ECE 65: Components & Circuits Lab

Lecture 3

Operational Amplifier limitations

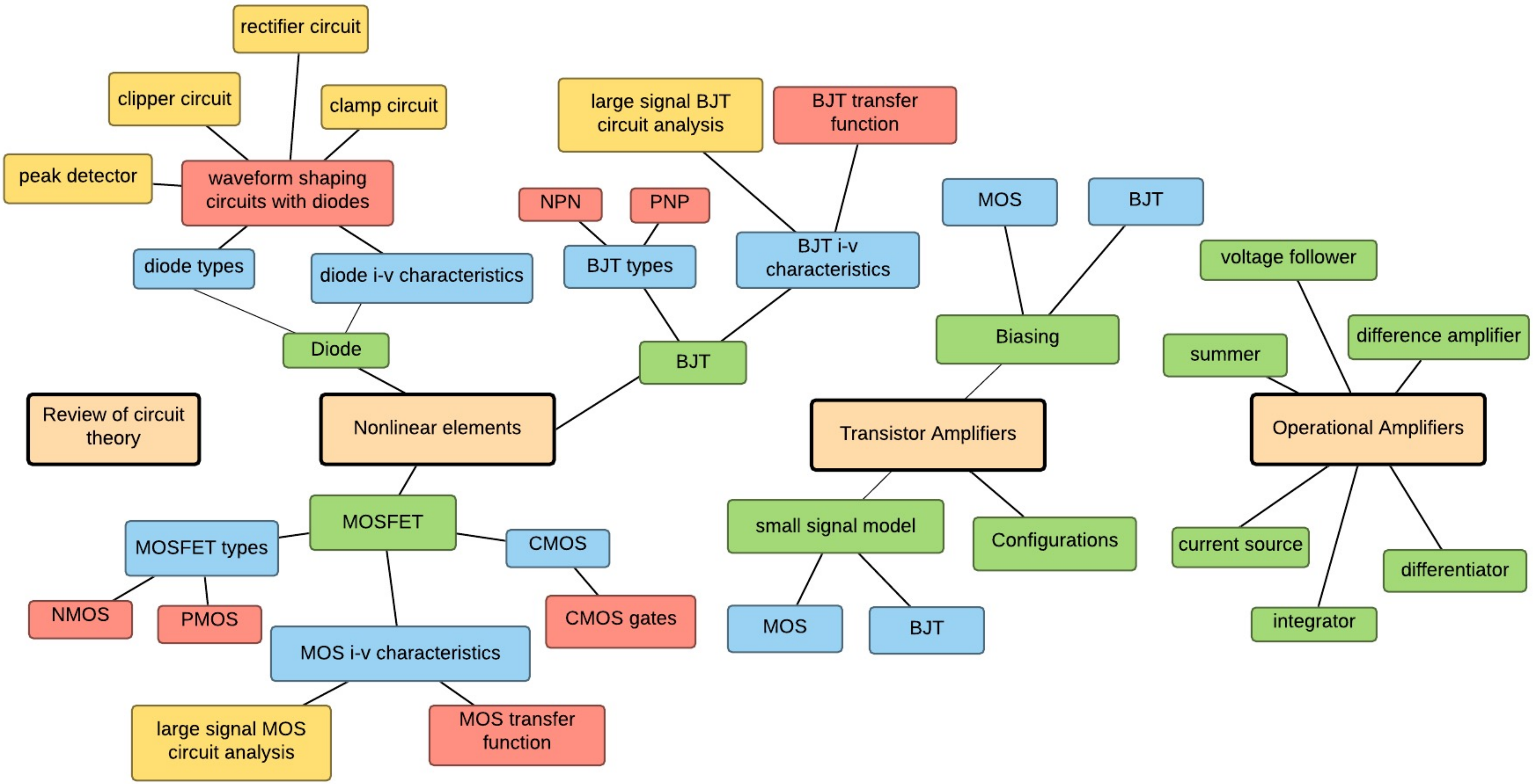
Reference notes: sections 7.5

Sedra & Smith (7th Ed): sections 2-2.3

Saharnaz Baghdadchi

Course map

7. Operational amplifiers

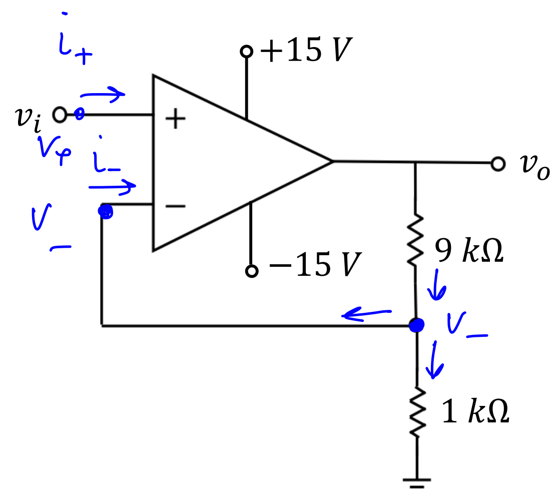


Voltage-supply limit or Saturation

As we saw before, the maximum output voltage of op-amps is limited by the positive and negative voltage sources (V_{S^+} and V_{S^-}) used to power up the op-amp chip.

$$V_{S^-} < V_o < V_{S^+}$$

$V_{sat^-} \leqslant V_o \leqslant V_{sat^+}$



$V_{sat+} = 14\,V$

$V_{sat-} = -14\,V$

Assume an ideal op-amp $\Longrightarrow i_+ = i_- = 0$

Because of negative feedback : $V_+ = V_-$

here, $V_+ = V_i$, $\dfrac{V_-}{1k\Omega} = \dfrac{V_o - V_-}{9k\Omega} \Longrightarrow V_o = 10\,V_- \Longrightarrow \boxed{V_o = 10\,V_i}$

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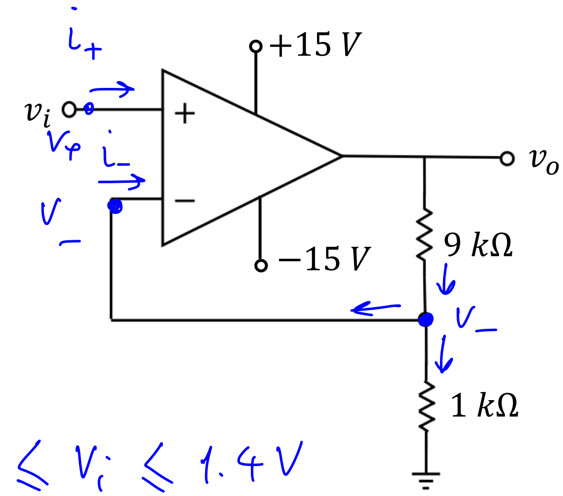

