

EE101: Op Amp circuits (Part 1)



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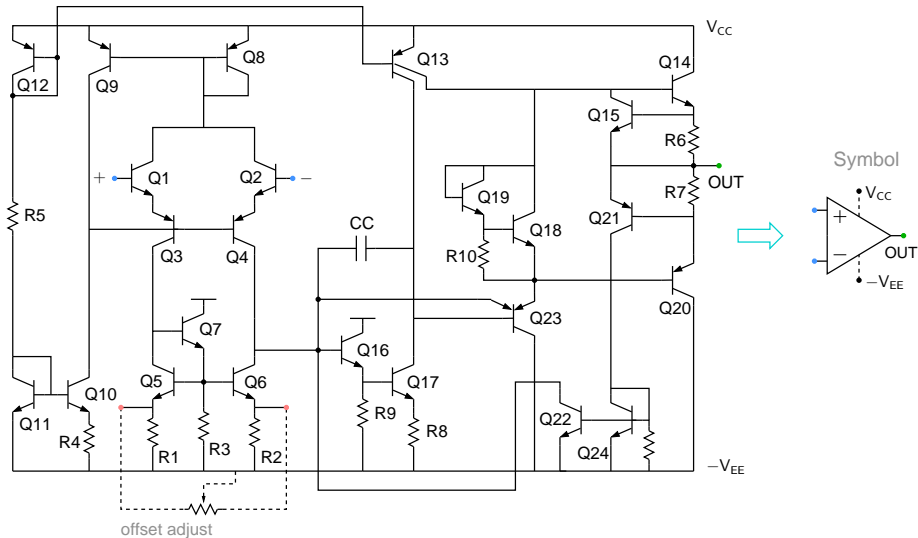
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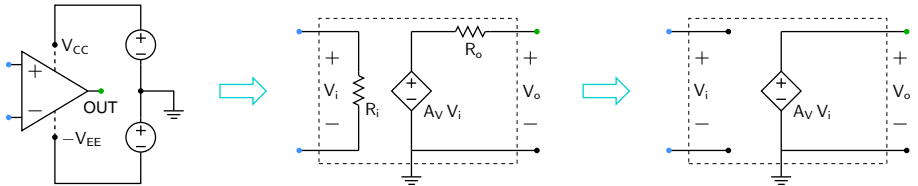
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- * The user can generally carry out circuit design without a thorough knowledge of the intricate details (next slide) of an Op Amp. This makes the design process simple.
- * However, as Einstein has said, we should “make everything as simple as possible,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

Op Amp 741

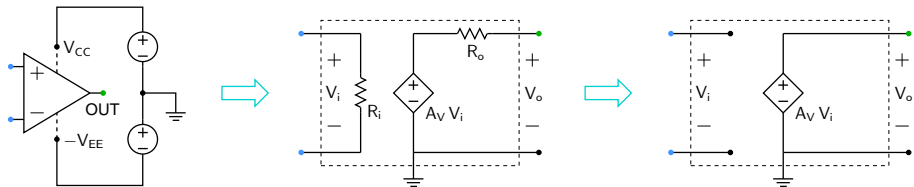
Actual circuit



Op Amp: equivalent circuit

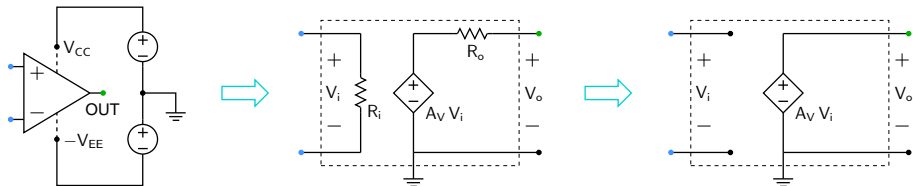


Op Amp: equivalent circuit



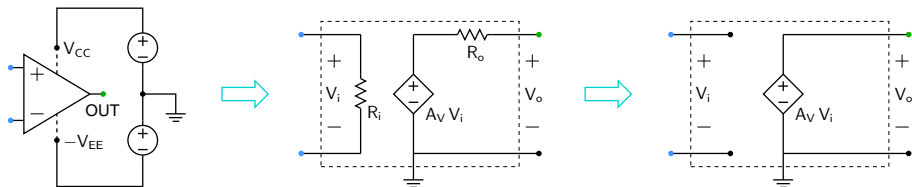
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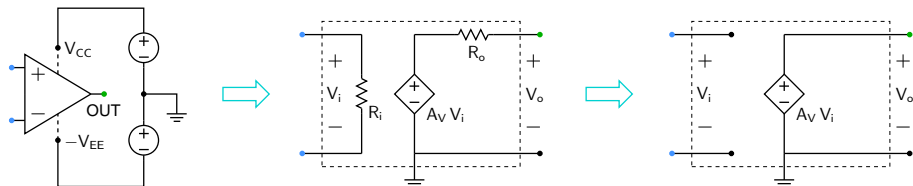
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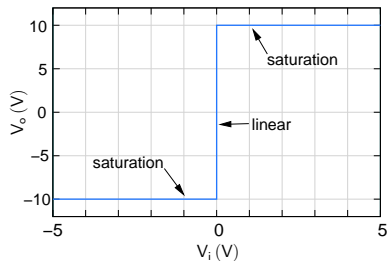
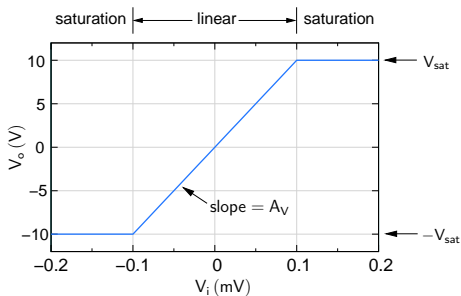
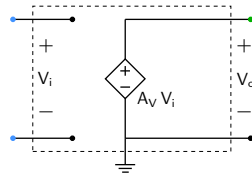
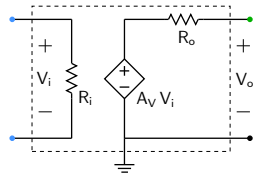
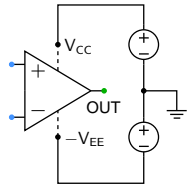


