V$, $i_1 = V_s/R_1 \rightarrow R_{\text{in}} = V_s/i_1 = R_1$.

Inverting or non-inverting?



Inverting amplifier

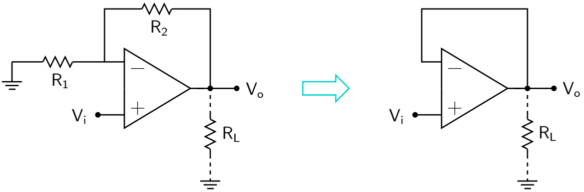


Non−inverting amplifier

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

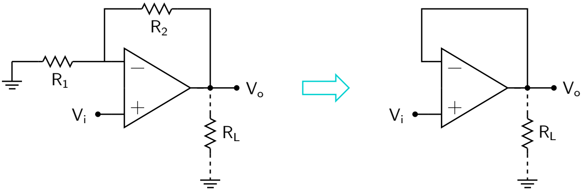
  $\rightarrow$ Non-inverting amplifier is better if a large R_{in} is required.

Non-inverting amplifier



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

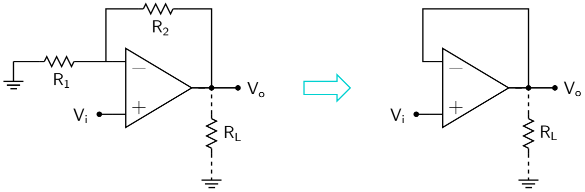
Non-inverting amplifier



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

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

Non-inverting amplifier

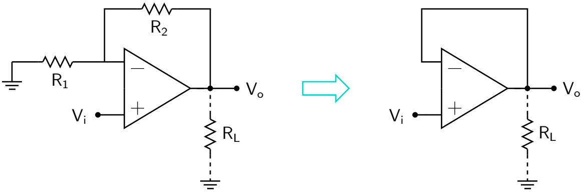


Consider $R_1 \rightarrow \infty$, $R_2 \rightarrow 0$.

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

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

Non-inverting amplifier



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

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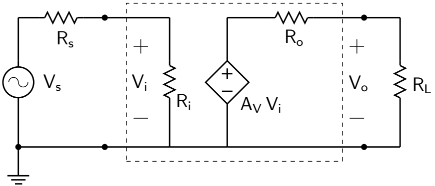
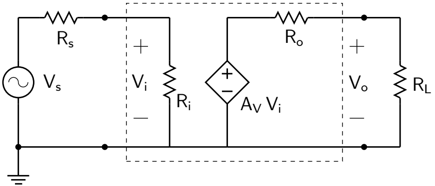
What has been achieved?



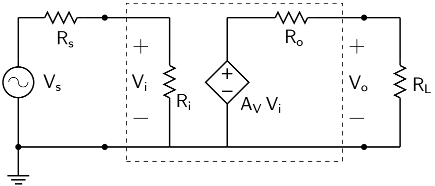
Consider an amplifier of gain A_V. We would like to have $V_o = A_V\, V_s$.



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

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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However, the actual output voltage is,

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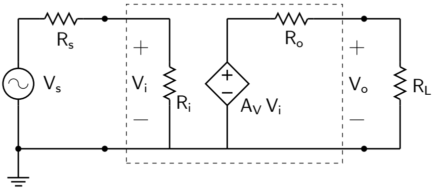
To obtain the desired V_o, we need $R_i \rightarrow \infty$ and $R_o \rightarrow 0$.



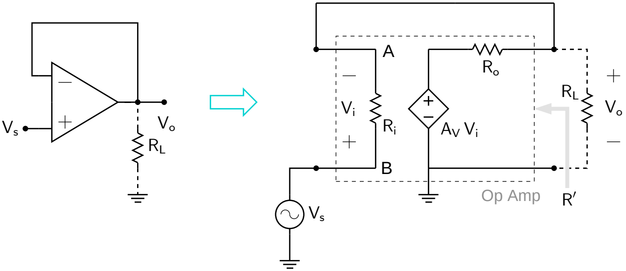
Consider an amplifier of gain A_V. We would like to have $V_o = A_V\, V_s$.

