ECE 65: Components & Circuits Lab

Lecture 2

Operational Amplifier (op-amp)

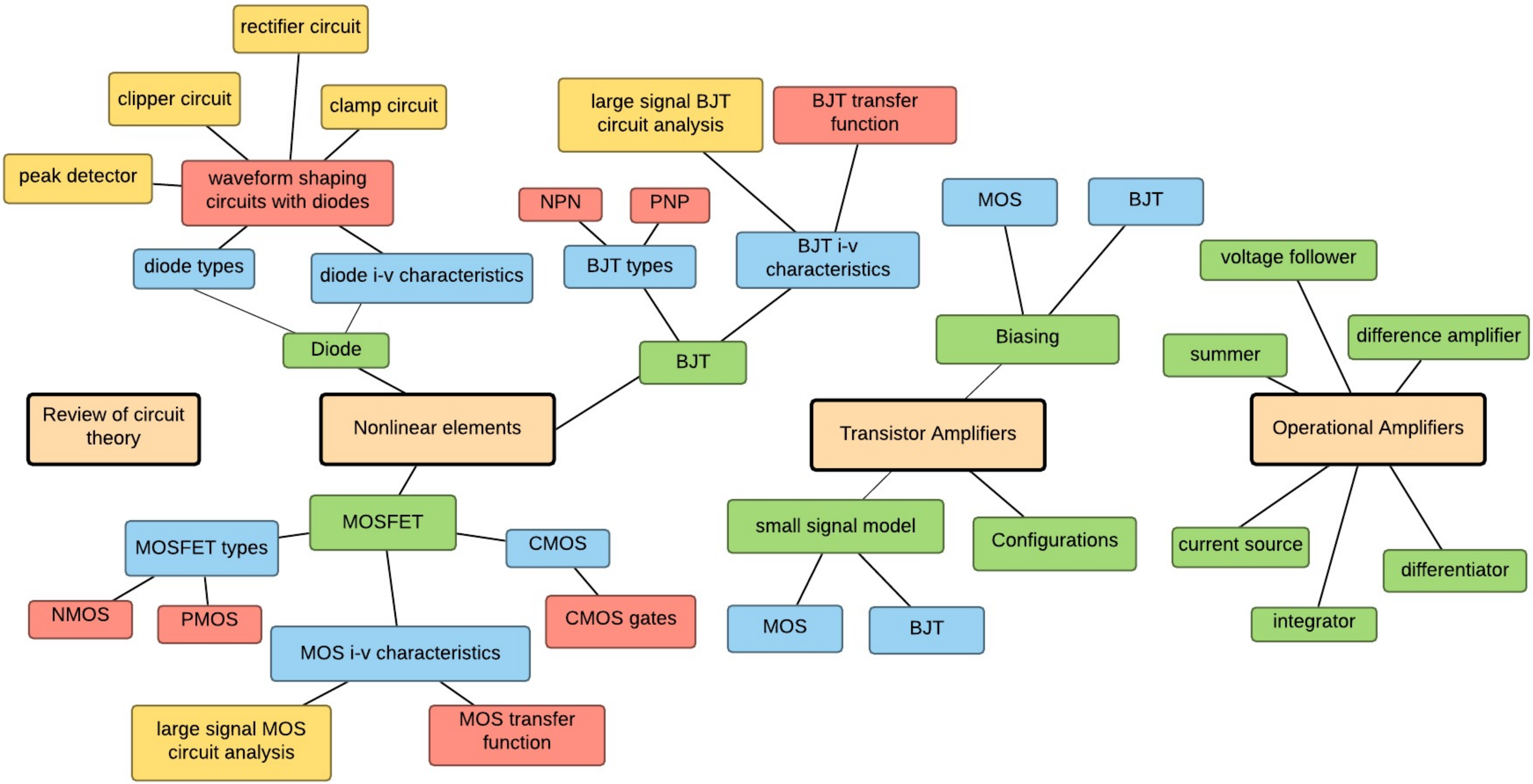
Reference notes: sections 7.1, 7.2

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

Saharnaz Baghdadchi

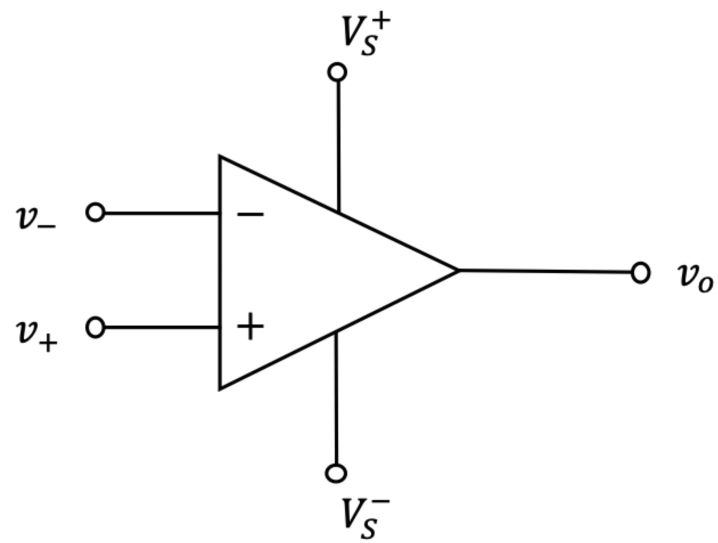
Course map

7. Operational amplifiers



Operational Amplifiers

Operational amplifiers (op-amps) are general purpose voltage amplifiers.



They are constructed such that they amplify the voltage difference between the two input signals.

$$v_o = A(v_+ - v_-) = Av_d$$

open-loop voltage gain

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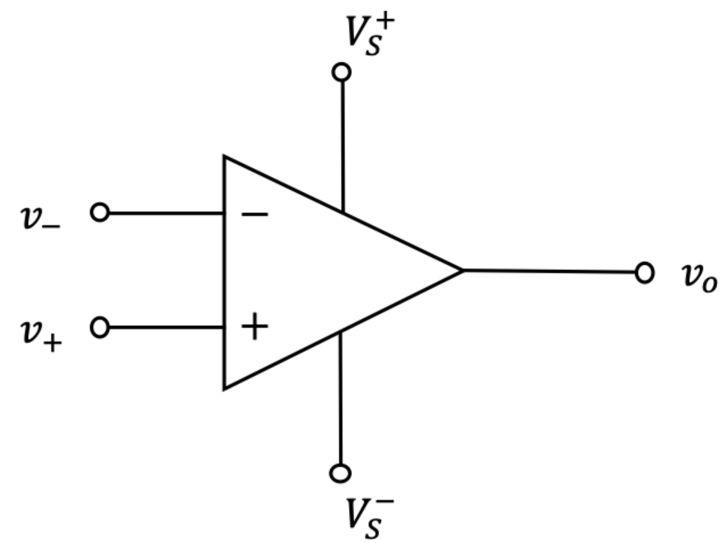

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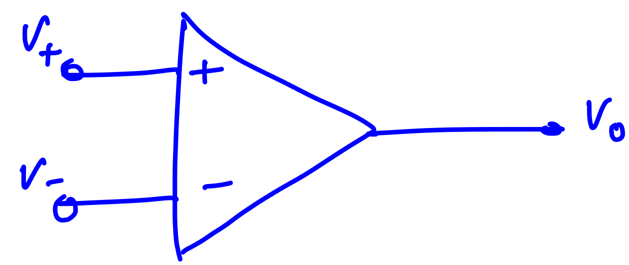

The $-$ and $+$ terminals are called the inverting and non-inverting terminals, respectively.

Operational Amplifiers

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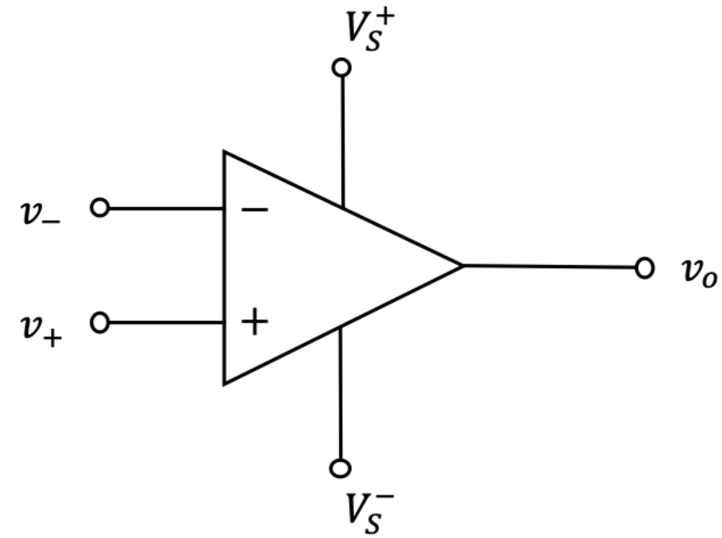
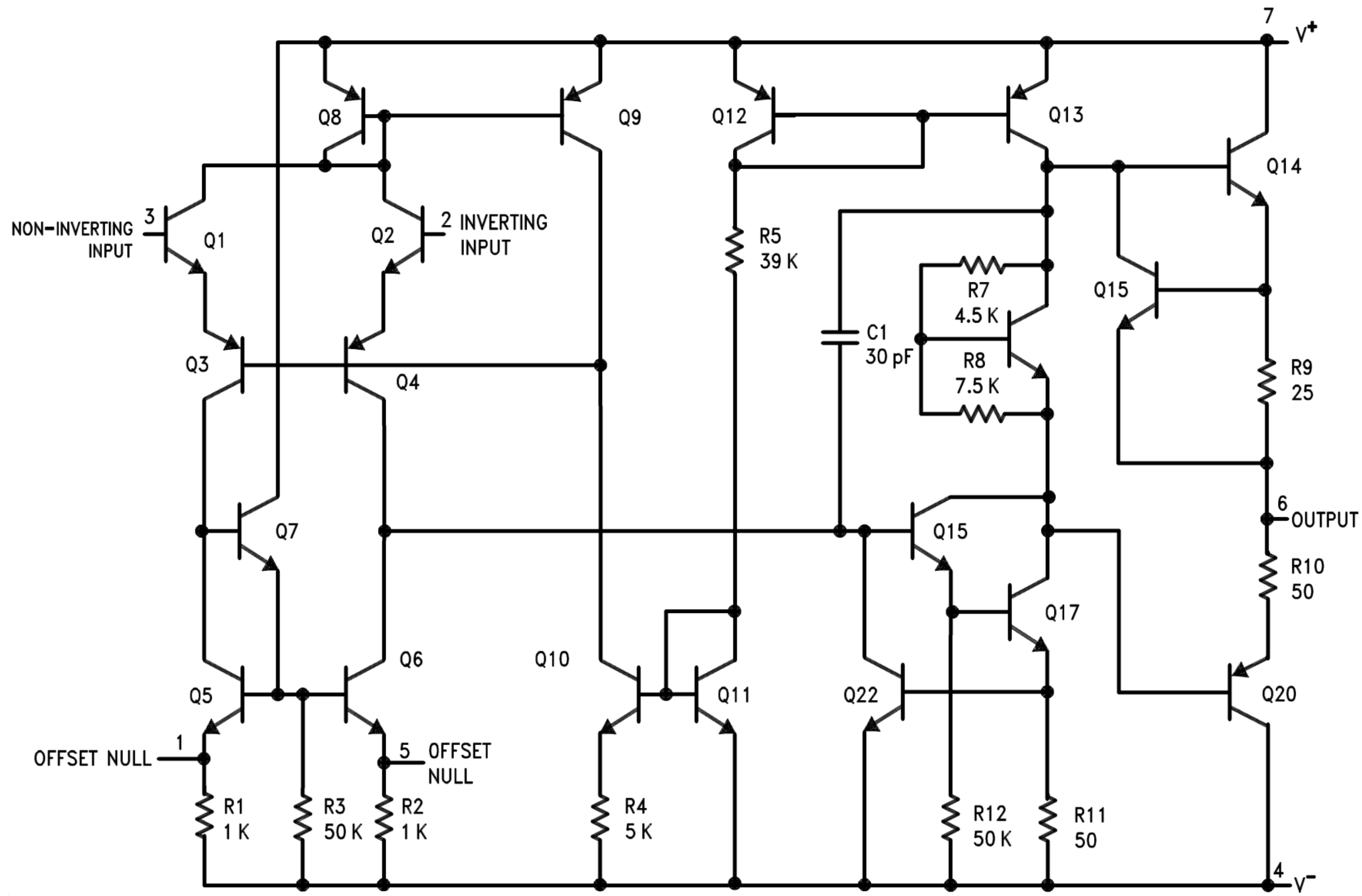


They are constructed such that they amplify the voltage difference between the two input signals.

$$v_o = A(v_+ - v_-) = Av_d$$

They have a very large gain. Typically, $\mathrm{A} \sim 10^5$ to 10^7.