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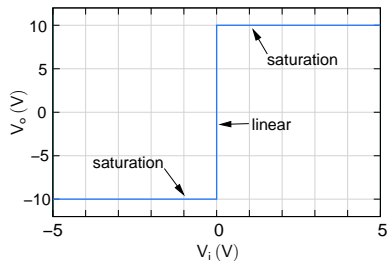
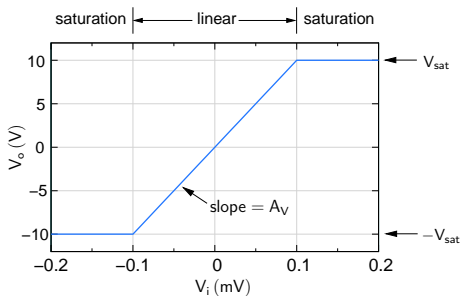
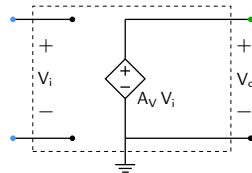
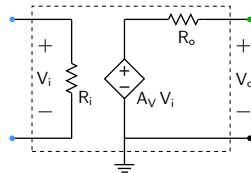
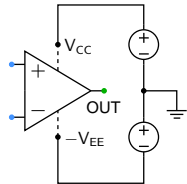
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Parameter	Ideal Op Amp	741
* A_v	∞	10^5 (100 dB)
R_i	∞	$2 M\Omega$
R_o	0	75Ω

Op Amp: equivalent circuit

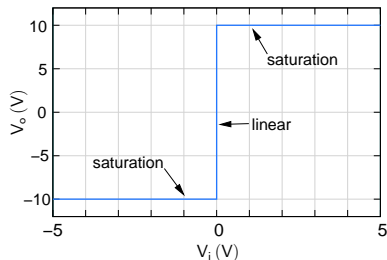
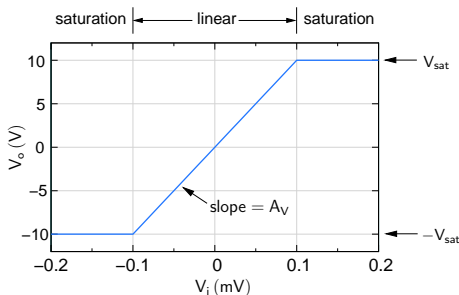
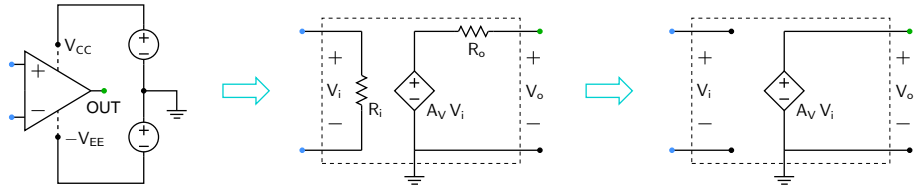


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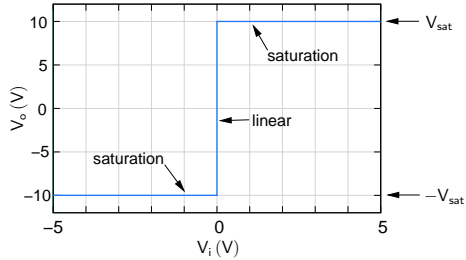
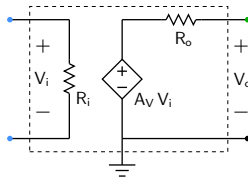
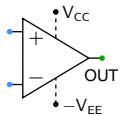
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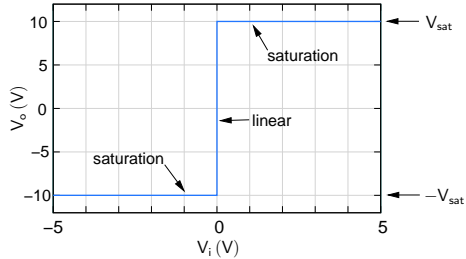
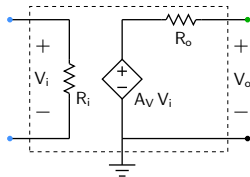
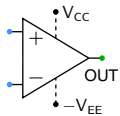


- * The output voltage V_o is limited to $\pm V_{sat}$, where $V_{sat} \sim 1.5 \text{ V}$ less than V_{CC} .
- * For $-V_{sat} < V_o < V_{sat}$, $V_i = V_+ - V_- = V_o/A_V$, which is very small
 $\rightarrow V_+$ and V_- are *virtually* the same.

Op Amp circuits

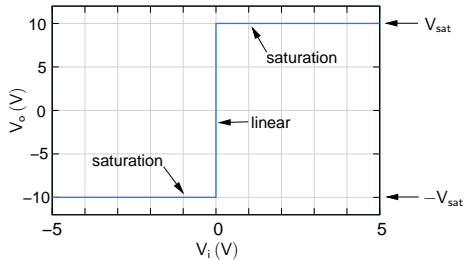
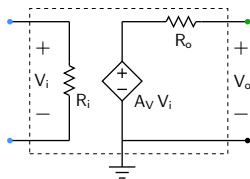
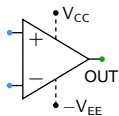