$V_{sat+} = 14V$

$V_{sat-} = -14V$

$V_o = 10\ V_i \Longrightarrow \frac{-14V}{10} \leq V_i \leq \frac{14}{10}\ V \Longrightarrow -1.4V \leq V_i \leq 1.4V$

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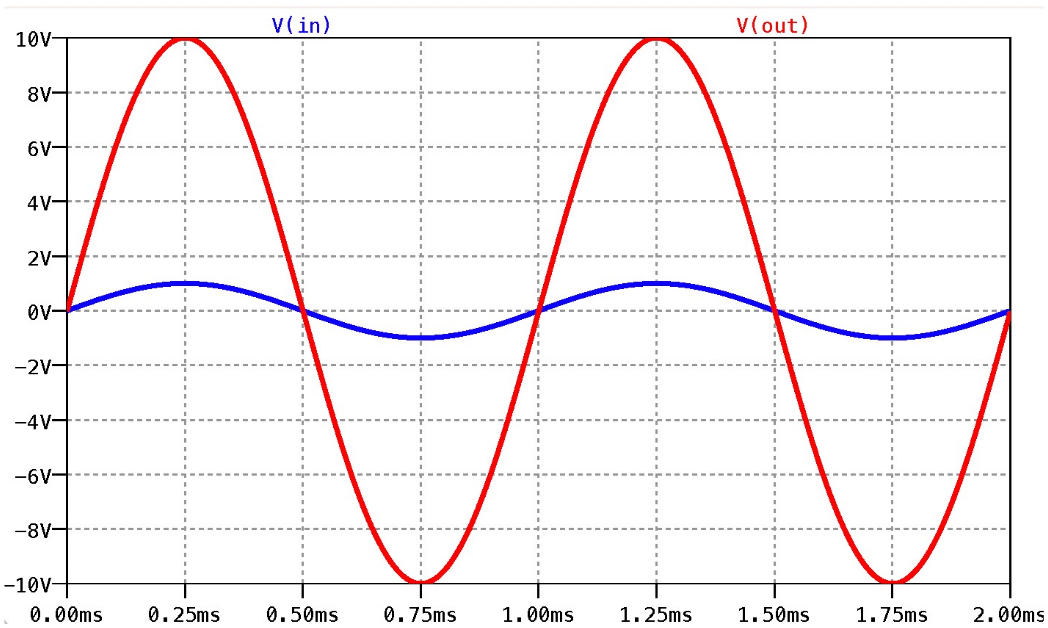

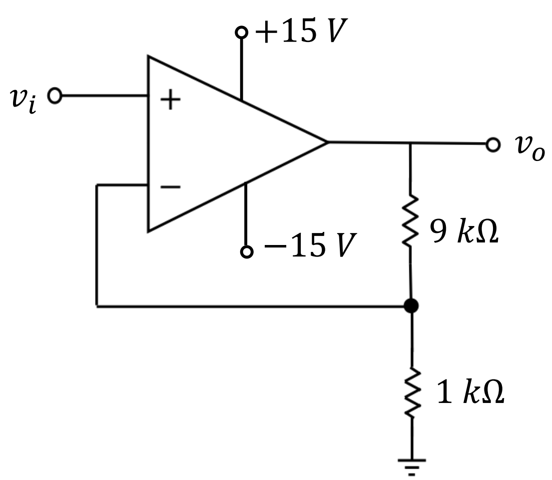

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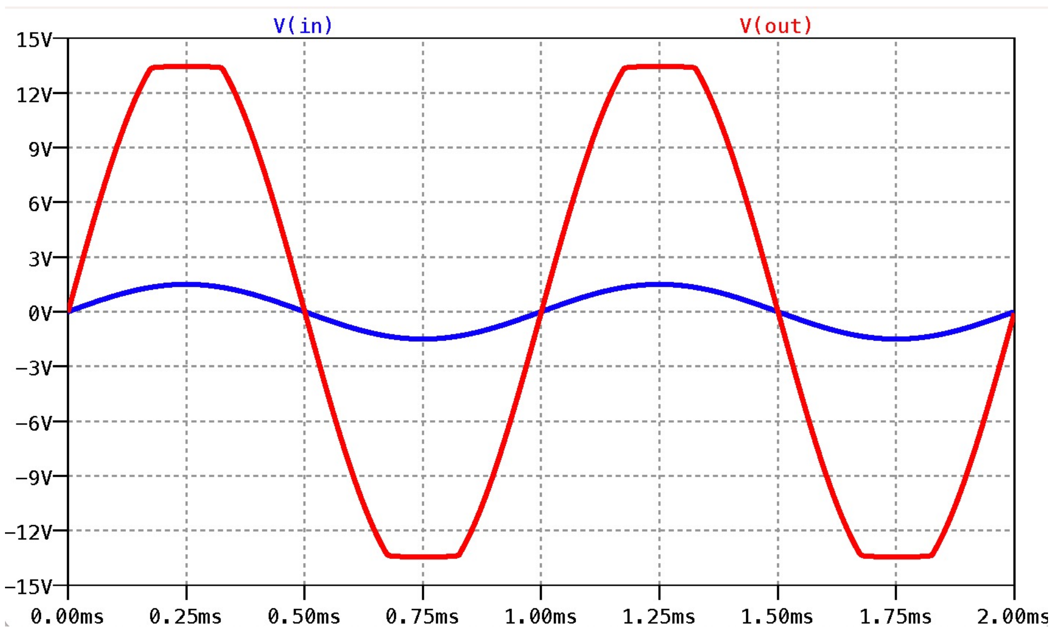
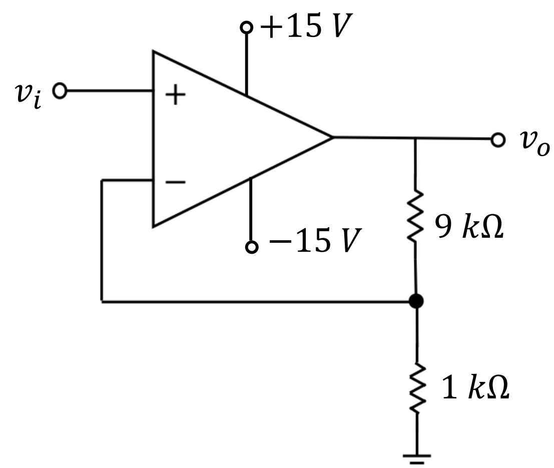
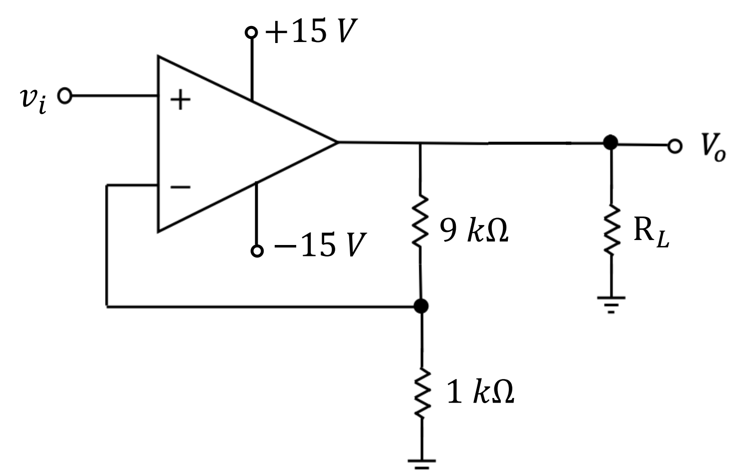