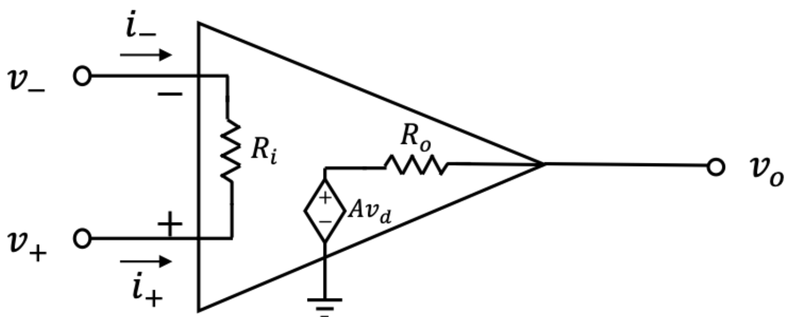
LM 741 op-amp



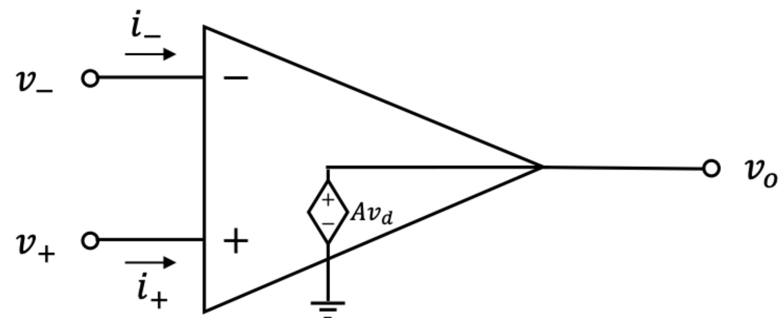
LM 741 op-amp (ti.com)

OpAmp models

Linear model



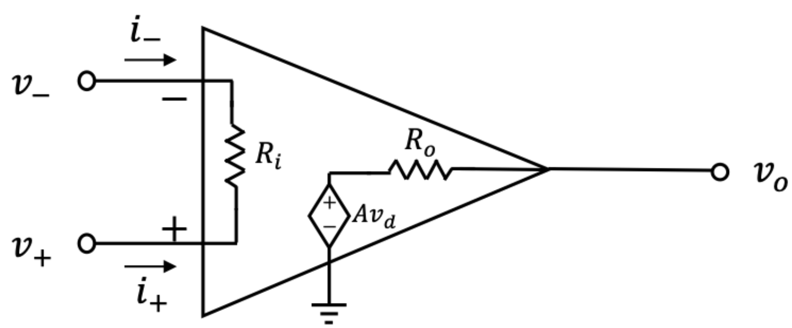
Ideal model



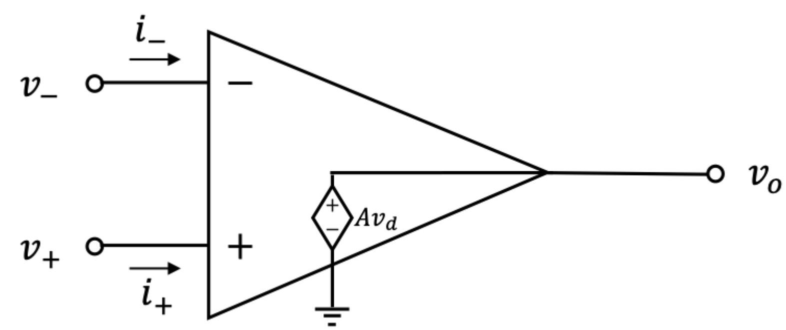
In op-amps, the input resistance, R_i , is very large, and the output resistance, R_o , is very small.

OpAmp models

Linear model



Ideal model

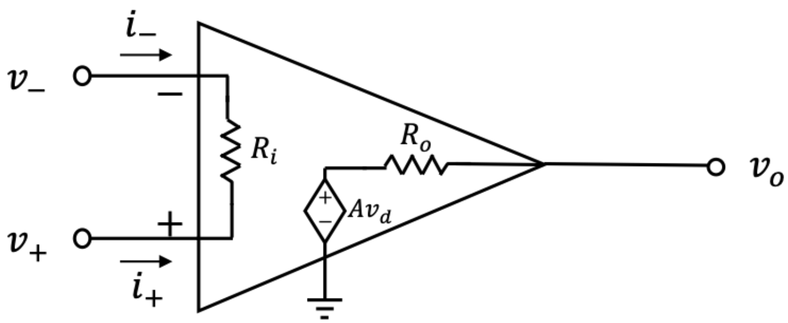


Because the input impedance of the op-amps is very large, the input current to the op-amp is very small.

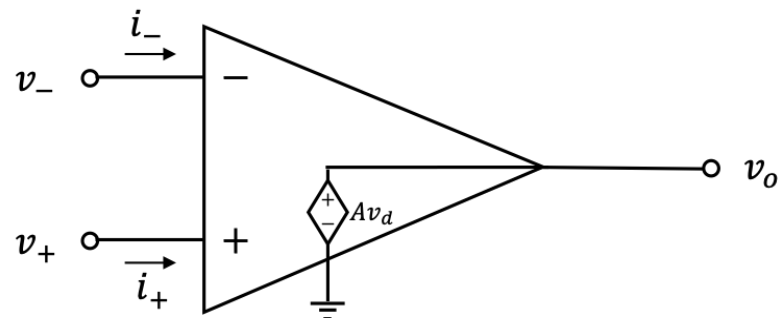
$$i_- \approx i_+ \approx 0$$

OpAmp models

Linear model



Ideal model

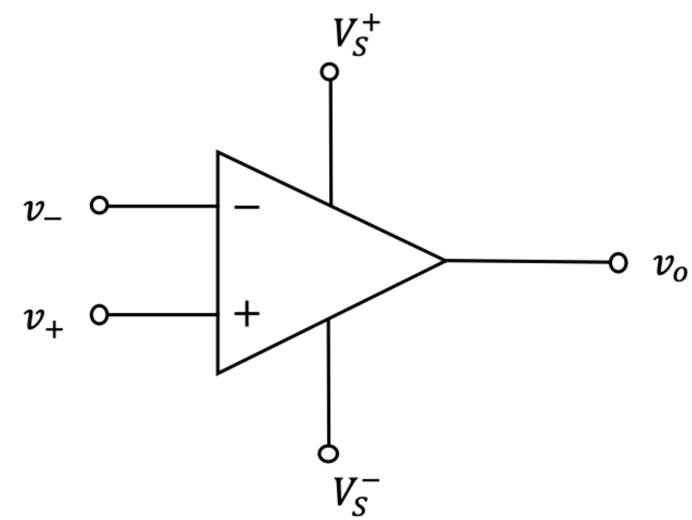


In the **ideal op-amp model**, $R_i = \infty$, $R_o = 0$, $i_- = i_+ = 0$

Output voltage and power supplies

The output voltage of an op-amp is limited by the power supplies used to power up the op-amp chip.

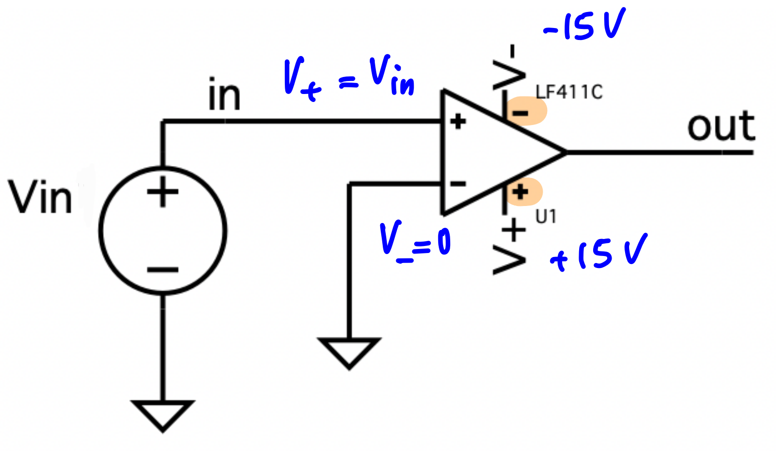
$$V_{S^-} < V_o < V_{S^+}$$

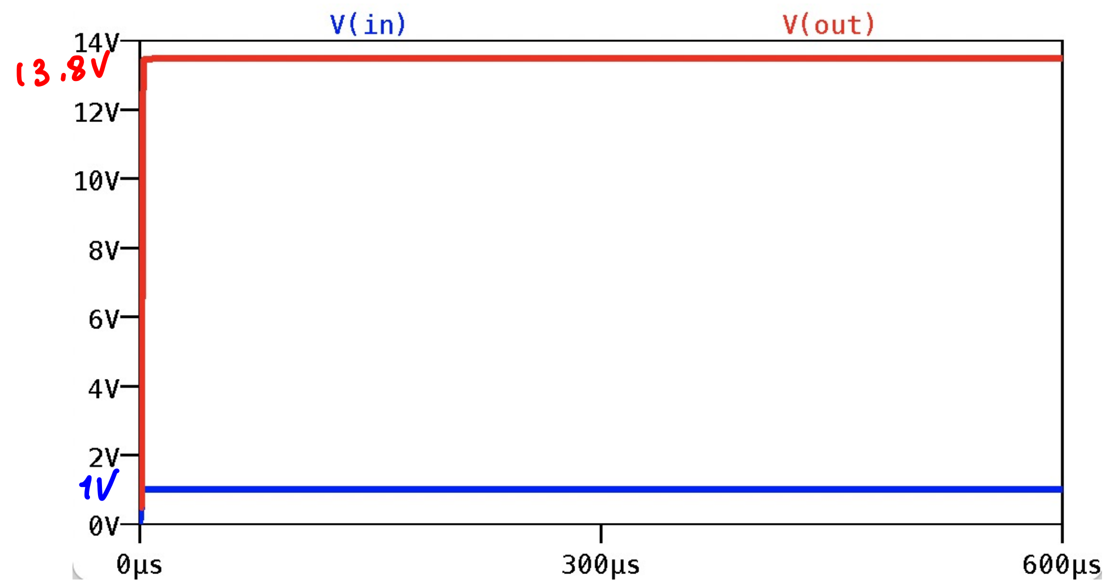


Open-loop operation of op-amps (no feedback)

$A = 10^5$

$V_o = A(V_+ - V_-) = 10^5 (V_{in} - 0) = 10^5 \times V_{in}$





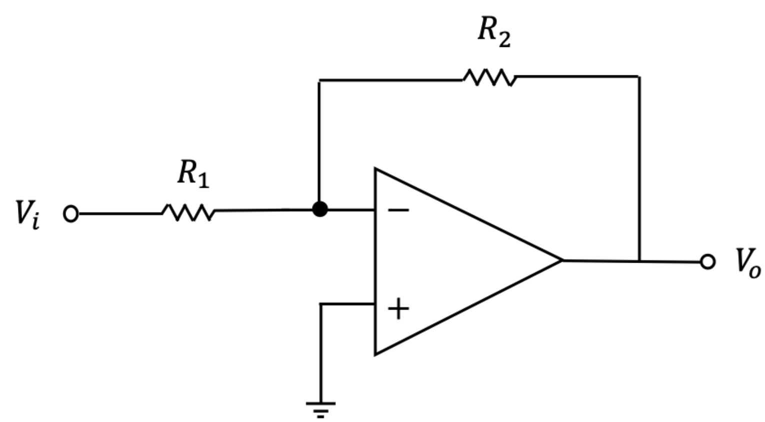
$V_{omax} = 13.8\,V$, here.