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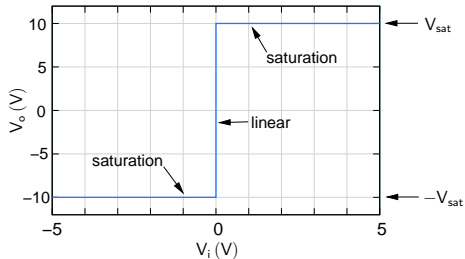
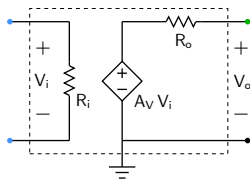
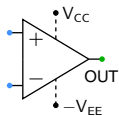
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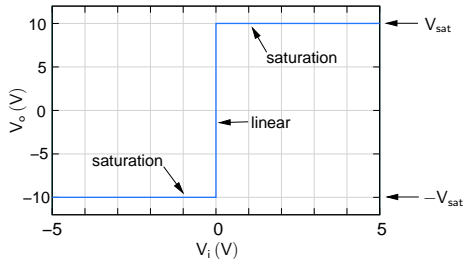
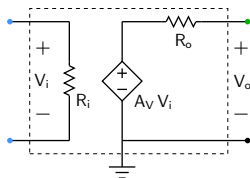
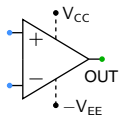
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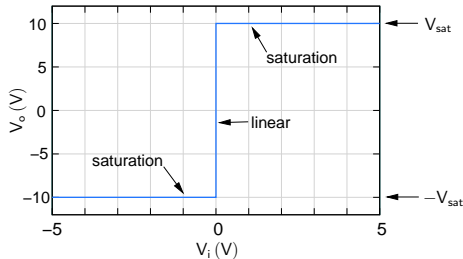
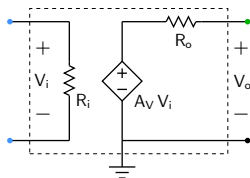
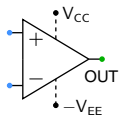
- Op Amp operating in the linear region
- Op Amp operating in the saturation region

Op Amp circuits



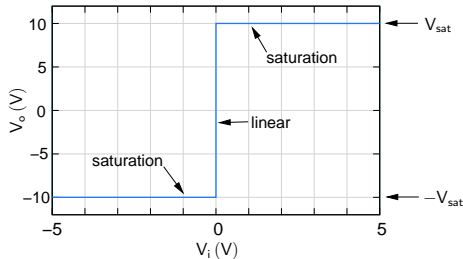
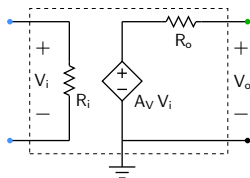
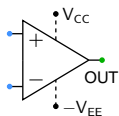
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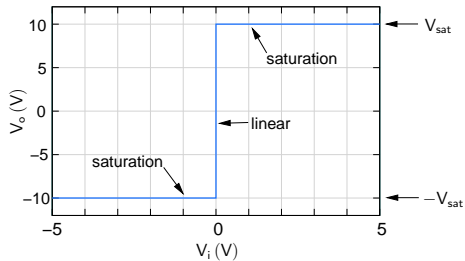
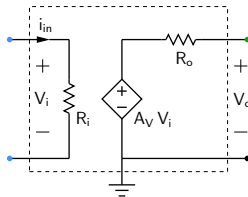
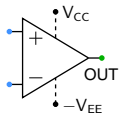
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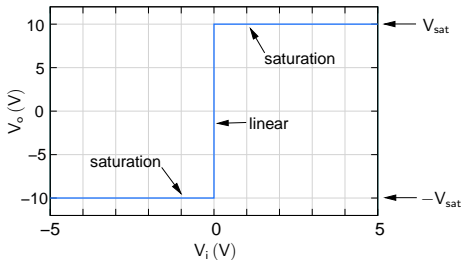
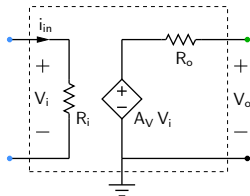
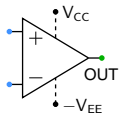


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 - type of feedback (negative or positive)(We will take a qualitative look at feedback later.)

Op Amp circuits (linear region)



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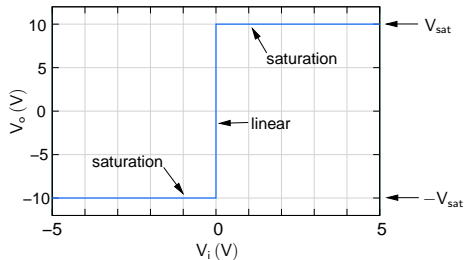
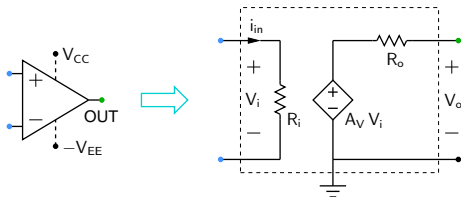


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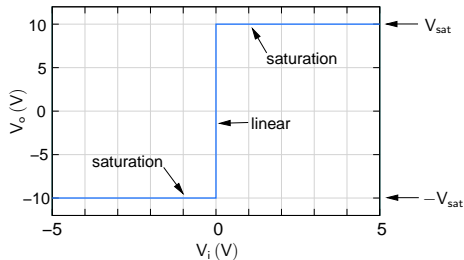
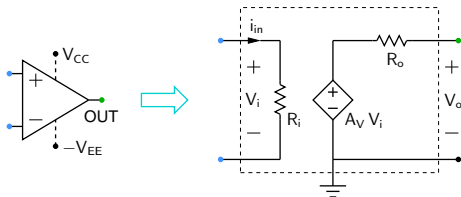
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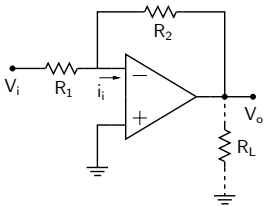
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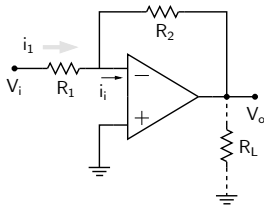
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These two “golden rules” enable us to understand several Op Amp circuits.

Op Amp circuits (linear region)



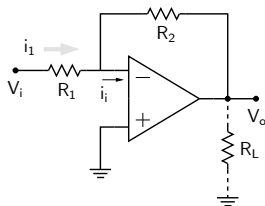
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Since $V_+ \approx V_-$, $V_- \approx 0 \text{ V} \rightarrow i_1 = (V_i - 0)/R = V_i/R$.