Maximum Output Current

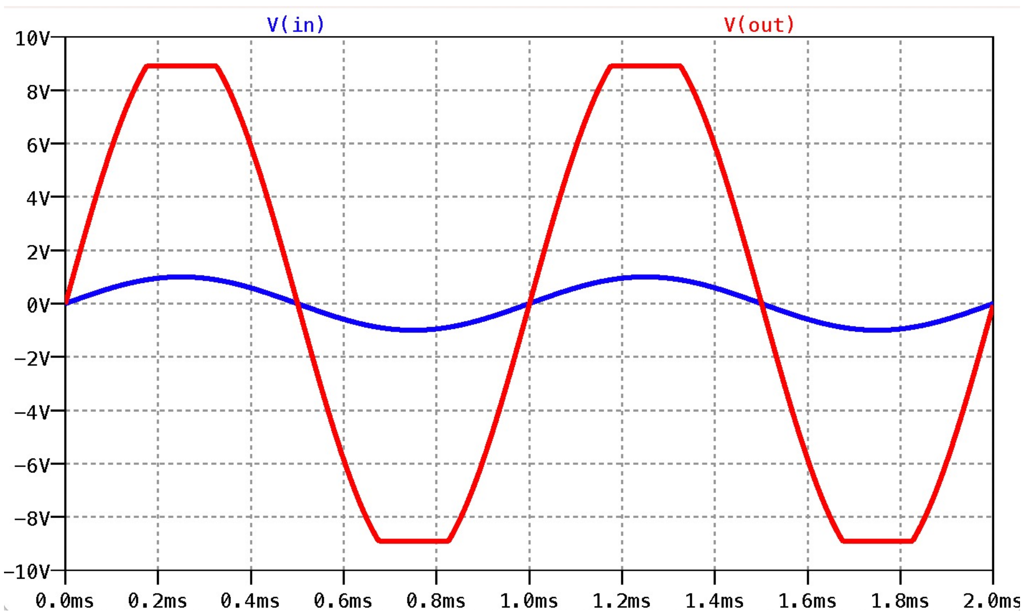
The output current of an op-amp is limited to a specified maximum value.

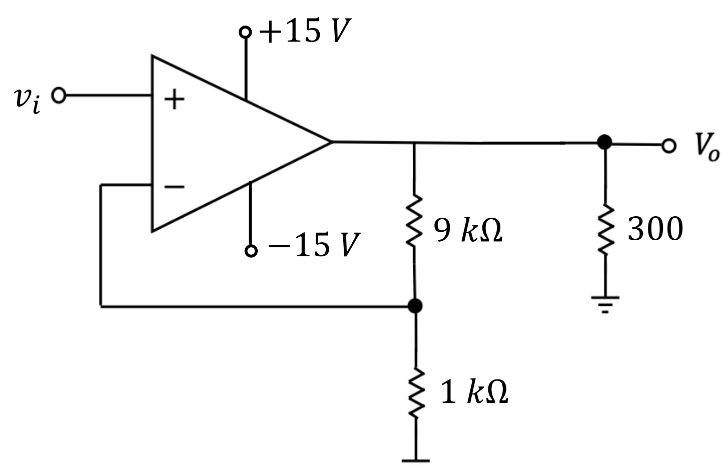
For example, in the 741 op-amp, the maximum output current is ±20mA.



Maximum Output Current

If the circuit requires a current larger than the maximum output current, in either direction, the output voltage will saturate at a level corresponding to the maximum allowed output current.

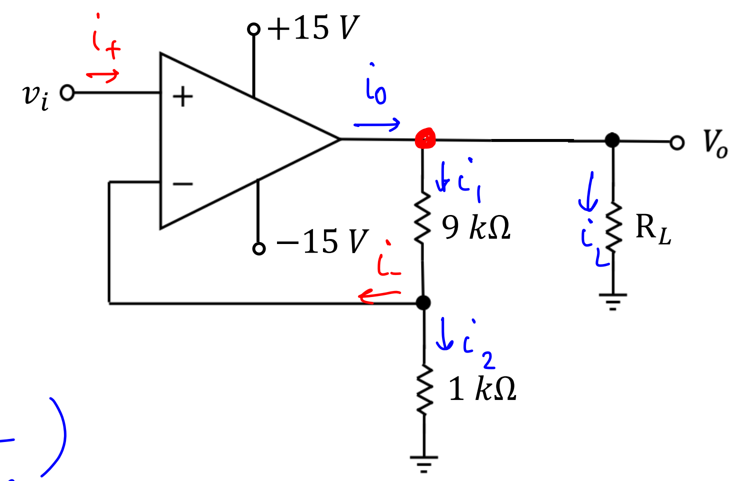




Maximum Output Current - Example

The following op-amp circuit is fed with a low-frequency sinusoidal signal with peak amplitude of $1\ V$. The maximum output current is $\pm 20mA$. If $R_L = 1\ k\Omega$, specify and sketch the output voltage.