However, the actual output voltage is,

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

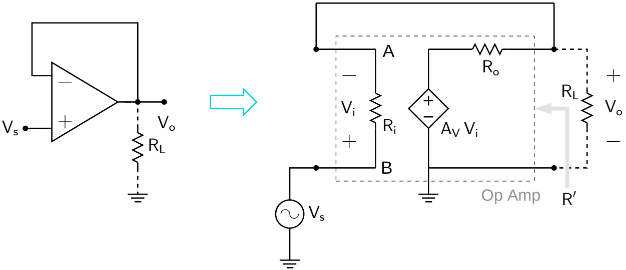
To obtain the desired V_o, we need $R_i \rightarrow \infty$ and $R_o \rightarrow 0$.

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



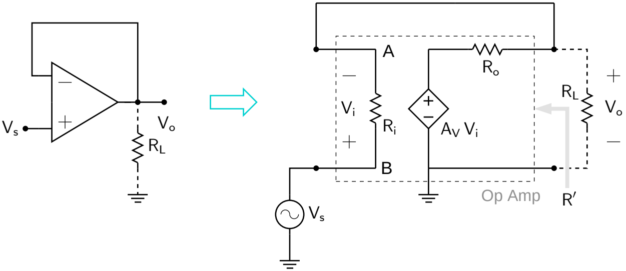
* The current drawn from the source (V_s) is small (since R_i of the Op Amp is large) → the buffer has a large input resistance.

Op Amp buffer

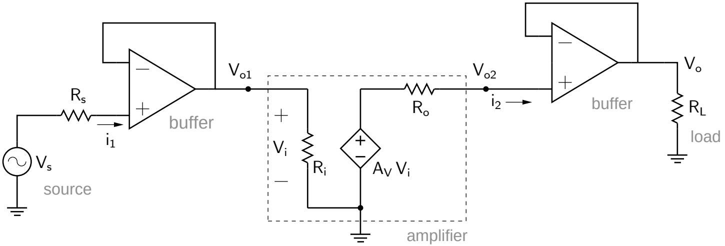


* The current drawn from the source (V_s) is small (since R_i of the Op Amp is large) $\rightarrow$ the buffer has a large input resistance.
* As we have seen earlier, A_V is large $\rightarrow$ $V_i \approx 0\ V$ $\rightarrow$ $V_A = V_B = V_s$.

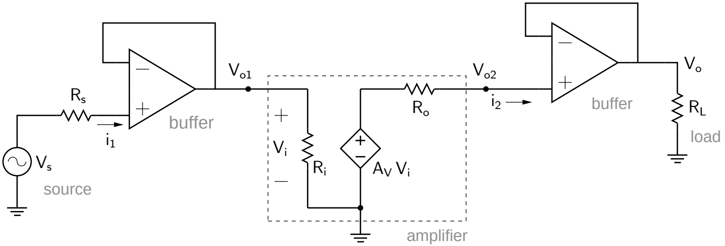
Op Amp buffer



* The current drawn from the source (V_s) is small (since R_i of the Op Amp is large) $\rightarrow$ the buffer has a large input resistance.
* 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) $\rightarrow A_V V_i = 0\ V$.)