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Op Amp circuits (linear region)

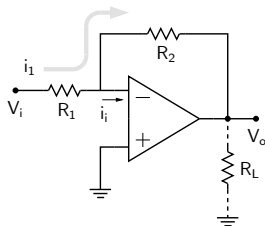


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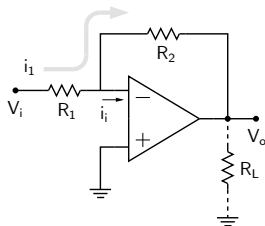


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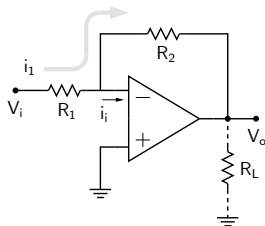
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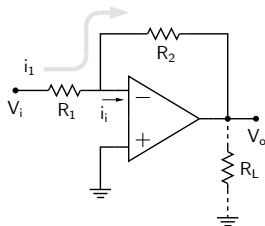
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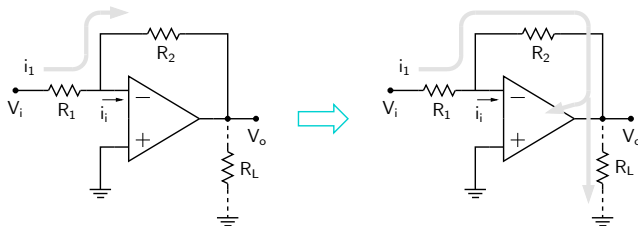
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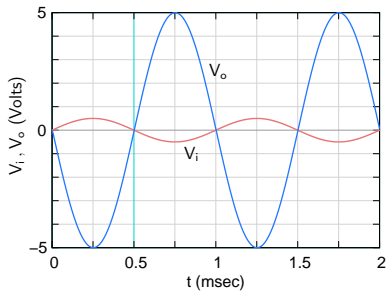
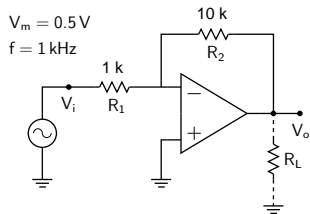
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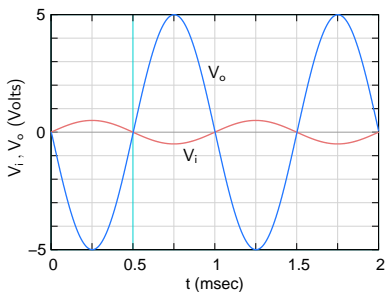
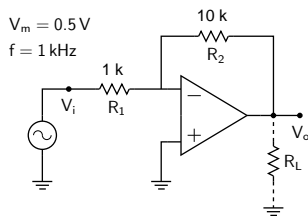
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Op Amp circuits: inverting amplifier

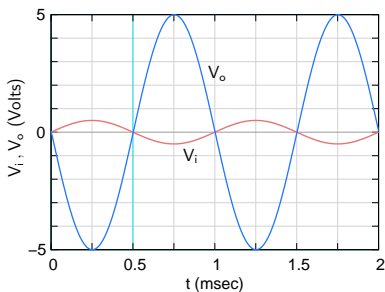
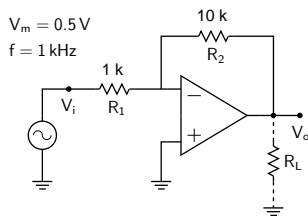


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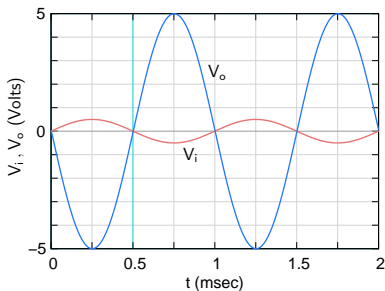
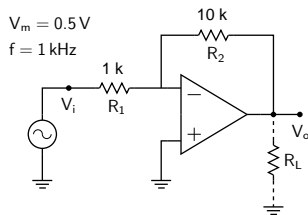
- * The gain of the inverting amplifier is $-R_2/R_1$. It is called the “closed-loop gain” (to distinguish it from the “open-loop gain” of the Op Amp which is $\sim 10^5$).

Op Amp circuits: inverting amplifier



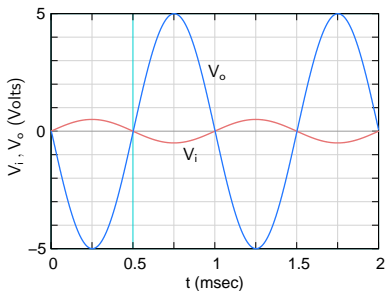
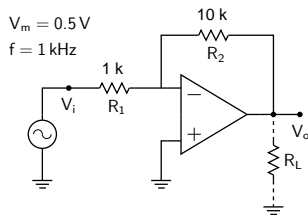
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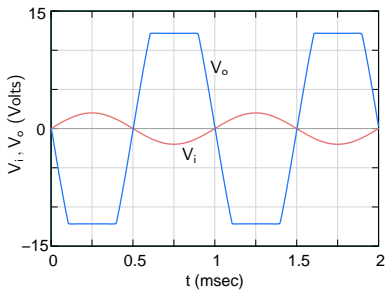
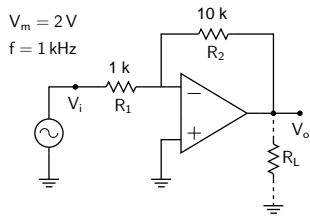
Op Amp circuits: inverting amplifier



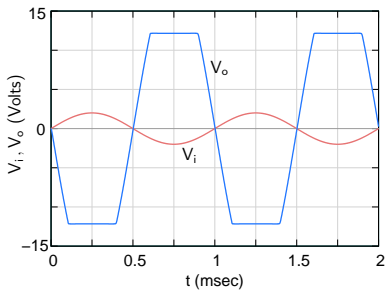
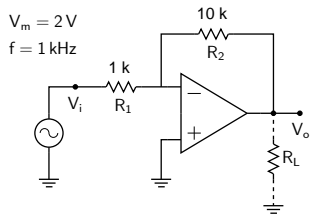
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(SEQUEL file: ee101_inv_amp.1.sqproj)

Op Amp circuits: inverting amplifier

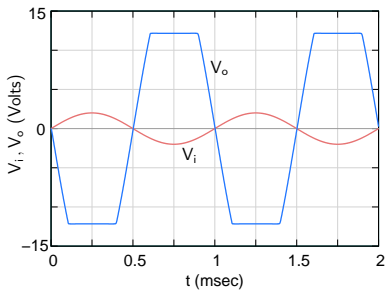
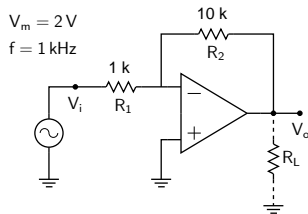


Op Amp circuits: inverting amplifier



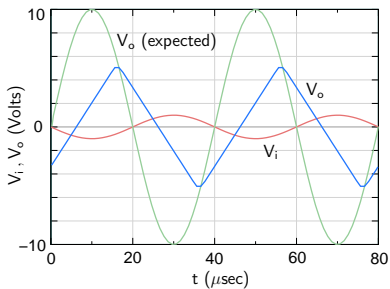
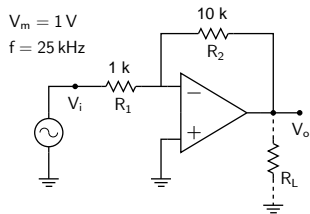
* The output voltage is limited to $\pm V_{sat}$.