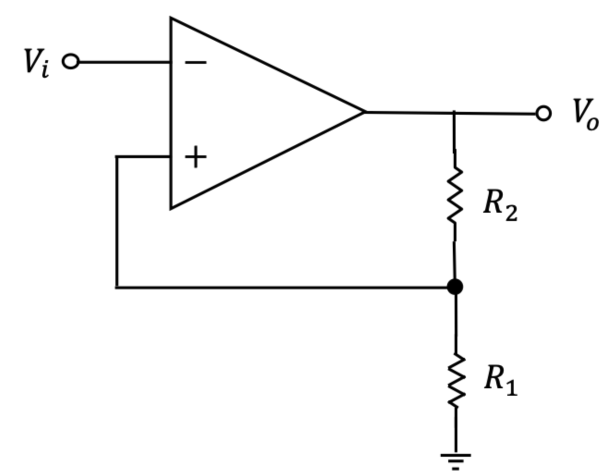
$V_o = 10^5 V_{in} \longrightarrow V_{in\,max} = \frac{V_{omax}}{10^5} = \frac{13.8V}{10^5} = 13.8\,V \times 10^{-5} = 138 \times 10^{-6}\,V = 138\,\mu V$

In open-loop configuration, op-amp cannot amplify input voltages greater than a few micro volts. It cannot be used as a voltage amplifier.

Feedback:
the concept, negative and positive feedback

- In circuits with feedback, a portion of the output signal is fed back to the circuit input.





- There are two types of feedback: Negative and Positive

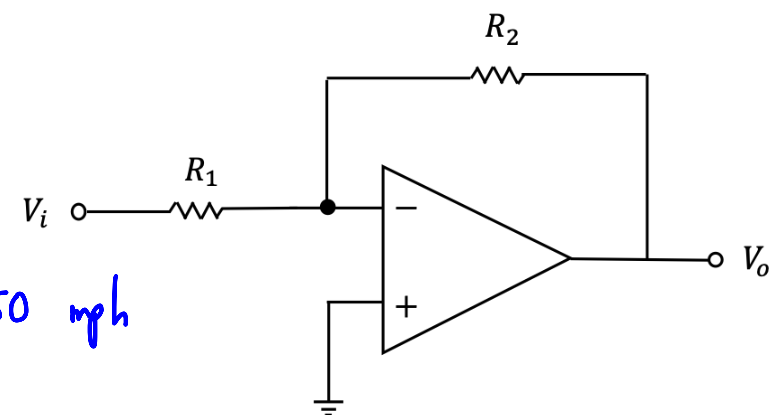
Feedback:
the concept, negative and positive feedback

Negative feedback: In circuits with negative feedback, as the output increases, the input will decrease, and vice versa, such that the output signal would reach the desired stable level.

desired output : speed of 50 mph

if output $\nearrow$ 55 mph

input $\swarrow$ $\Longrightarrow$ output $\swarrow$ $\longrightarrow$ output : 50 mph



if output $\swarrow$ 45 mph

input $\nearrow$ $\Longrightarrow$ output $\nearrow$ $\longrightarrow$ output : 50 mph

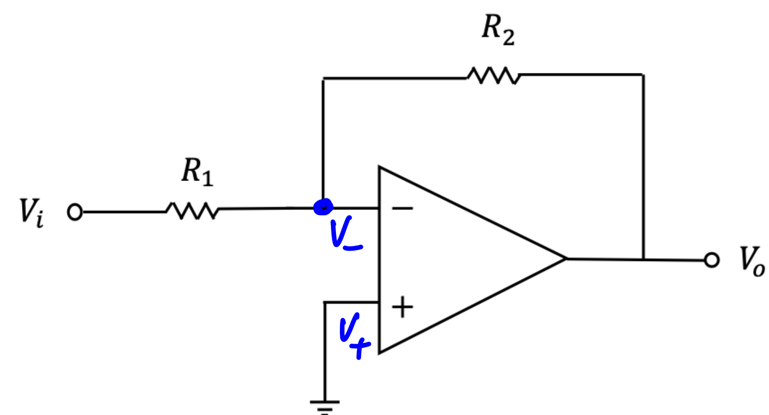
Feedback:
the concept, negative and positive feedback

Negative feedback: In circuits with negative feedback, as the output increases, the input will decrease, and vice versa, such that the output signal would reach the desired stable level.

$$V_o = A\,V_d$$

$$V_d = V_+ - V_-$$

$$V_- = \frac{R_2}{R_1+R_2} V_i + \frac{R_1}{R_1+R_2} V_o$$

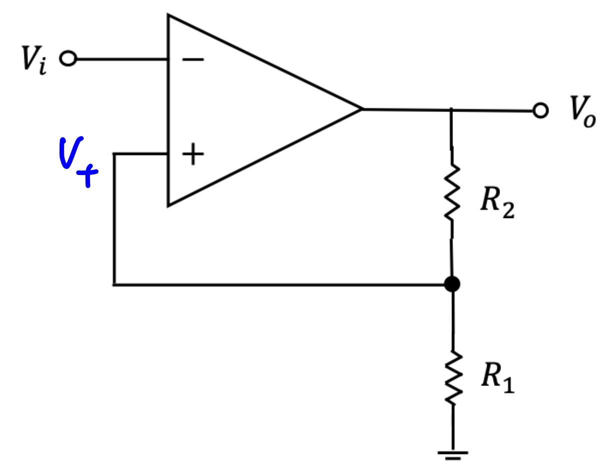


Feedback:
the concept, negative and positive feedback

Positive feedback: In circuits with positive feedback, when the output increases, the input will also increase, and vice versa. The output of circuits with positive feedback is always at its limits.

$$V_+ = \frac{R_1}{R_1+R_2} V_o$$

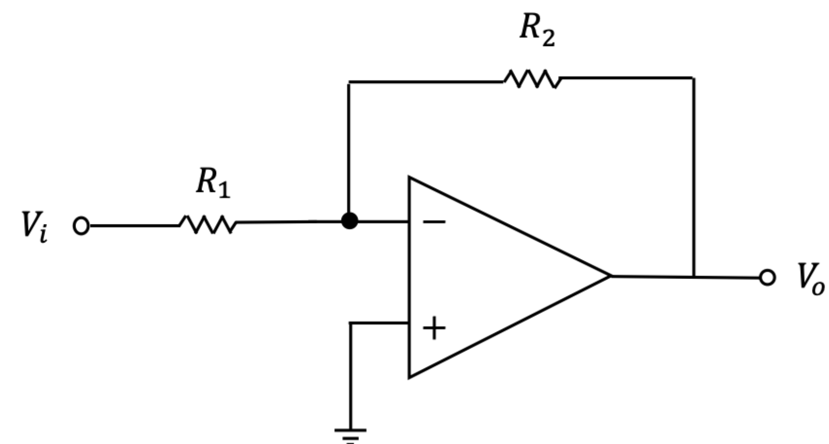
$$V_o = A(V_+ - V_-) = A(V_+ - V_i)$$



Solving op-amp circuits – example 1

Comprehensive solution

Find $\frac{v_o}{v_i}$ in the following op-amp circuit assuming an ideal op-amp.



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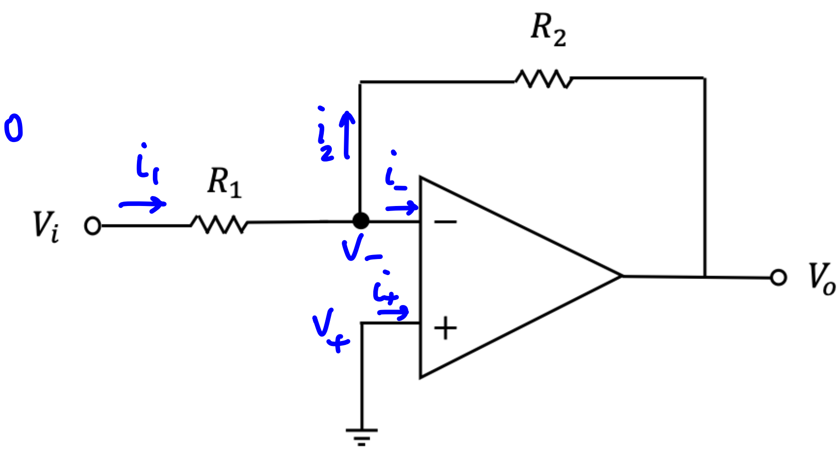


assume an ideal op-amp: $i_+ = i_- = 0$

$V_+ = 0$

$V_o = A(V_+ - V_-) \longrightarrow V_o = -AV_-$

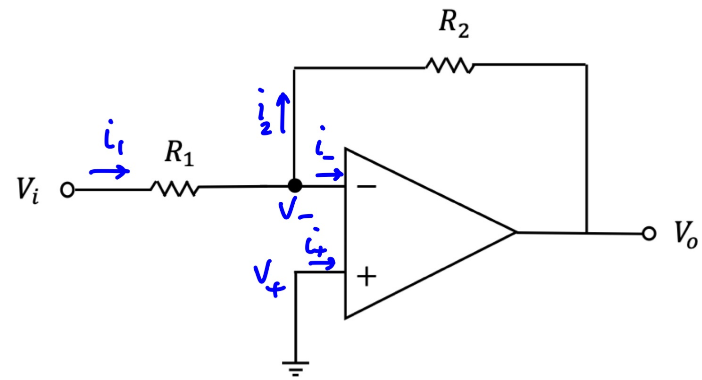
KCL at the inverting input node:

$i_1 = i_2 + i_-$, $i_- = 0 \longrightarrow i_1 = i_2$

$i_1 = \dfrac{V_i - V_-}{R_1}$, $i_2 = \dfrac{V_- - V_o}{R_2}$

Solving op-amp circuits – example 1

Comprehensive solution



$$i_1 = \frac{V_i - V_-}{R_1}, \quad i_2 = \frac{V_- - V_o}{R_2}$$

$$i_1 = i_2 \longrightarrow \frac{V_i - V_-}{R_1} = \frac{V_- - V_o}{R_2}$$

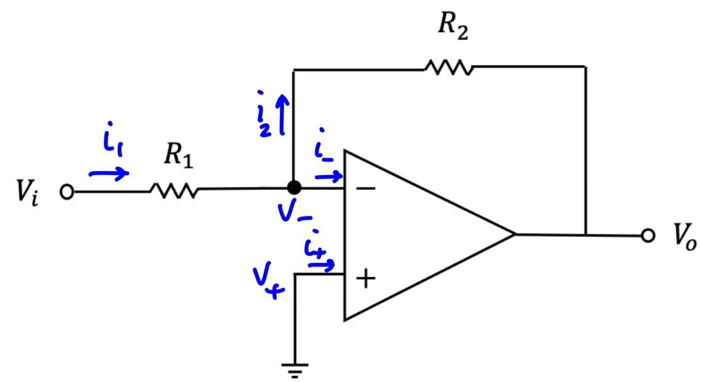
$$\left(\frac{-1}{R_1} - \frac{1}{R_2}\right) V_- = \frac{-1}{R_1} V_i - \frac{1}{R_2} V_o$$