assume an ideal op-amp : $i_+ = i_- = 0 \Longrightarrow i_1 = i_2$



KCL : $i_o = i_1 + i_L$

$$i_o = \frac{V_o}{9k\Omega + 1k\Omega} + \frac{V_o}{R_L}$$

$$i_o = \frac{V_o}{10\ k\Omega} + \frac{V_o}{1k\Omega} = V_o\left(\frac{1}{10\ k\Omega} + \frac{1}{1k\Omega}\right)$$

$$= V_o \times 1.1$$

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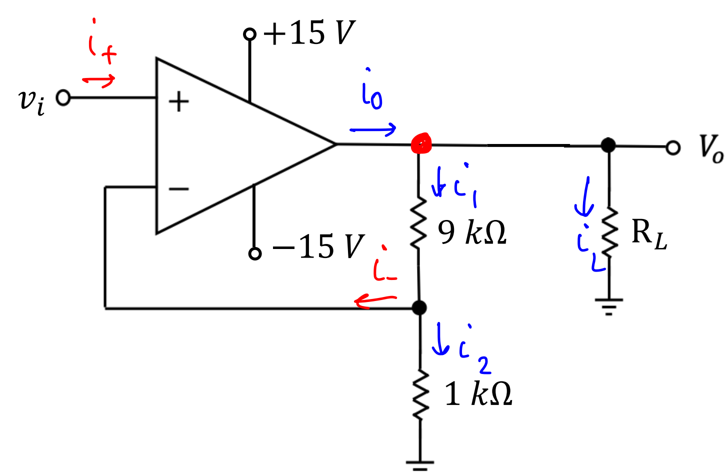


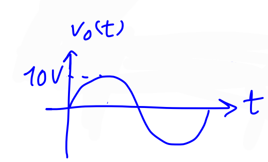
$i_o = V_o \times 1.1$

Assume linear amplification :

$\frac{V_o}{V_i} = 10\ V/V \Longrightarrow$ if $V_{i_{max}} = 1V \Longrightarrow V_{o_{max}} = 10\ V$

$\Rightarrow i_{o_{max}} = 10 \times 1.1 = 11\ mA < +20mA$

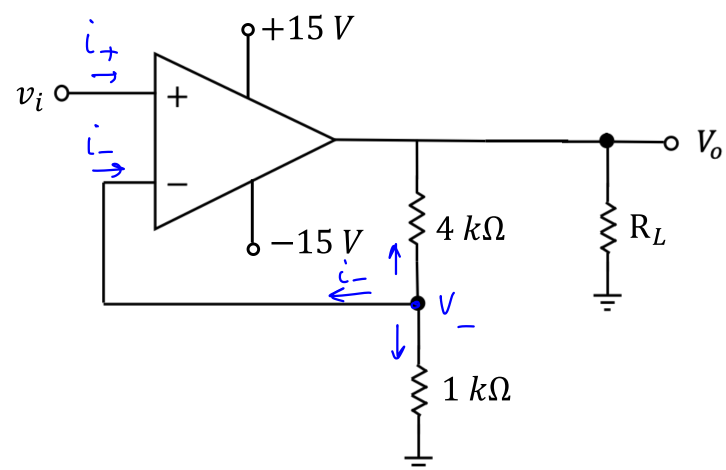
$\Rightarrow$ We are not limited by the maximum output current $\Rightarrow V_{o_{max}} = 10\ V$



Lecture 3 reading quiz

The following op-amp circuit is fed with a low-frequency sinusoidal signal with the peak amplitude of $\mathrm{V_P}$. The output saturation voltage is $\pm 13\ V$, and the maximum output current is $\pm 20\ mA$. If $\mathrm{R_L} = 0.5\ k\Omega$, find the maximum value of $\mathrm{V_P}$ for which an undistorted sinusoidal signal is obtained at the output?

Let's first find the voltage gain of the amplifier:



Assume an ideal op-amp: $i_+ = i_- = 0$

Negative feedback : $V_+ = V_-$

$V_+ = V_i \longrightarrow V_- = V_+ = V_i$

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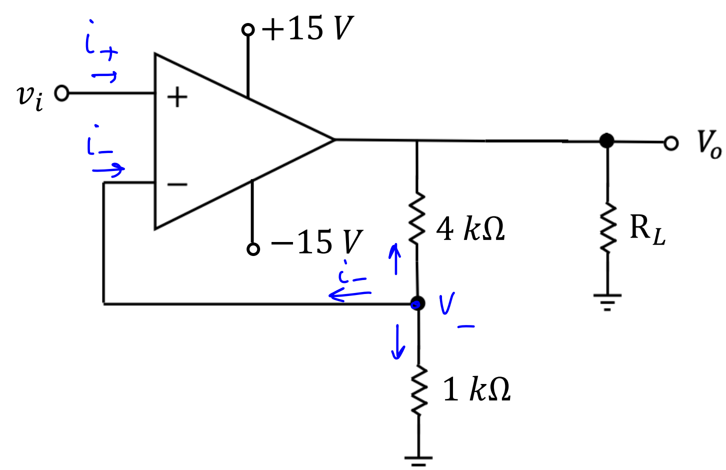

Assume an ideal op-amp: $i_+ = i_- = 0$

Negative feedback: $V_+ = V_-$

$V_+ = V_i \longrightarrow V_- = V_+ = V_i$

This relationship is valid if there is no distortion.