Op Amp circuits: inverting amplifier

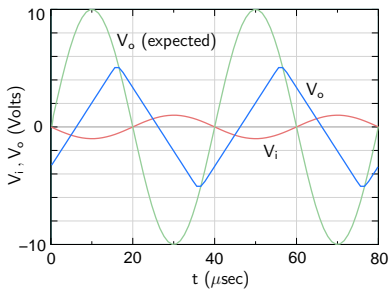
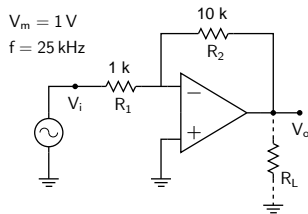


- * The output voltage is limited to $\pm V_{\text{sat}}$.
- * V_{sat} is $\sim 1.5\text{ V}$ less than the supply voltage V_{CC} .

Op Amp circuits: inverting amplifier

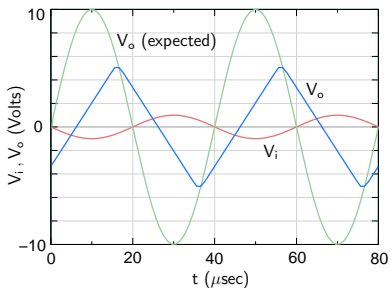
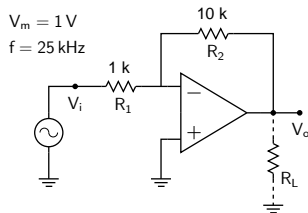


Op Amp circuits: inverting amplifier



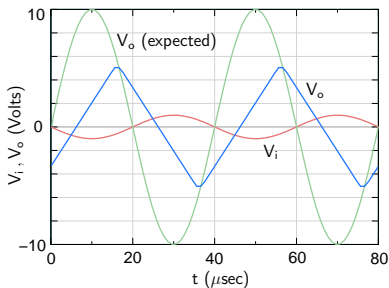
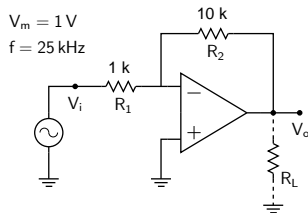
- * If the signal frequency is too high, a practical Op Amp cannot keep up with the input due to its “slew rate” limitation.

Op Amp circuits: inverting amplifier



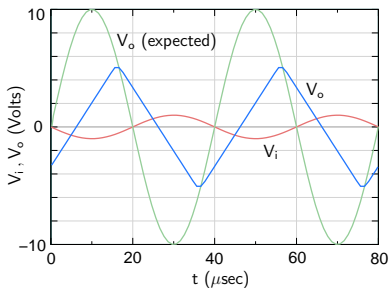
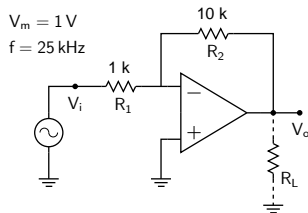
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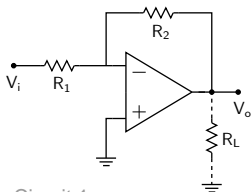
Op Amp circuits: inverting amplifier



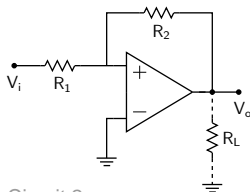
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(SEQUEL file: ee101_inv_amp_2.sqproj)

Op Amp circuits: inverting amplifier



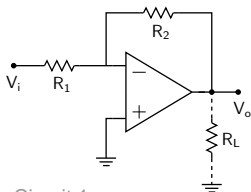
Circuit 1



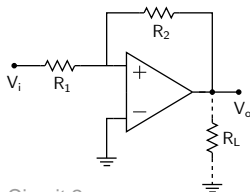
Circuit 2

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

Op Amp circuits: inverting amplifier



Circuit 1

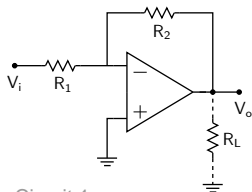


Circuit 2

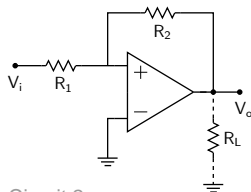
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Op Amp circuits: inverting amplifier



Circuit 1



Circuit 2

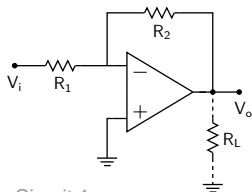
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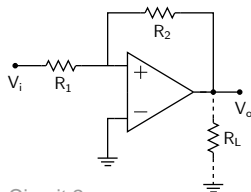
However, from Circuit 1 to Circuit 2, the nature of the feedback changes from negative to positive.

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

Op Amp circuits: inverting amplifier



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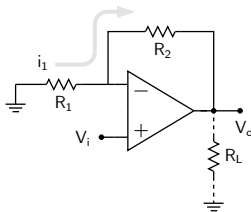
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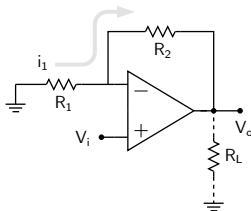
(Circuit 2 is also useful, and we will discuss it later.)