R$_s$
i$_1$
V$_s$
source
buffer
V$_{o1}$
+
V$_i$
−
R$_i$
A$_V$ V$_i$
R$_o$
amplifier
V$_{o2}$
i$_2$
buffer
V$_o$
R$_L$
load

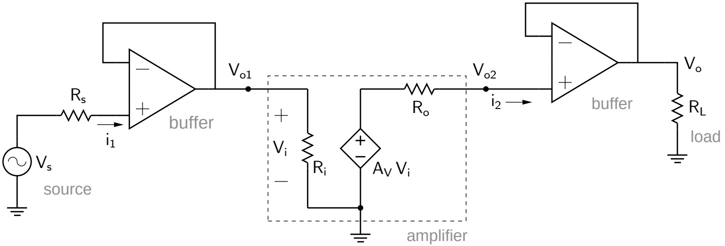
Op Amp buffer



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

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

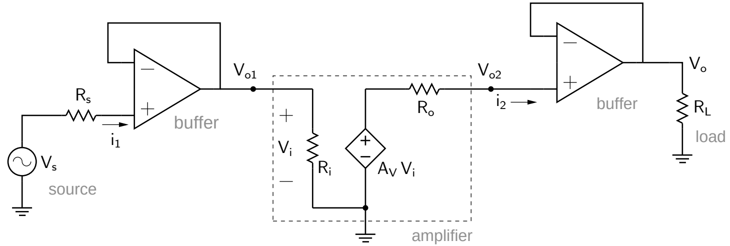
Op Amp buffer



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

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

Similarly, $i_2 \approx 0\,A$, and $V_{o2} = A_V\, V_s$.

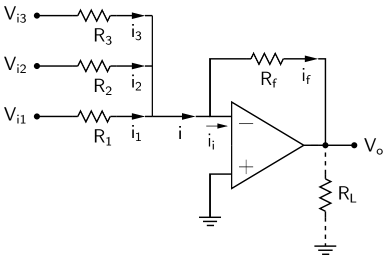


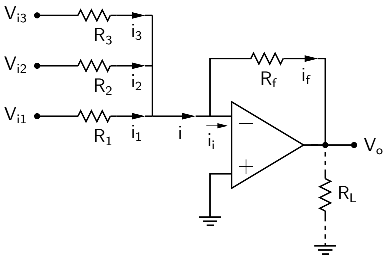
Since the buffer has a large input resistance, $i_1 \approx 0\,A$,

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

Similarly, $i_2 \approx 0\,A$, and $V_{o2} = A_V\, V_s$.

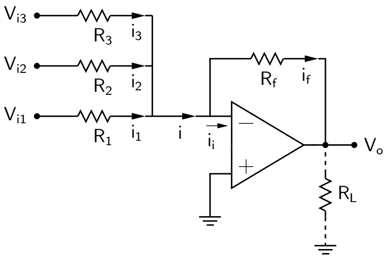
Finally, $V_o = V_{o2} = A_V\, V_s$, as desired, *irresepective* of R_S and R_L.


V_i3
R_3
i_3
V_i2
R_2
i_2
V_i1
R_1
i_1
i
i_i
R_f
i_f
V_o
R_L



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

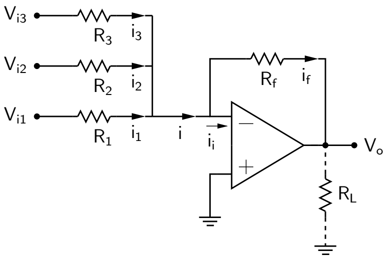
Op Amp circuits (linear region)



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

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

Op Amp circuits (linear region)



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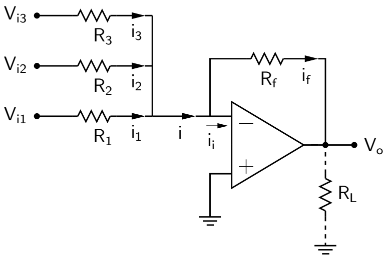
$i = i_1 + i_2 + i_3 = \left(\dfrac{V_{i1}}{R_1} + \dfrac{V_{i2}}{R_2} + \dfrac{V_{i3}}{R_3}\right).$

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



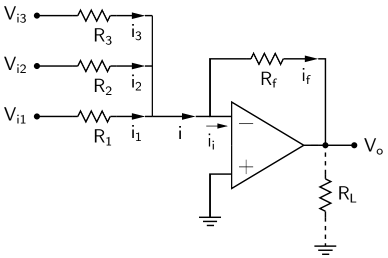
$V_- \approx V_+ = 0\ V \rightarrow i_1 = V_{i1}/R_1,\ i_1 = V_{i2}/R_2,\ i_1 = V_{i3}/R_3$.