KCL: $\dfrac{V_-}{1k\Omega} = \dfrac{V_o - V_-}{4k\Omega} \Longrightarrow V_o = 5V_- = 5V_i \Longrightarrow \boxed{V_o = 5V_i}$

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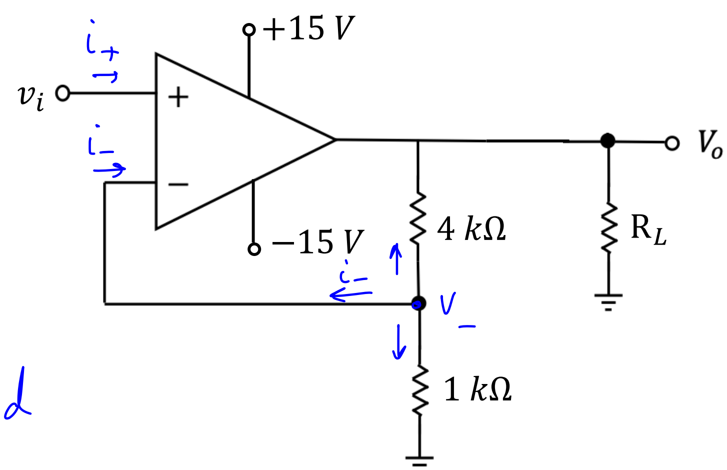

let's assume that the output voltage can reach the max possible ±13V. We need to check if the op-amp can supply the required output current to maintain ±13 V across R_L.

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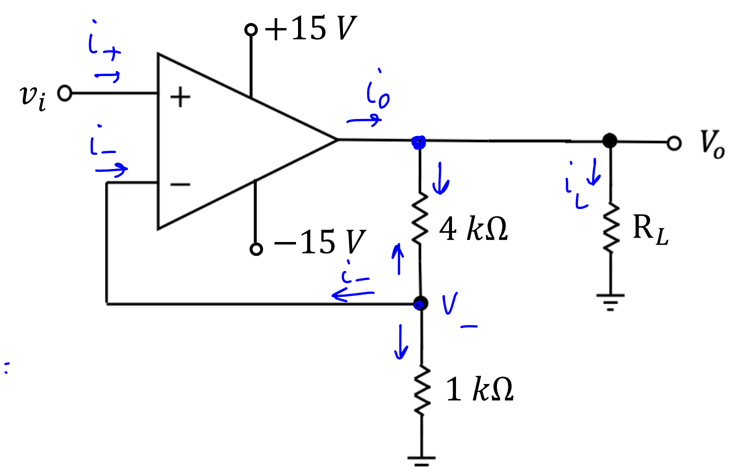
KCL at the output node:



$$i_o = \frac{V_o}{R_L} + \frac{V_o}{4k\Omega + 1k\Omega}$$

The required i_o to reach $V_{o\,max} = \pm 13\ V$ is:

$$|i_o| = \frac{13\ V}{0.5\ k\Omega} + \frac{13\ V}{5\ k\Omega} = 28.6\ mA > 20\ mA$$

$\Rightarrow$ the output voltage cannot reach to $\pm 13\ V$.

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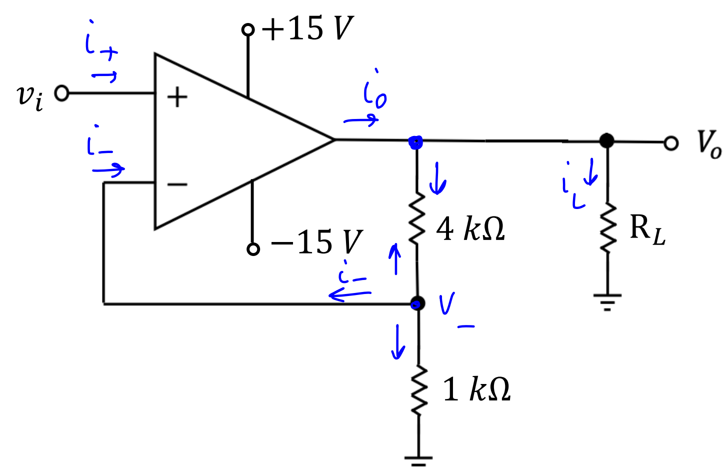
We can find the maximum output voltage using the same KCL and $i_{o_{max}}$.



KCL at the output node:

$$i_{o_{max}} = \frac{V_{o_{max}}}{R_L} + \frac{V_{o_{max}}}{4k\Omega + 1k\Omega} \longrightarrow 20\ mA = V_{o\,max}\left(\frac{1}{0.5\,k\Omega} + \frac{1}{5\,k\Omega}\right)$$

$$\longrightarrow V_{o\,max} = 9.09\ V$$

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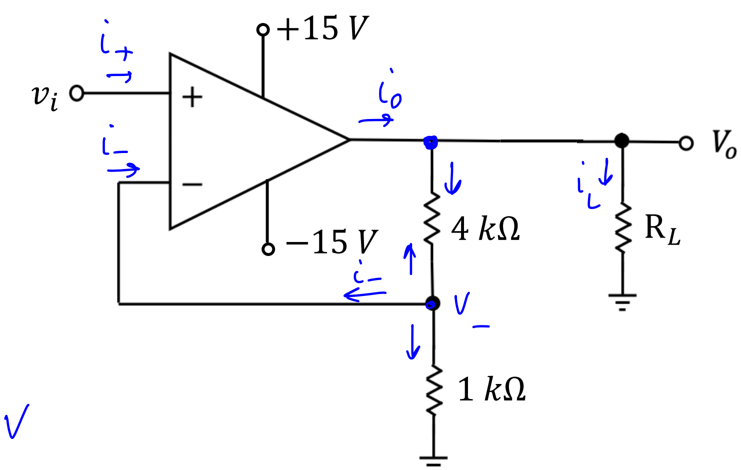
$V_{o_{max}} = 9.09\ V$

To get an undistorted signal:

$V_o = 5 V_i \Longrightarrow V_{i_{max}} = V_p = \frac{9.09}{5} = 1.82\ V$

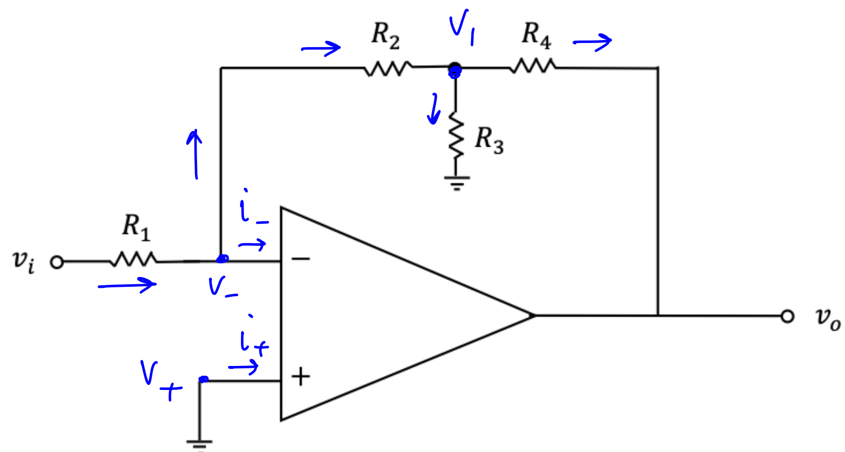


Discussion question 1.