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

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

Solving op-amp circuits – example 1

Comprehensive solution



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

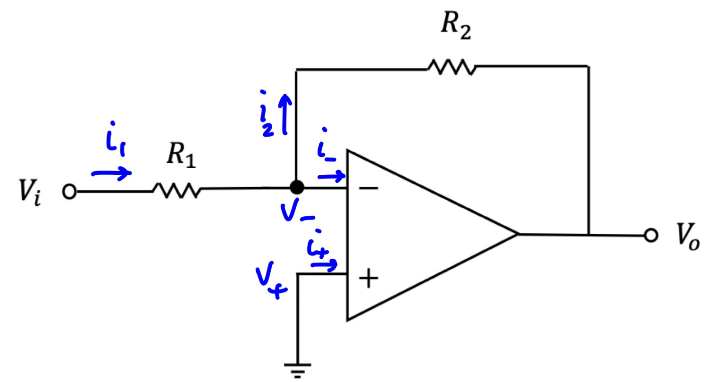
$$V_- = \frac{R_1 R_2}{R_1+R_2}\left(\frac{1}{R_1} V_i + \frac{1}{R_2} V_0\right)$$

$$\boxed{V_- = \left(\frac{R_2}{R_1+R_2}\right) V_i + \left(\frac{R_1}{R_1+R_2}\right) V_0}$$

Solving op-amp circuits – example 1

Comprehensive solution

$$\boxed{V_- = \left(\frac{R_2}{R_1+R_2}\right) V_i + \left(\frac{R_1}{R_1+R_2}\right) V_0}$$



$$\boxed{V_0 = -A V_-}$$

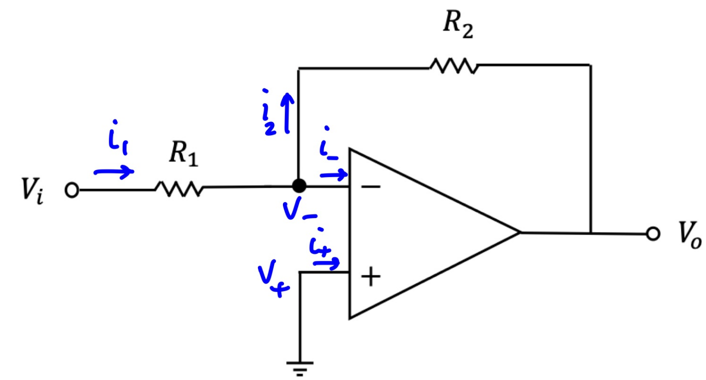
$$V_0 = -A\left[\left(\frac{R_2}{R_1+R_2}\right) V_i + \left(\frac{R_1}{R_1+R_2}\right) V_0\right]$$

$$V_0 + \left(\frac{A R_1}{R_1+R_2}\right) V_0 = -\left(A \frac{R_2}{R_1+R_2}\right) V_i$$

$$\left[1 + \left(\frac{A R_1}{R_1+R_2}\right)\right] V_0 = -\left(A \frac{R_2}{R_1+R_2}\right) V_i$$

Solving op-amp circuits – example 1

Comprehensive solution



$$\left[1+\left(\frac{A R_1}{R_1+R_2}\right)\right] V_0 = -\left(A \frac{R_2}{R_1+R_2}\right) V_i$$

define $B = \dfrac{R_1}{R_1+R_2}$

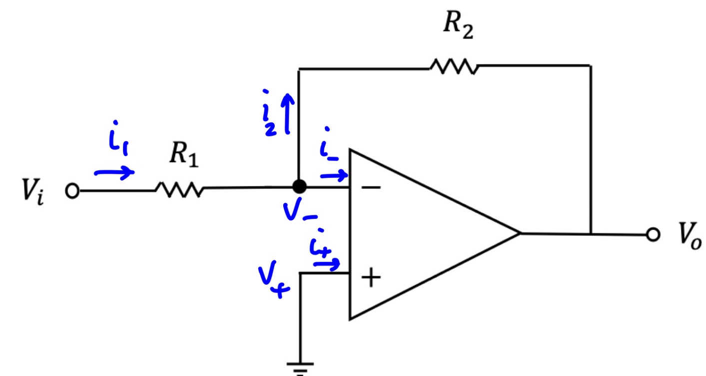
$$\rightarrow \frac{R_2}{R_1+R_2} = \frac{R_2}{R_1} \times \frac{R_1}{R_1+R_2} = \frac{R_2}{R_1} \times B$$

$$(1 + AB)\, V_0 = -\frac{R_2}{R_1} AB\, V_i$$

Solving op-amp circuits – example 1

Comprehensive solution

$$B = \frac{R_1}{R_1 + R_2}$$



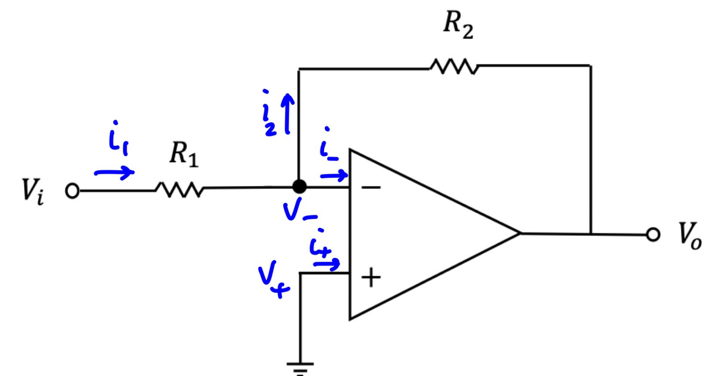
$$\frac{1}{AB} \times \left(1 + AB\right) V_o = \frac{1}{AB} \times -\frac{R_2}{R_1} AB \; V_i$$

$$\left(\frac{1}{AB} + 1\right) V_o = -\frac{R_2}{R_1} V_i$$

$$\frac{V_o}{V_i} = -\frac{R_2}{R_1} \cdot \frac{1}{1 + \frac{1}{AB}}$$

Solving op-amp circuits – example 1

Comprehensive solution



$$\frac{V_o}{V_i} = -\frac{R_2}{R_1} \cdot \frac{1}{1 + \frac{1}{A\beta}}$$

$$\beta = \frac{R_1}{R_1 + R_2}$$

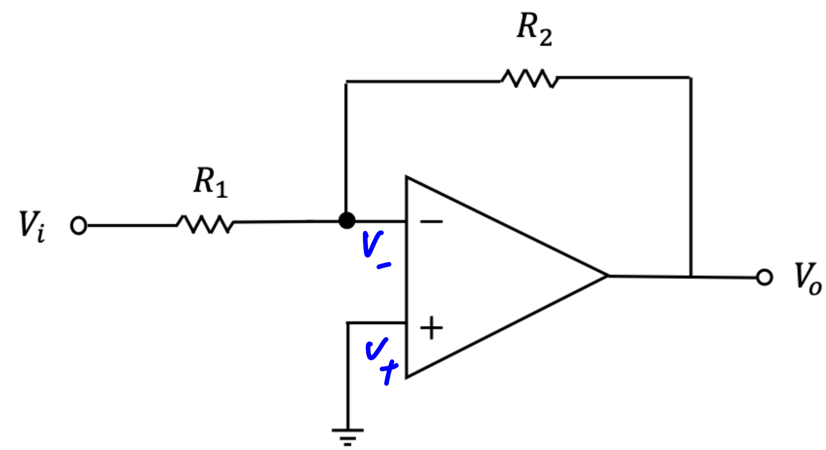
Example numbers : $R_1 = 1k\Omega$, $R_2 = 9\ k\Omega$, $A = 10^5$

$$\beta = \frac{1k\Omega}{1k\Omega + 9\ k\Omega} = 0.1$$

$$\frac{V_o}{V_i} = -\frac{9k\Omega}{1k\Omega} \times \frac{1}{1 + \frac{1}{10^5 \times 0.1}} = -9 \times \frac{1}{\underbrace{1 + 10^{-4}}_{\simeq 1}} \simeq -9\ \frac{V}{V}$$

virtual short principle in op-amp circuits with negative feedback

$v_o \approx$ a finite value



$$v_o = A v_d \longrightarrow v_d = \frac{v_o}{A} \approx 0$$

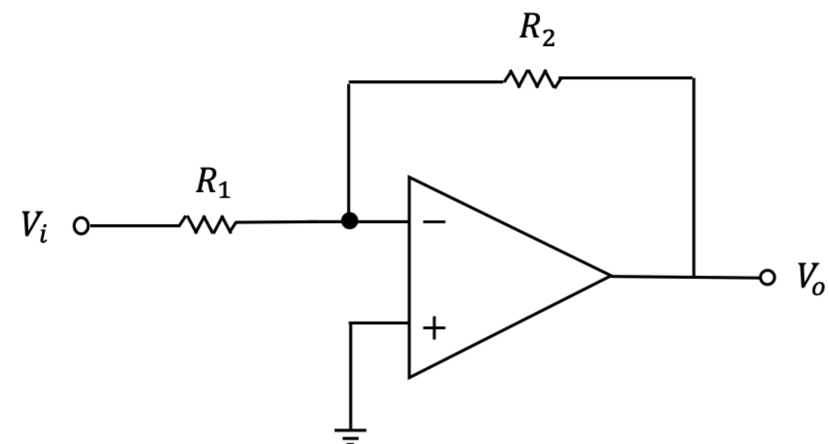
$$\Rightarrow v_+ \approx v_-$$

In op-amps with negative feedback and large open-loop gain, the op-amp adjusts its output voltage such that $v_d \approx 0$.

Solving op-amp circuits – example 1

Approximate solution

Find $\frac{v_o}{v_i}$ in the following op-amp circuit assuming an ideal op-amp.



Solving op-amp circuits – example 1

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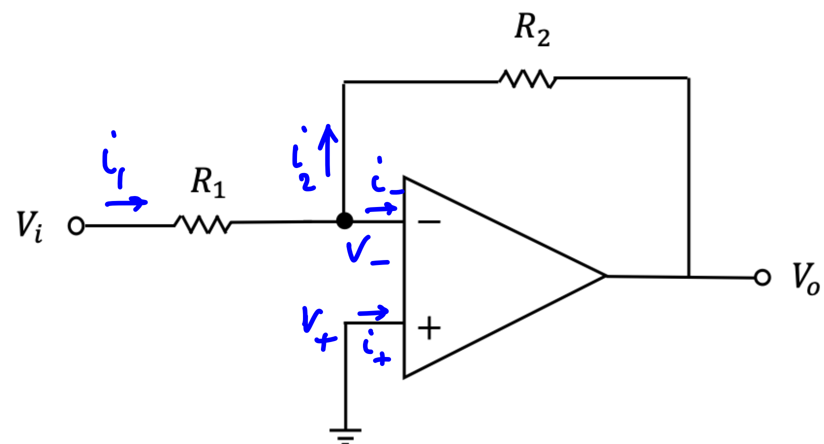


ideal op-amp : $i_+ = i_- = 0$

There is negative feed back : $v_+ \approx v_-$

$v_+ = 0 \longrightarrow v_- = 0$

KCL at the inverting terminal : $i_1 = i_2 + i_- = i_2$

$i_1 = i_2 \Longrightarrow \frac{v_i - v_-}{R_1} = \frac{v_- - v_o}{R_2}$;

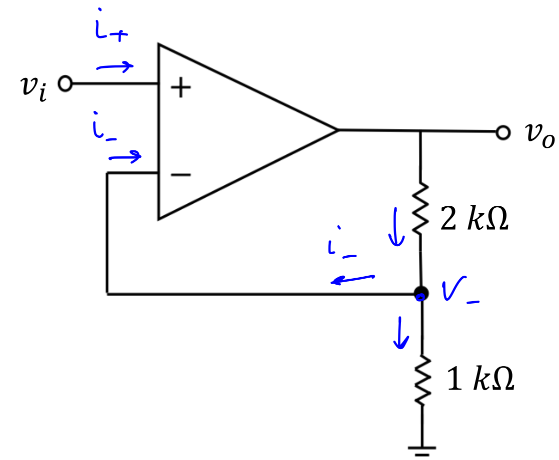
$v_- = 0 \longrightarrow \frac{v_i - 0}{R_1} = \frac{0 - v_o}{R_2} \Longrightarrow \frac{v_o}{v_i} = \frac{-R_2}{R_1}$

Lecture 2 reading quiz.