Op Amp circuits (linear region)



* $V_+ \approx V_- = V_i$

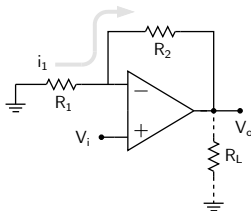
Op Amp circuits (linear region)



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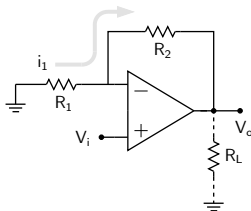


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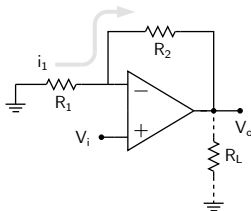
$$* V_o = V_+ - i_1 R_2 = V_i - \left(-\frac{V_i}{R_1}\right) R_2 = V_i \left(1 + \frac{R_2}{R_1}\right).$$

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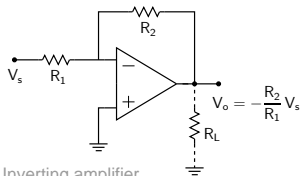
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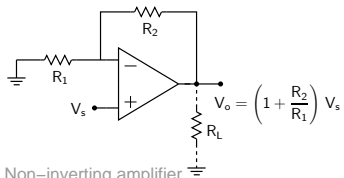
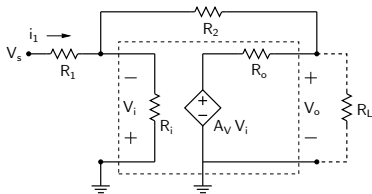


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- * Again, interchanging + and - changes the nature of the feedback from negative to positive, and the circuit operation becomes completely different.

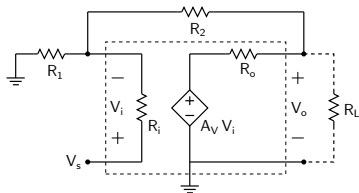
Inverting or non-inverting?



Inverting amplifier

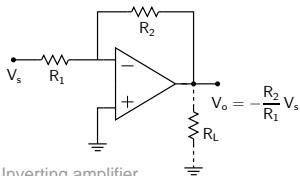


Non-inverting amplifier

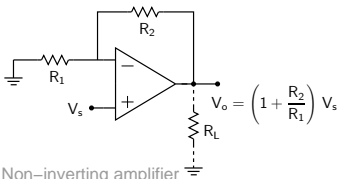
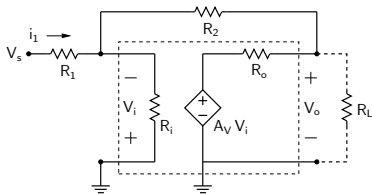


- * If the sign of the output voltage is not a concern, which configuration should be preferred?

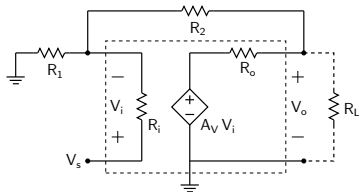
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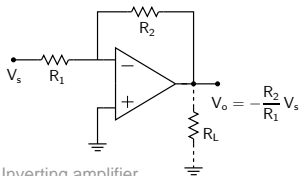


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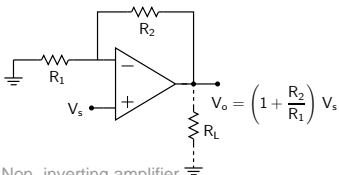
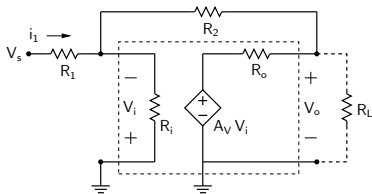


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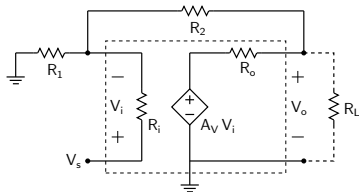
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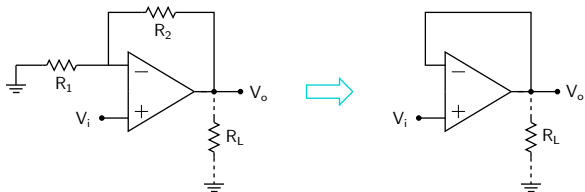


Non-inverting amplifier



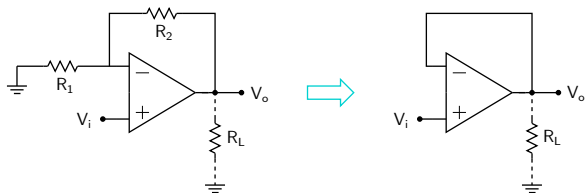
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- * For the non-inverting amplifier, $R_{in} \sim R_i$ of the Op Amp, which is a few $\text{M}\Omega$.
 → Non-inverting amplifier is better if a large R_{in} is required.

Non-inverting amplifier



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

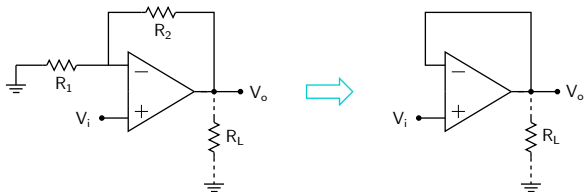
Non-inverting amplifier



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

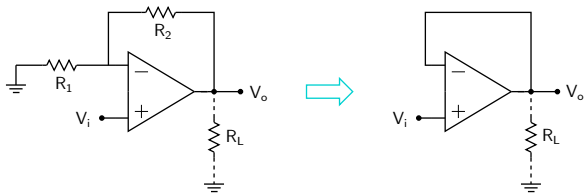


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$$\frac{V_o}{V_i} \rightarrow 1 + \frac{R_2}{R_1} \rightarrow 1, \text{ i.e., } V_o = V_i.$$

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

Non-inverting amplifier



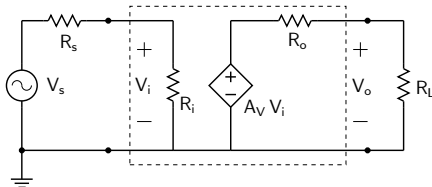
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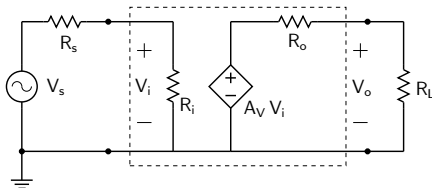
What has been achieved?