What is v_o/v_i in this op-amp circuit? Assume an ideal op-amp.

ideal op-amp : $i_+ = i_- = 0$

negative feedback: $V_+ = V_-$



KCL at the inverting terminal:

$$\begin{cases} \dfrac{V_i - V_-}{R_1} = \dfrac{V_- - V_1}{R_2} \\ V_- = V_+ = 0 \end{cases} \Rightarrow \frac{V_i}{R_1} = \frac{-V_1}{R_2} \Rightarrow V_1 = \frac{-R_2}{R_1} V_i$$

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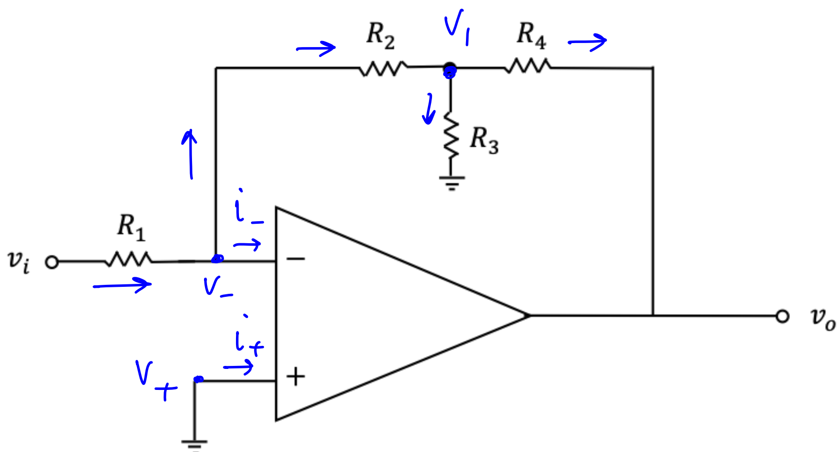


KCL at node V_1 :

$$\frac{\overset{0}{V_-} - V_1}{R_2} = \frac{V_1}{R_3} + \frac{V_1 - V_0}{R_4} \Rightarrow \frac{V_0}{R_4} = \left(\frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}\right) V_1$$

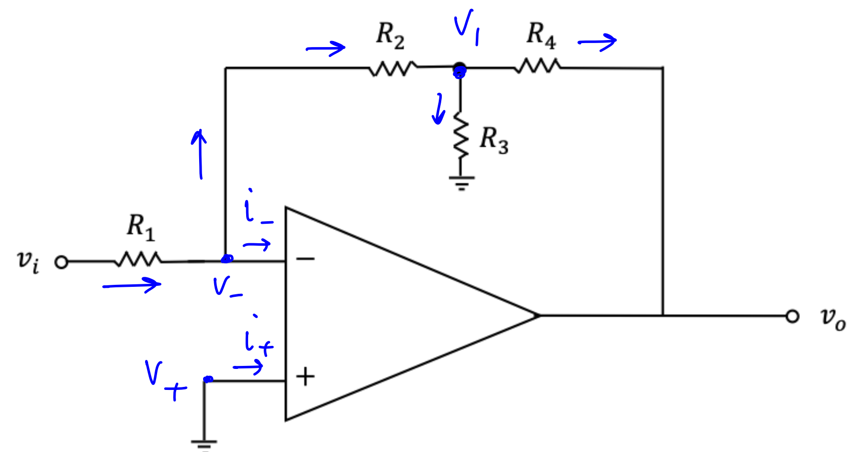
$$V_0 = \left(1 + \frac{R_4}{R_2} + \frac{R_4}{R_3}\right) V_1$$

Discussion question 1.

What is v_o/v_i in this op-amp circuit? Assume an ideal op-amp.

$$\begin{cases} V_0 = \left(1 + \dfrac{R_4}{R_2} + \dfrac{R_4}{R_3}\right) V_1 \\[2ex] V_1 = \dfrac{-R_2}{R_1} V_i \end{cases}$$

$$\Rightarrow V_0 = \frac{-R_2}{R_1}\left(1 + \frac{R_4}{R_2} + \frac{R_4}{R_3}\right) V_i$$



Discussion question 2.

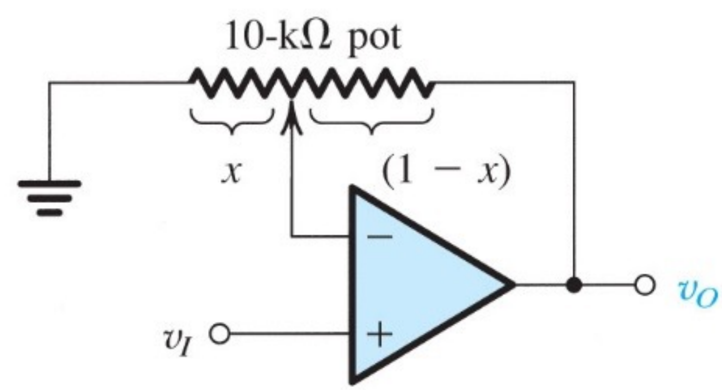
The following circuit uses a $10\ k\Omega$ potentiometer to obtain an adjustable gain amplifier.

a) Derive an expression for the gain as a function of the potentiometer setting x.

b) What is the range of the gain obtained?

c) Show how to add a fixed resistor so that the gain range can be 1 to 11 V/V. What is the value of that resistor?

Assume an ideal op-amp.