In the following amplifier circuit, the input signal is $v_i(t) = 1.5\sin(2\pi \times 10^3 t)\ V$. Which one of the options could be the output signal, $v_o(t)$?

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

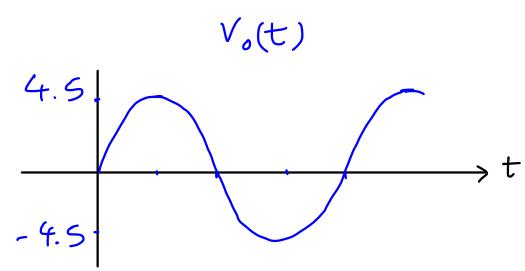
negative feedback : $V_+ = V_-$



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

KCL : $\dfrac{V_-}{1k} + i_- = \dfrac{V_o - V_-}{2k} \longrightarrow \dfrac{V_-}{1k\Omega} = \dfrac{V_o - V_-}{2k}$

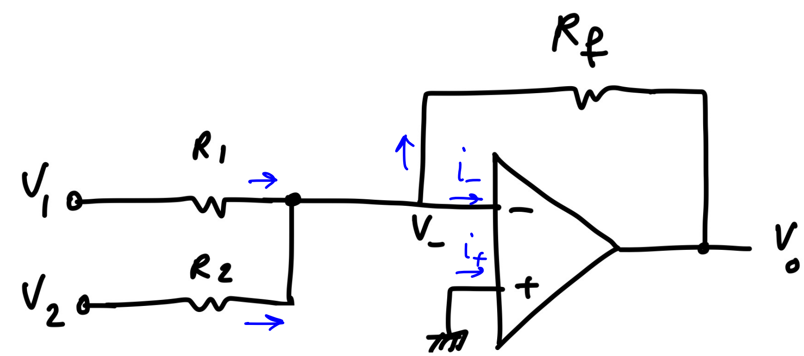
$\rightarrow V_o = 2\left(1 + \frac{1}{2}\right)V_- = 3\ V_- \longrightarrow V_o = 3\ V_i$



Discussion question 1. (weighted summer)

Design the following op-amp circuit to achieve the weighted sum of input 1 and input 2 at the output. It is required that $v_o = -(v_1 + 5v_2)$.

Assume an ideal op-amp.



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

negative feedback: $V_+ = V_-$

KCL at the inverting input terminal: $\frac{V_1 - V_-}{R_1} + \frac{V_2 - V_-}{R_2} = \frac{V_- - V_o}{R_f} + i_-$

$V_- = V_+ = 0 \longrightarrow \frac{V_1 - 0}{R_1} + \frac{V_2 - 0}{R_2} = \frac{0 - V_o}{R_f} \Longrightarrow V_o = \left(\frac{-R_f}{R_1}\right) V_1 + \left(\frac{-R_f}{R_2}\right) V_2$

$V_o = -V_1 - 5V_2 \Longrightarrow \frac{R_f}{R_1} = 1$ and $\frac{R_f}{R_2} = 5$, we can choose $R_f = 5\,k\Omega$, $R_1 = 5\,k\Omega$, $R_2 = 1\,k\Omega$

ECE 65: Components & Circuits Lab

Lecture 3

Operational Amplifier limitations

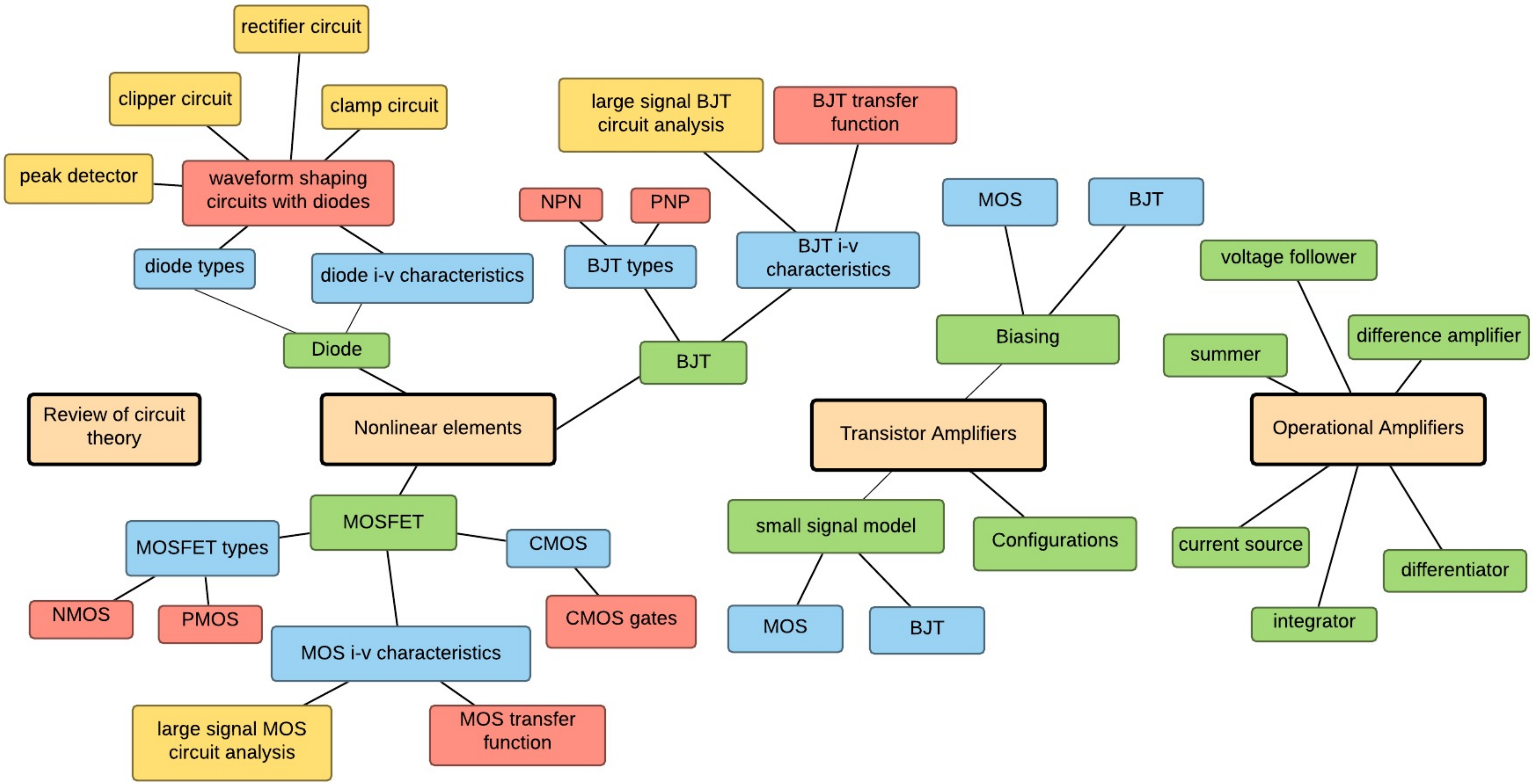
Reference notes: sections 7.5

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

Saharnaz Baghdadchi

Course map

7. Operational amplifiers

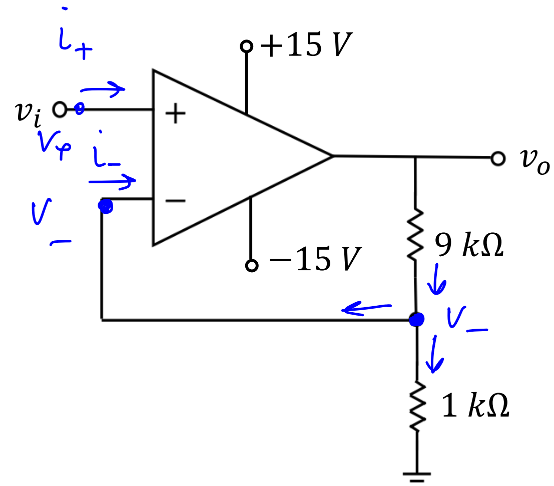


Voltage-supply limit or Saturation

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 $\Rightarrow i_+ = i_- = 0$

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

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

Voltage-supply limit or Saturation

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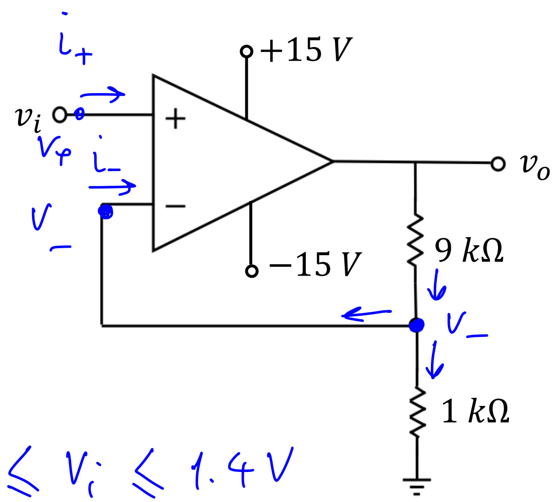
$$V_{S^-} < V_o < V_{S^+}$$

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



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

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

$$V_o = 10\,V_i \implies \frac{-14V}{10} \leqslant V_i \leqslant \frac{14}{10}\,V \implies -1.4\,V \leqslant V_i \leqslant 1.4\,V$$