Loading effects



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

Loading effects

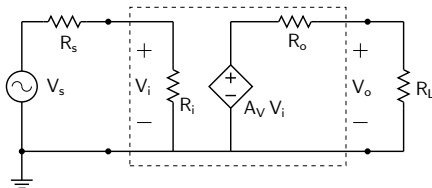


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However, the actual output voltage is,

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

Loading effects



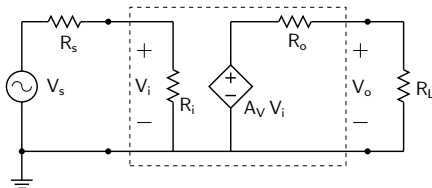
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To obtain the desired V_o , we need $R_i \rightarrow \infty$ and $R_o \rightarrow 0$.

Loading effects



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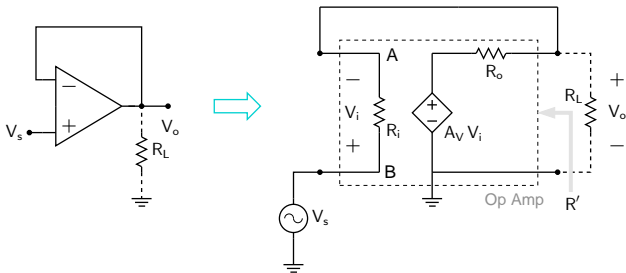
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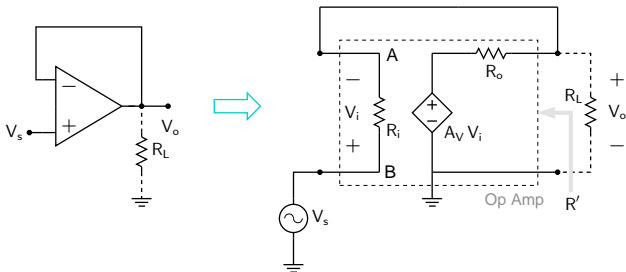
The buffer (voltage follower) provides this feature (next slide).

Op Amp buffer



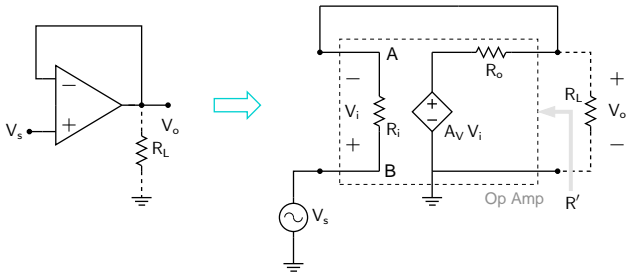
- * The current drawn from the source (V_s) is small (since R_i of the Op Amp is large) \rightarrow the buffer has a large input resistance.

Op Amp buffer



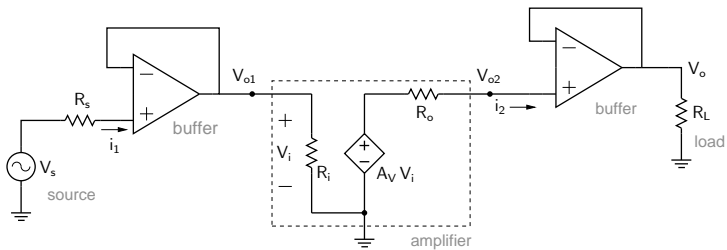
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- * As we have seen earlier, A_V is large $\rightarrow V_i \approx 0\text{ V} \rightarrow V_A = V_B = V_s$.

Op Amp buffer

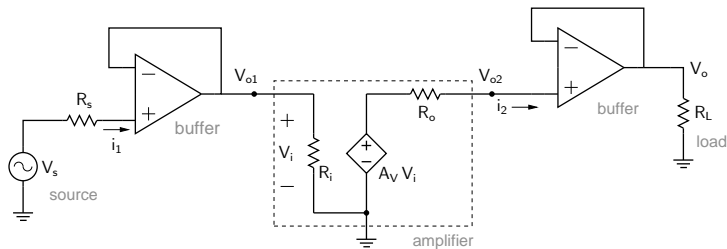


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- * The resistance seen by R_L is $R' \approx R_o$, which is small \rightarrow the buffer has a small output resistance. (To find R' , deactivate the input voltage source (V_s) $\rightarrow A_V V_i = 0 \text{ V}$.)

Op Amp buffer

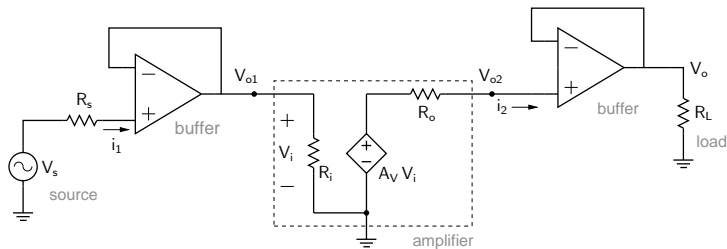


Op Amp buffer



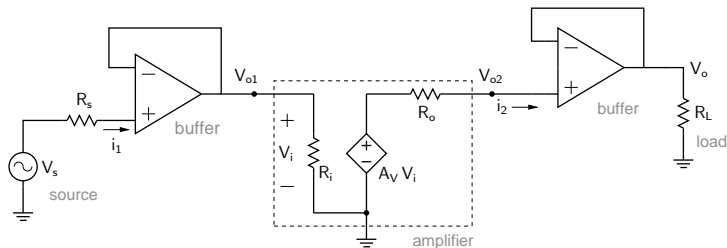
Since the buffer has a large input resistance, $i_1 \approx 0$ A, and V_+ (on the source side) = $V_s \rightarrow V_{o1} = V_s$.

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

Op Amp buffer

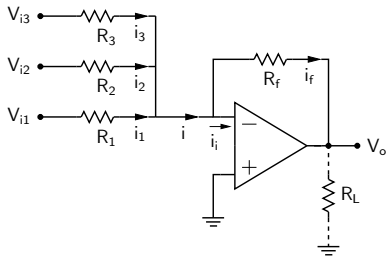


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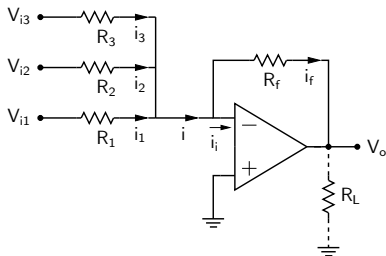
Similarly, $i_2 \approx 0$ A, and $V_{o2} = A_V V_s$.