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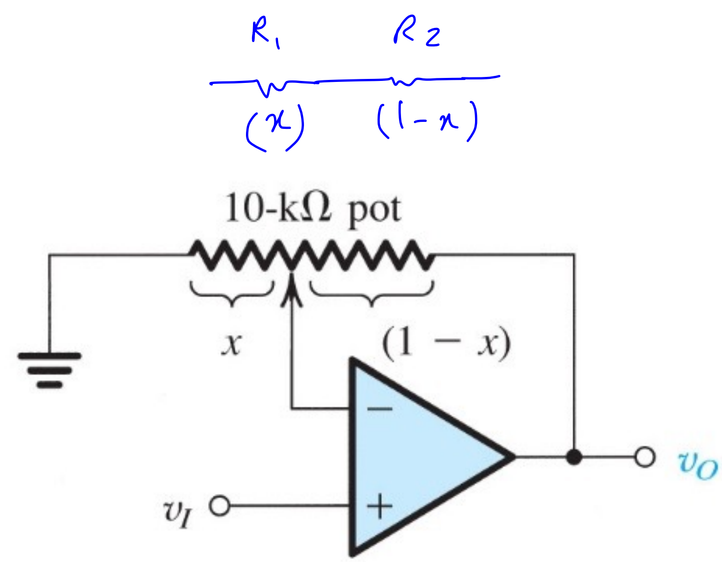


$R_1 = x \times 10\ k\Omega$

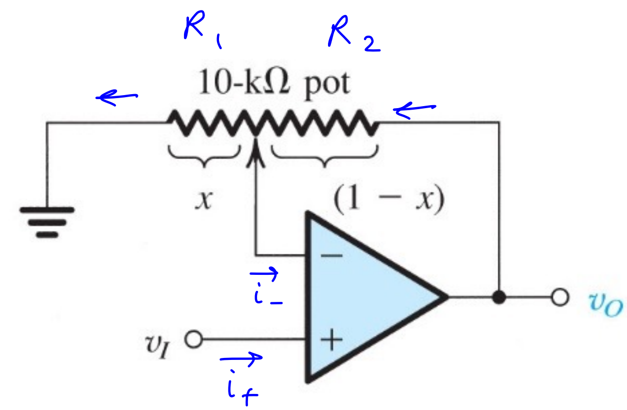
$R_2 = (1-x) \times 10\ k\Omega$

$R_1 + R_2 = 10\ k\Omega$

Discussion question 2.

a) Derive an expression for the gain as a function of the potentiometer setting x.

Assume an ideal op-amp.



$\begin{cases} \text{ideal op-amp : } i_+ = i_- = 0 \\ \text{negative feedback: } V_+ = V_- \end{cases}$

$V_+ = V_I \longrightarrow V_- = V_+ = V_I$

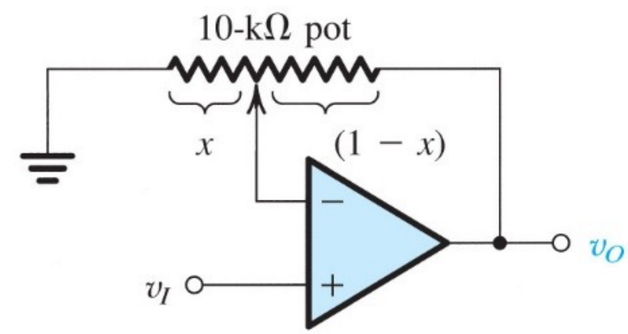
KCL at the inverting terminal: $\dfrac{V_-}{R_1} = \dfrac{V_o - V_-}{R_2} \longrightarrow \dfrac{V_I}{R_1} = \dfrac{V_o - V_I}{R_2}$

$\Rightarrow V_o = \left(1 + \dfrac{R_2}{R_1}\right) V_I$

$R_1 = 10x$ and $R_2 = 10(1-x)$ $\Rightarrow V_o = \left(1 + \dfrac{1-x}{x}\right) V_I = \dfrac{V_I}{x}$

Discussion question 2.

a) What is the range of the gain obtained?
Assume an ideal op-amp.



Voltage gain $= \dfrac{V_o}{V_i} = \dfrac{1}{x}$

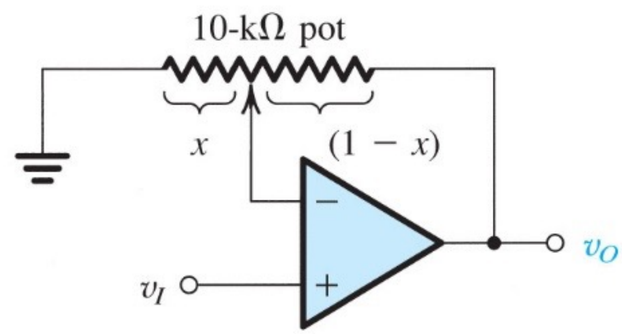
$0 \leq x \leq 1 \;\rightarrow\; 1 \leq$ Voltage gain $< \infty$

not achievable

V_{out} will not exceed V_{sat}

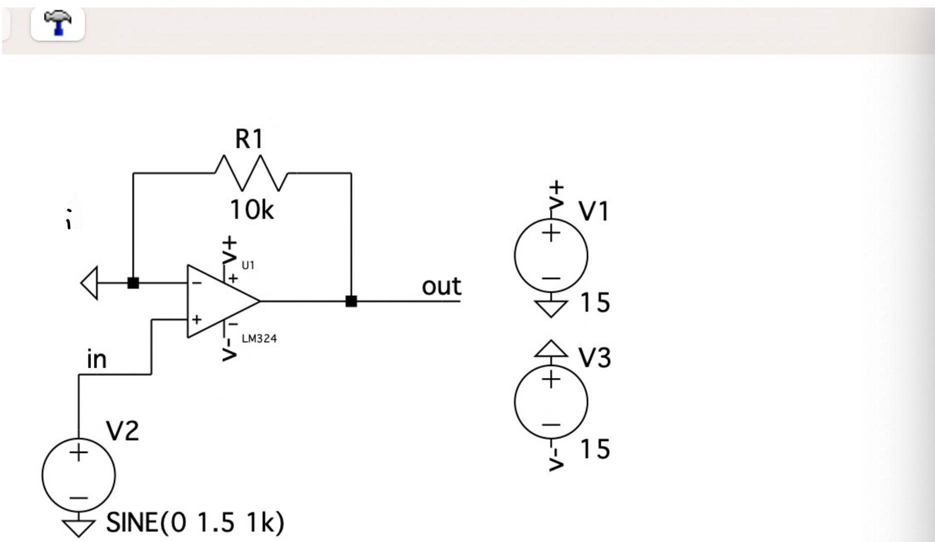
Discussion question 2.