Voltage-supply limit or Saturation

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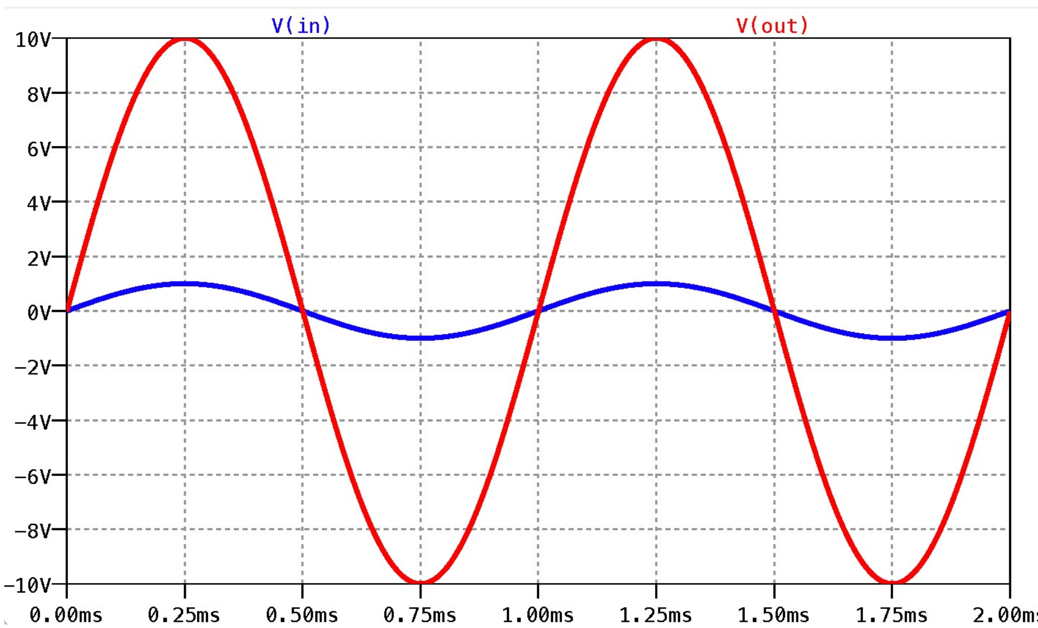
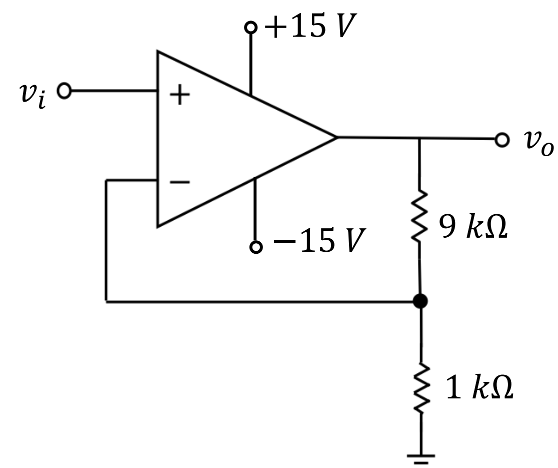
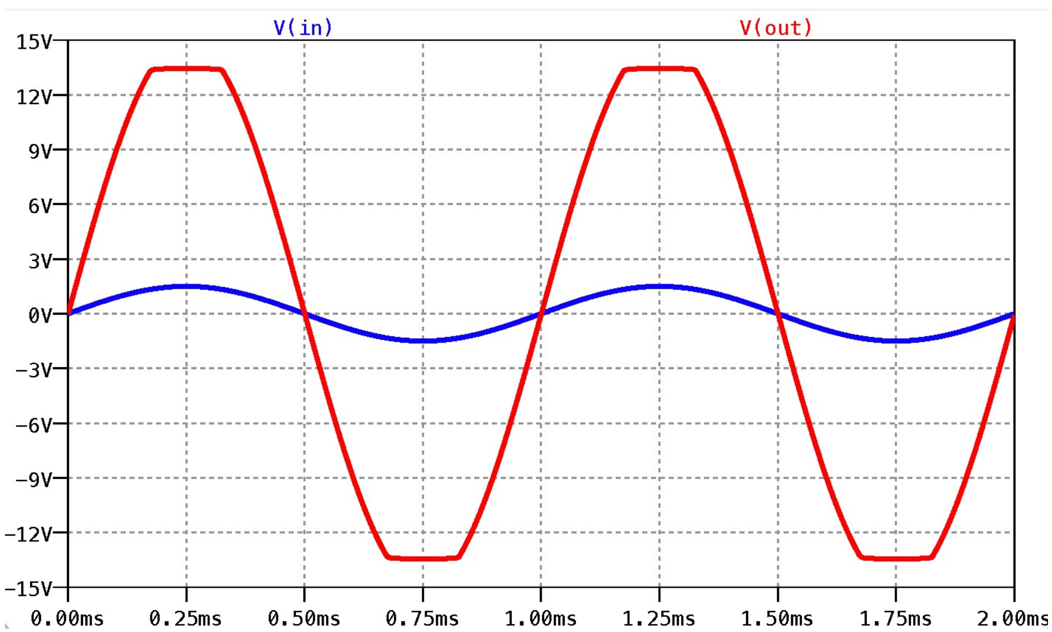
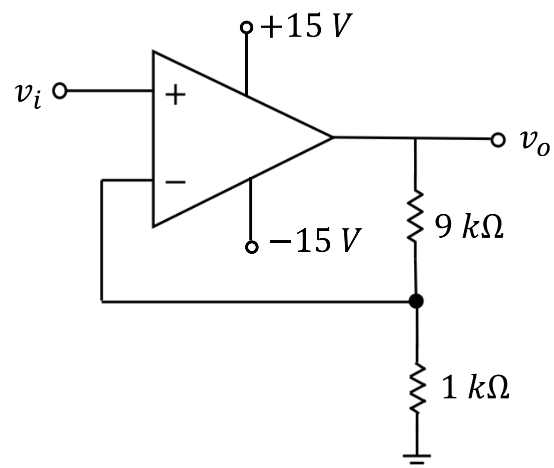




Voltage-supply limit or Saturation

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.

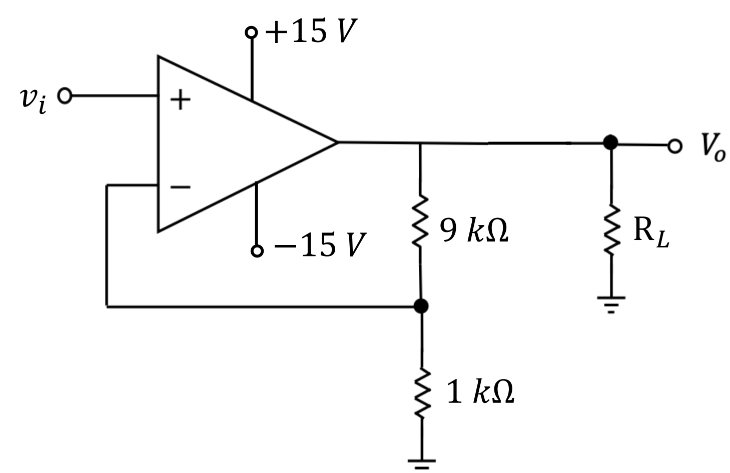




Maximum Output Current

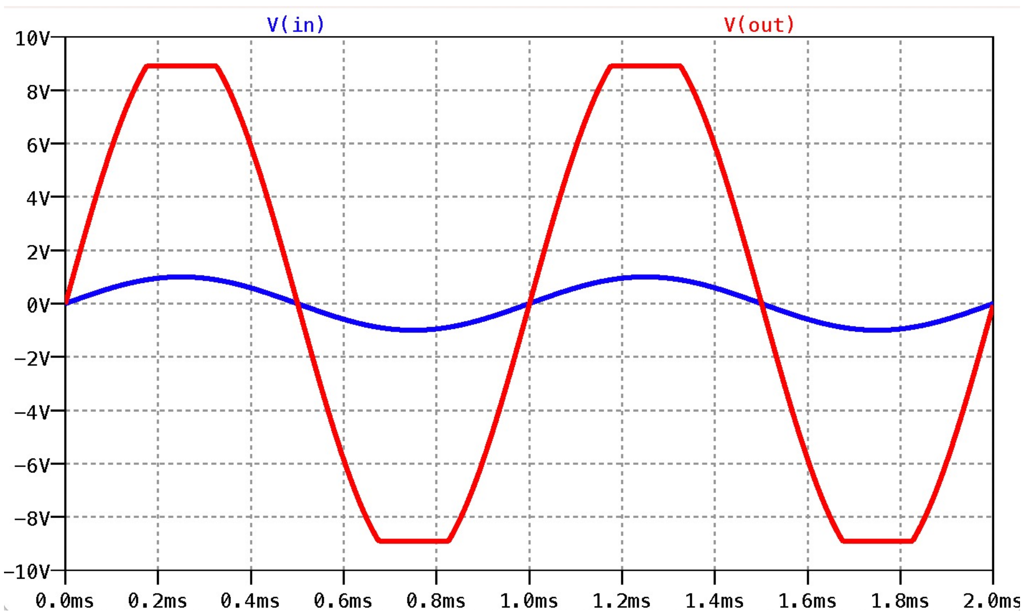
The output current of an op-amp is limited to a specified maximum value.

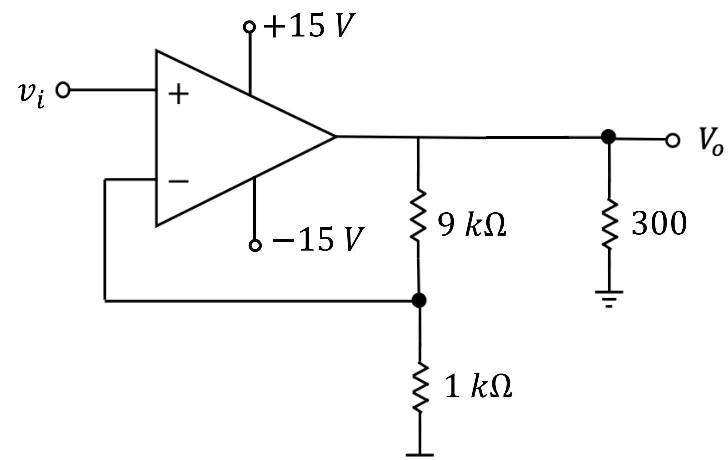
For example, in the 741 op-amp, the maximum output current is ±20mA.



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.

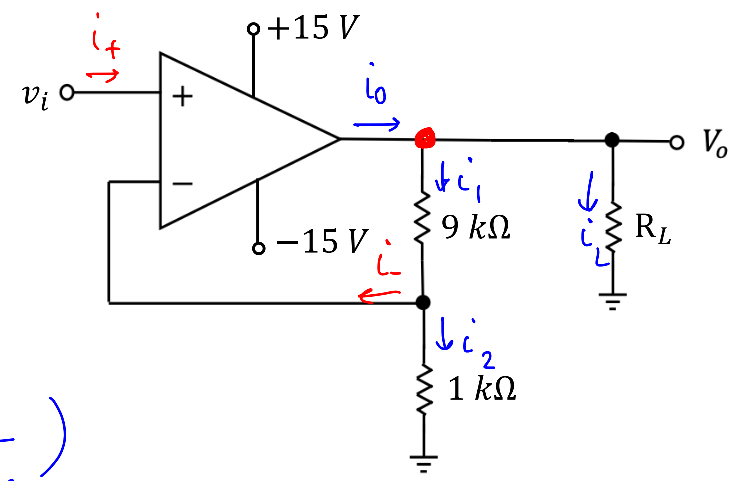




Maximum Output Current - Example

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 $\mathrm{R_L} = 1\ k\Omega$, specify and sketch the output voltage.

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



KCL : $i_o = i_1 + i_L$

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

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

$$= V_o \times 1.1$$

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 $\mathrm{R_L} = 1\ k\Omega$, specify and sketch the output voltage.