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

Op Amp circuits (linear region)

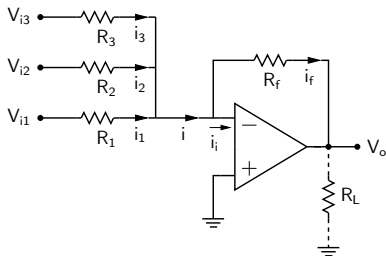


Op Amp circuits (linear region)



$$V_- \approx V_+ = 0 \text{ V} \rightarrow i_1 = V_{i1}/R_1, i_2 = V_{i2}/R_2, i_3 = V_{i3}/R_3.$$

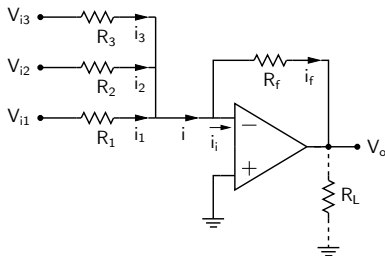
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$$i = i_1 + i_2 + i_3 = \left(\frac{V_{i1}}{R_1} + \frac{V_{i2}}{R_2} + \frac{V_{i3}}{R_3} \right).$$

Op Amp circuits (linear region)

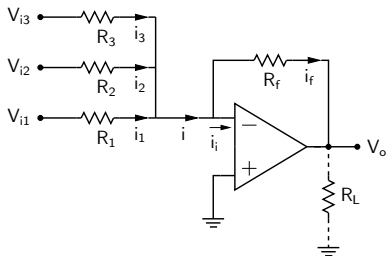


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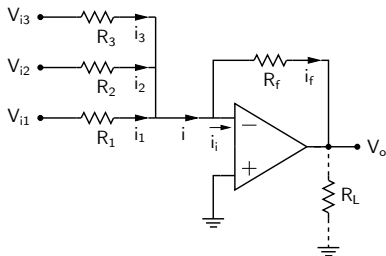
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$$V_o = V_- - i_f R_f = 0 - \left(\frac{V_{i1}}{R_1} + \frac{V_{i2}}{R_2} + \frac{V_{i3}}{R_3} \right) R_f = - \left(\frac{R_f}{R_1} V_{i1} + \frac{R_f}{R_2} V_{i2} + \frac{R_f}{R_3} V_{i3} \right),$$

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

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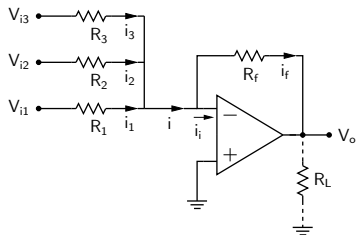
i.e., V_o is a *weighted sum* of V_{i1} , V_{i2} , V_{i3} .

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

$V_o = -K (V_{i1} + V_{i2} + V_{i3})$

 with $K = R_f/R$.

Summer example

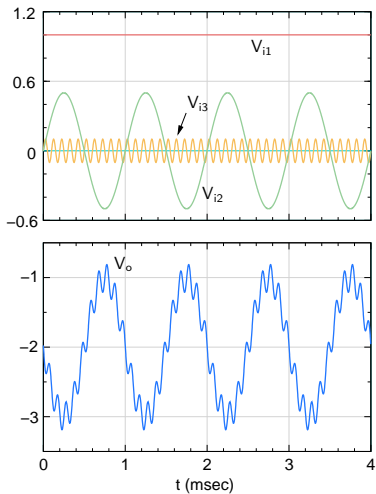


$$R_1 = R_2 = R_3 = 1 \text{ k}\Omega$$

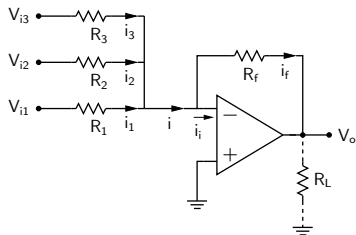
$$R_f = 2 \text{ k}\Omega$$

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

SEQUEL file: ee101_summer.sqproj



Summer example

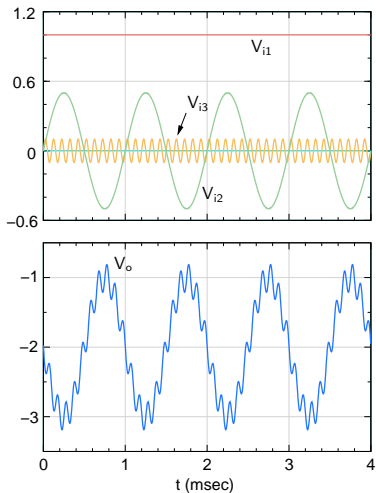


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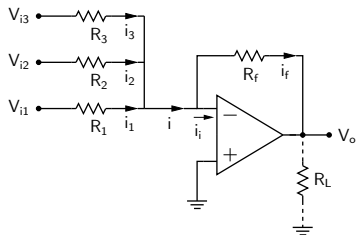
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- * Note that the summer also works with DC inputs. This is true about the inverting and non-inverting amplifiers as well.

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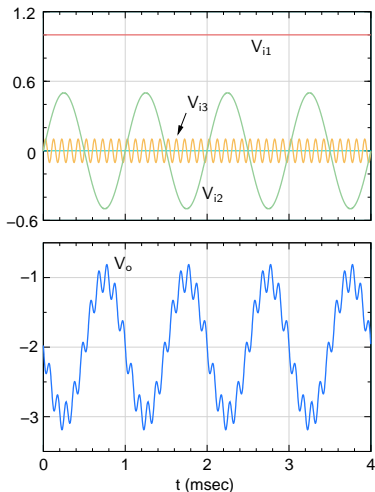


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- * Note that the summer also works with DC inputs. This is true about the inverting and non-inverting amplifiers as well.
- * Op Amps make life simpler! Think of adding voltages in any other way.