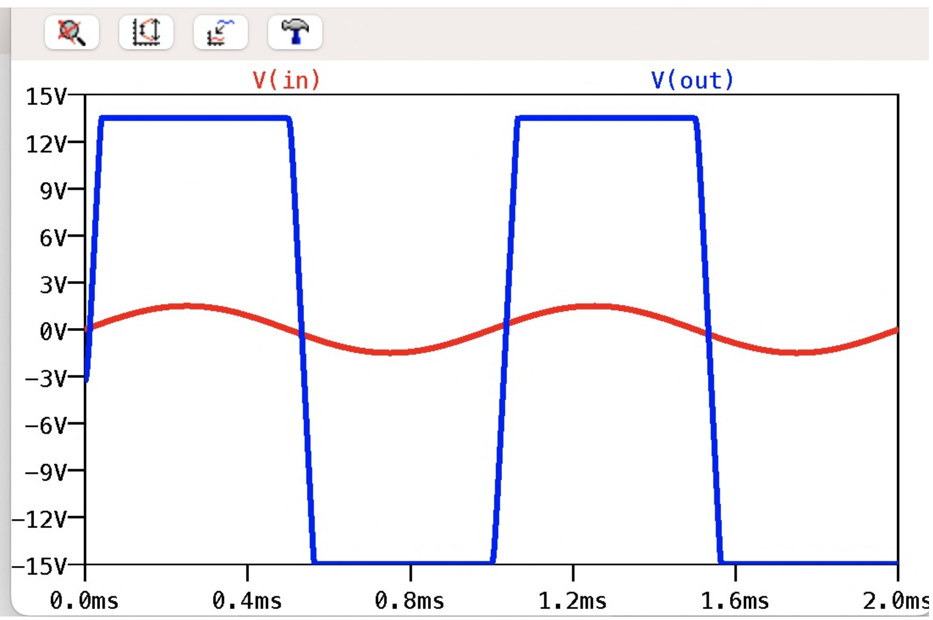
a) What is the range of the gain obtained? Assume an ideal op-amp.



$V_o = A(V_+ - V_-) = A V_+ = A V_{in}$

output will quickly go to V_{sat}^+ when V_i is positive and will quickly go to V_{sat}^- when V_i is negative.





Discussion question 2.

a) Show how to add a fixed resistor so that the gain range can be 1 to 11 V/V. What is the value of that resistor?

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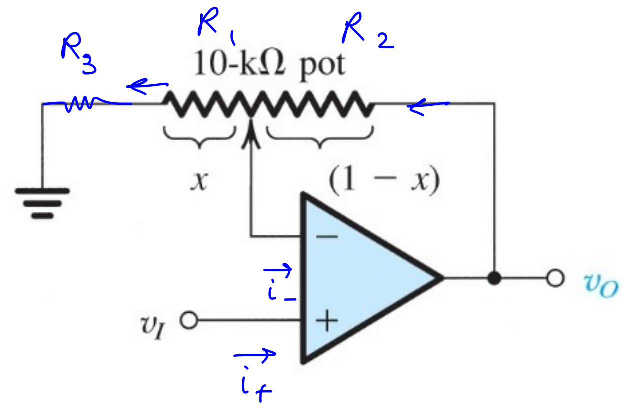

ideal op-amp : $i_+ = i_- = 0$

negative feedback: $V_+ = V_-$

$V_+ = V_I \longrightarrow V_- = V_+ = V_I$

KCL at the inverting terminal: $\dfrac{V_-}{R_1 + R_3} = \dfrac{V_0 - V_-}{R_2}$

$$\Rightarrow V_0 = \left(1 + \frac{R_2}{R_1 + R_3}\right) V_I$$

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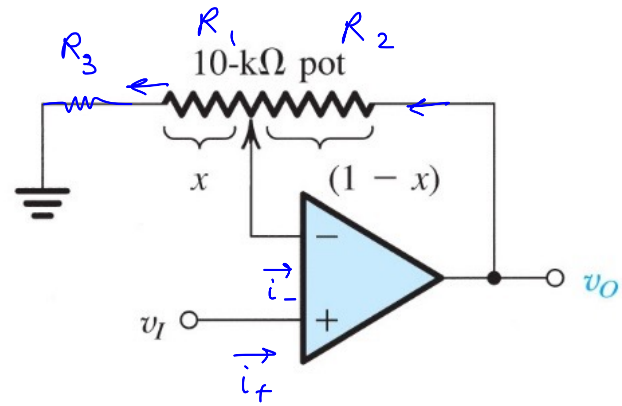

$$V_o = \left(1 + \frac{R_2}{R_1 + R_3}\right) V_I$$

$R_1 = 10x$ and $R_2 = 10(1-x)$

$$V_o = \left(1 + \frac{10(1-x)}{10x + R_3}\right) V_I = \left(1 + \frac{1-x}{x + \frac{R_3}{10}}\right) V_I$$

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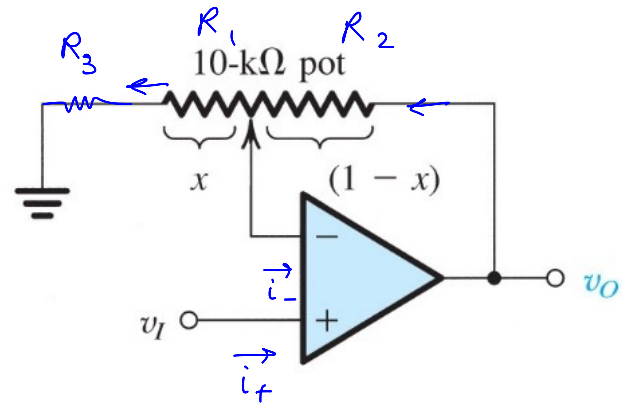

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$R_1 = 10x$ and $R_2 = 10(1-x)$

$$V_o = \left(1 + \frac{10(1-x)}{10x + R_3}\right) V_I = \left(1 + \frac{1-x}{x + \frac{R_3}{10}}\right) V_I$$

$0 \leqslant x \leqslant 1$, to have $\frac{V_o}{V_I} = 11$ V/V $\longrightarrow$ $x = 0$ and $1 + \frac{1}{\frac{R_3}{10}} = 11$

$$\Longrightarrow \boxed{R_3 = 1\ k\Omega}$$