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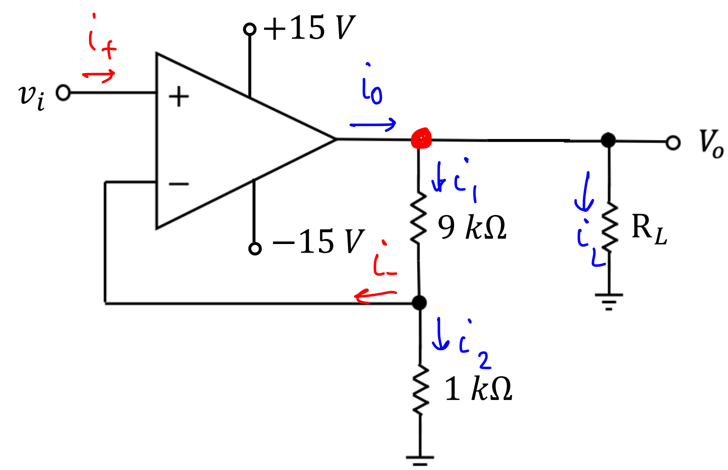


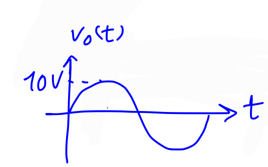
$i_o = V_o \times 1.1$

Assume linear amplification:

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

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

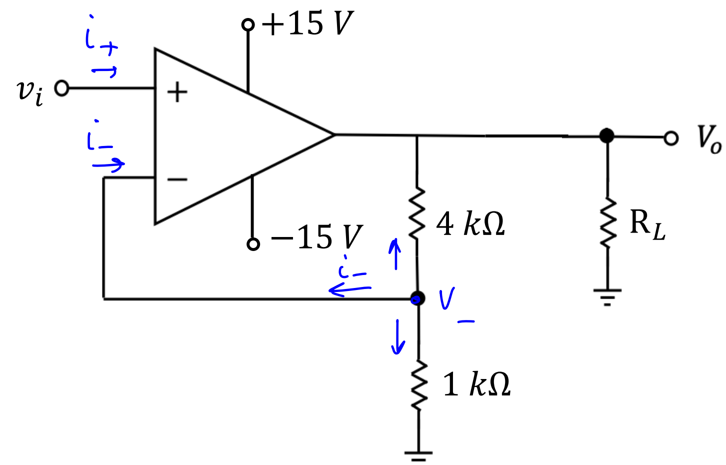
$\Rightarrow$ We are not limited by the maximum output current $\Rightarrow V_{o_{max}} = 10\ V$



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:



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

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

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?

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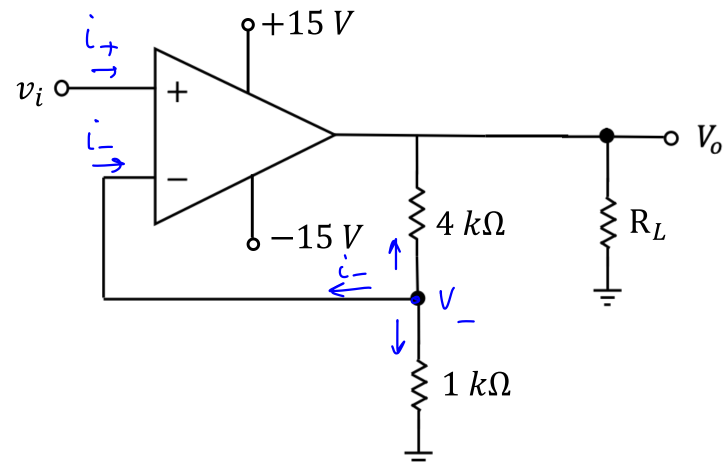


Assume an ideal op-amp: $i_+ = i_- = 0$

Negative feedback: $V_+ = V_-$

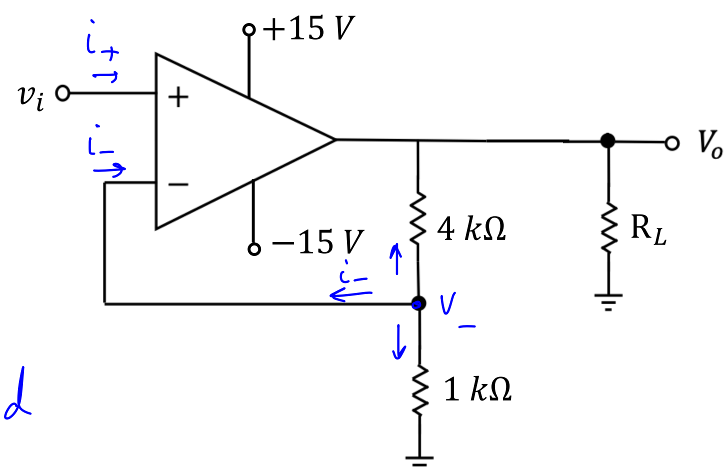
$V_+ = V_i \longrightarrow V_- = V_+ = V_i$

This relationship is valid if there is no distortion.

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

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?

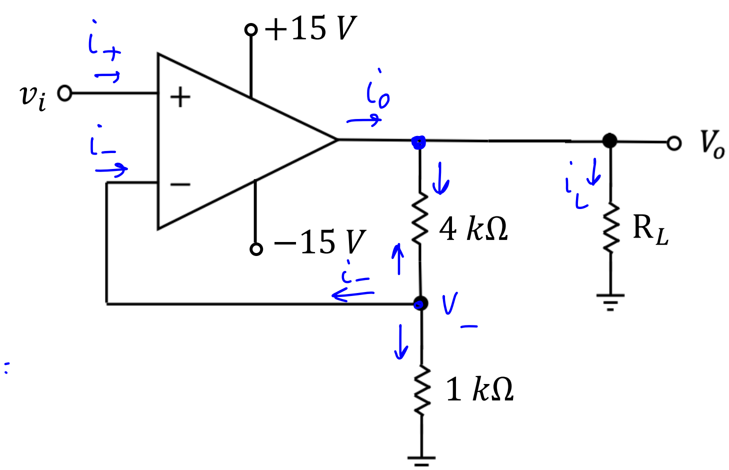


Let's assume that the output voltage can reach the max possible ±13V. We need to check if the op-amp can supply the required output current to maintain ±13 V across R_L.

Lecture 3 reading quiz

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

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:

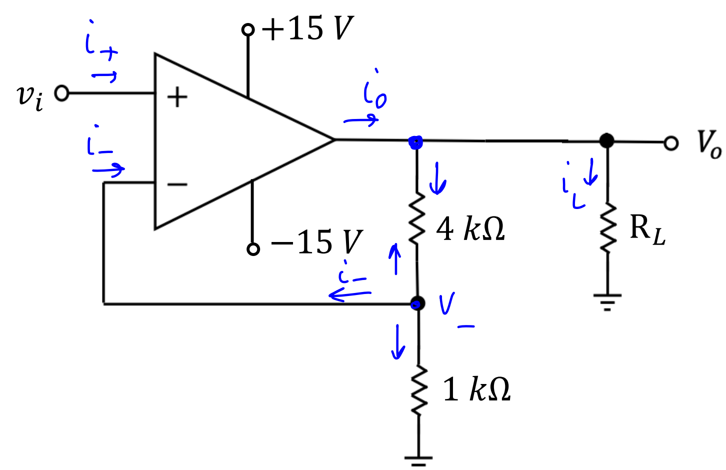
$$|i_o| = \frac{13\ V}{0.5\ k\Omega} + \frac{13\ V}{5\ k\Omega} = 28.6\ mA > 20\ mA$$

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

Lecture 3 reading quiz

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

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



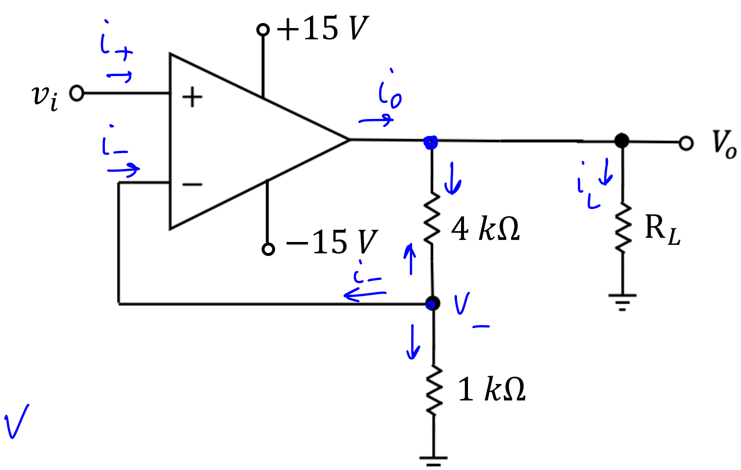
KCL at the output node:

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

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

Lecture 3 reading quiz

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



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

To get an undistorted signal:

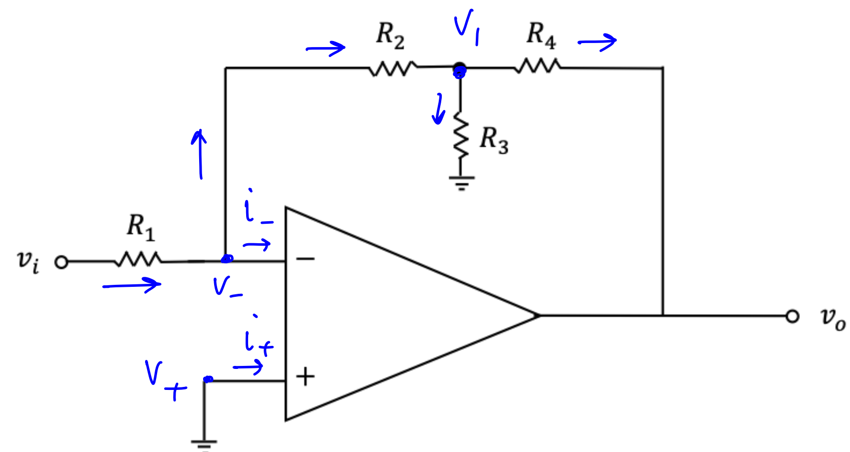
$V_o = 5\,V_i \implies V_{i_{max}} = V_p = \frac{9.09}{5} = 1.82\ V$

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: $V_+ = V_-$

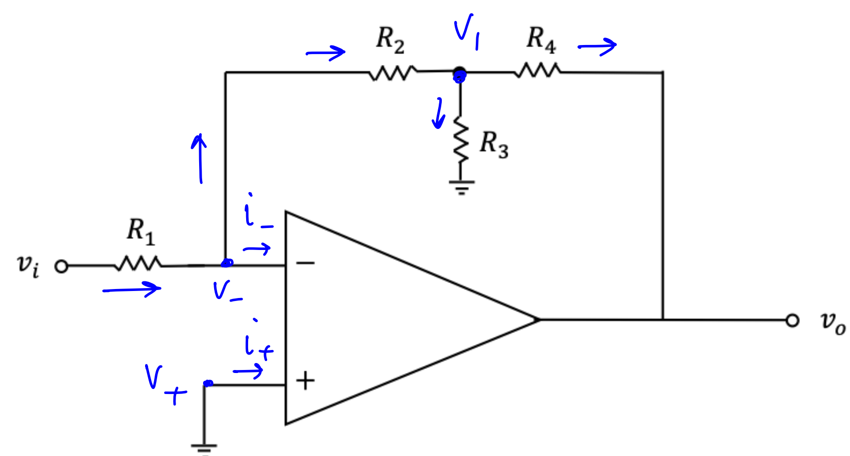


KCL at the inverting terminal:

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

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 node V_1 :

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

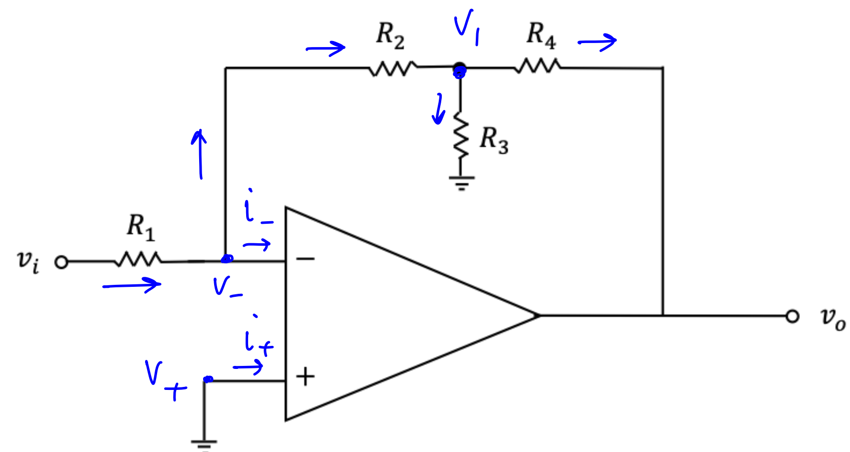
$$V_o = \left(1 + \frac{R_4}{R_2} + \frac{R_4}{R_3}\right) V_1$$

Discussion question 1.