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

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

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

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



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

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

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

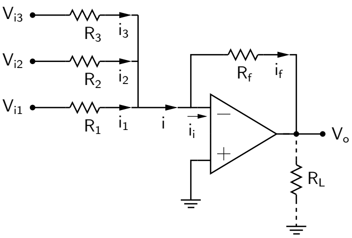
$$V_o = V_- - i_f\,R_f = 0 - \left(\frac{V_{i1}}{R_1} + \frac{V_{i2}}{R_2} + \frac{V_{i3}}{R_3} \right) R_f = - \left(\frac{R_f}{R_1}\,V_{i1} + \frac{R_f}{R_2}\,V_{i2} + \frac{R_f}{R_3}\,V_{i3} \right),$$

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

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

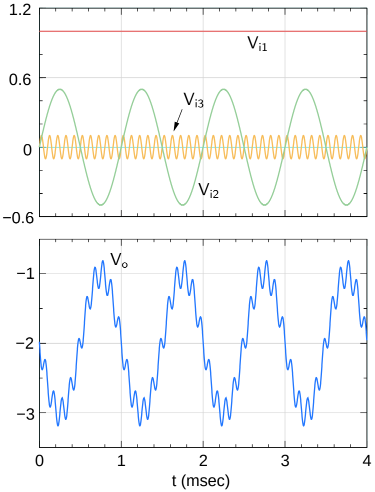


$R_1 = R_2 = R_3 = 1\ k\Omega$

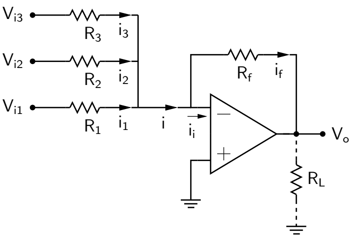
$R_f = 2\ k\Omega$

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

SEQUEL file: ee101_summer.sqproj



Summer example



$R_1 = R_2 = R_3 = 1\ k\Omega$

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

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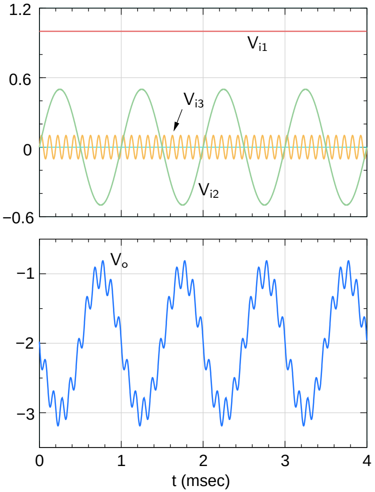
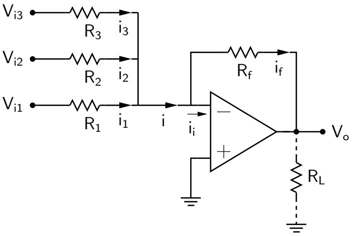
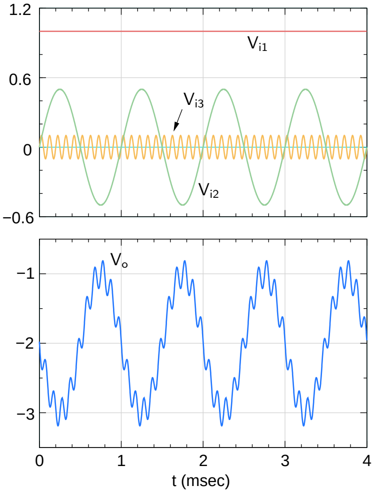


* Note that the summer also works with DC inputs. This is true about the inverting and non-inverting amplifiers as well.

Summer example





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

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

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

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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.
* Op Amps make life simpler! Think of adding voltages in any other way.