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

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

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

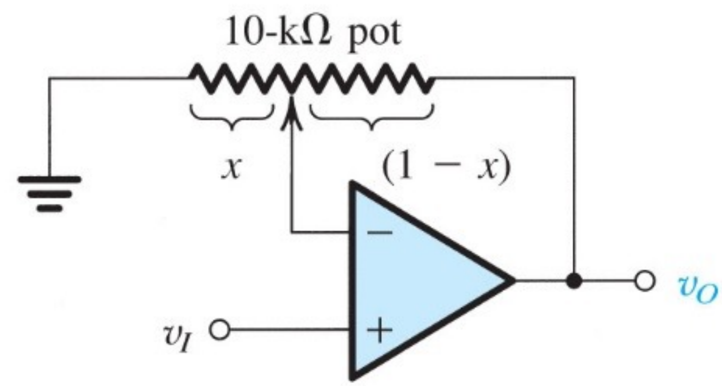


Discussion question 2.

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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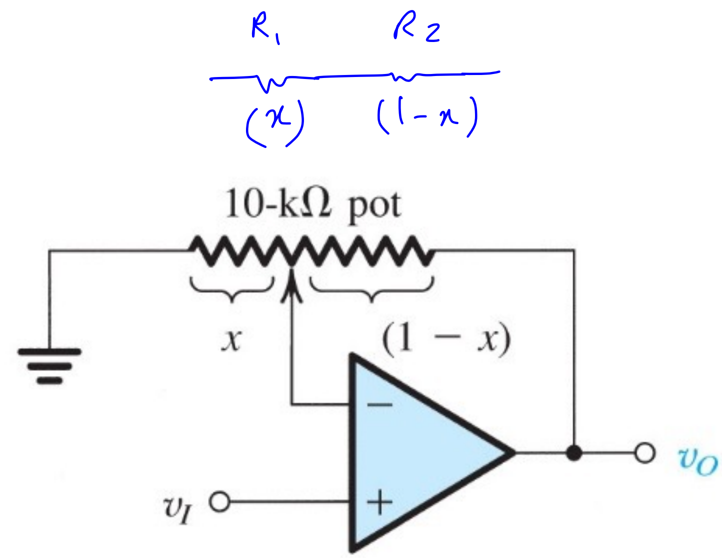


$R_1 = x \times 10\ k\Omega$

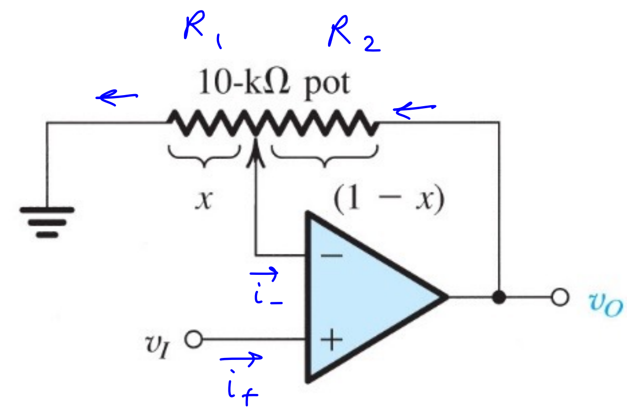
$R_2 = (1-x) \times 10\ k\Omega$

$R_1 + R_2 = 10\ k\Omega$

Discussion question 2.

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

Assume an ideal op-amp.



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

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

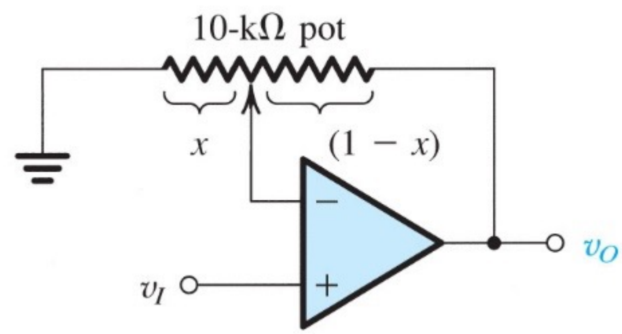
KCL at the inverting terminal: $\dfrac{V_-}{R_1} = \dfrac{V_o - V_-}{R_2} \rightarrow \dfrac{V_I}{R_1} = \dfrac{V_o - V_I}{R_2}$

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

$R_1 = 10x$ 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.



$$\text{Voltage gain} = \frac{V_o}{V_i} = \frac{1}{x}$$

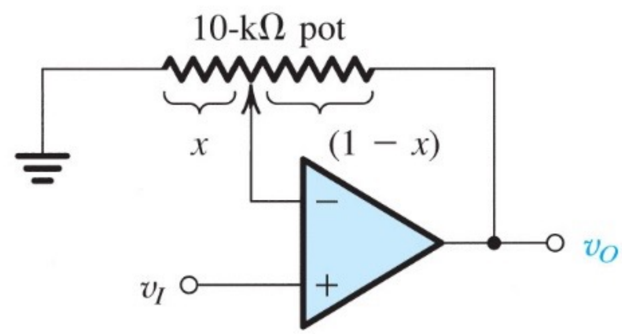
$0 \leqslant x \leqslant 1 \longrightarrow 1 \leqslant \text{Voltage gain} < \infty$

not achievable

V_{out} will not exceed V_{sat}

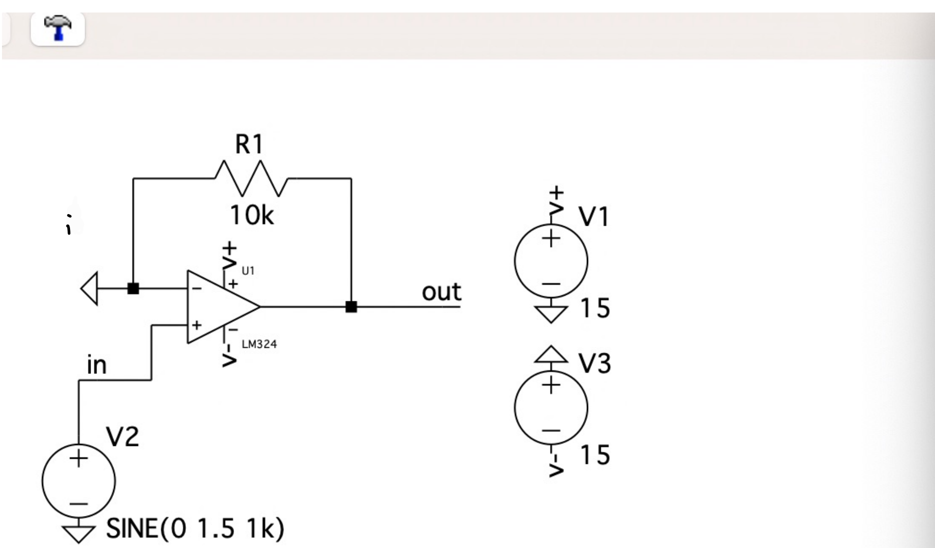
Discussion question 2.

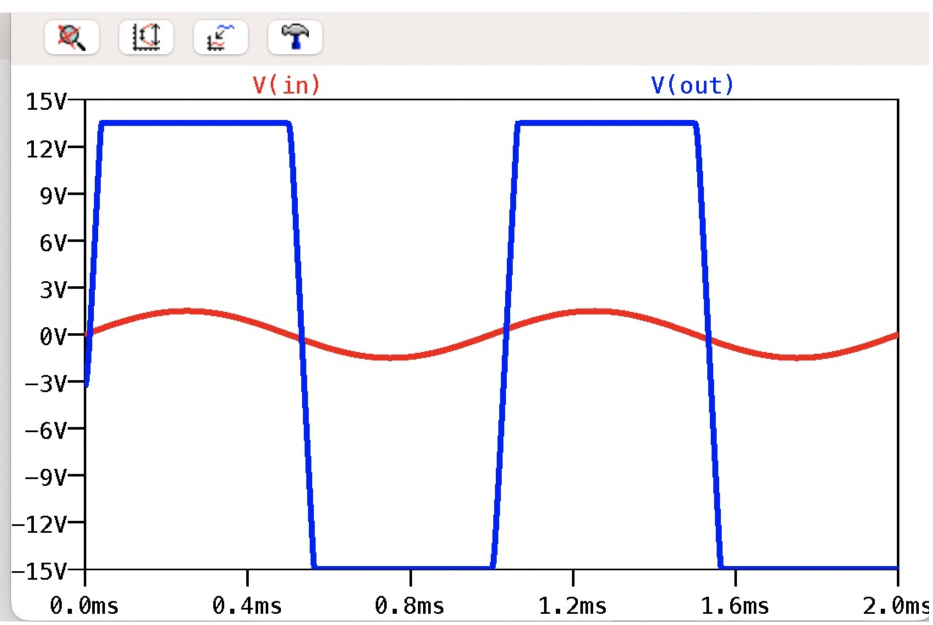
a) What is the range of the gain obtained? Assume an ideal op-amp.



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

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

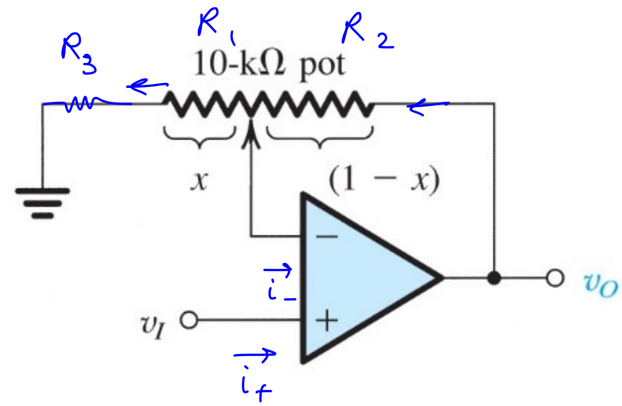




Discussion question 2.

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?

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: $\dfrac{V_-}{R_1 + R_3} = \dfrac{V_o - V_-}{R_2}$

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

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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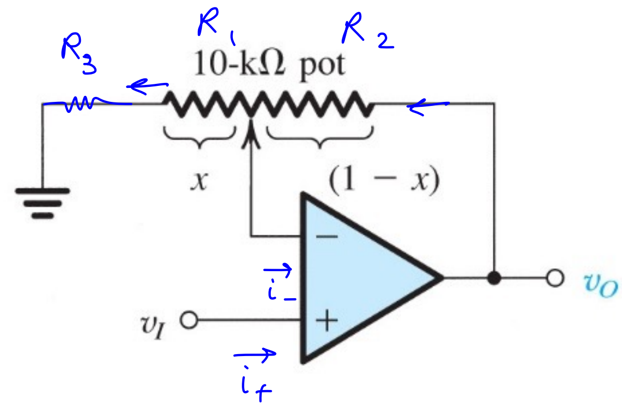


$$V_o = \left(1 + \frac{R_2}{R_1 + R_3}\right) V_I$$

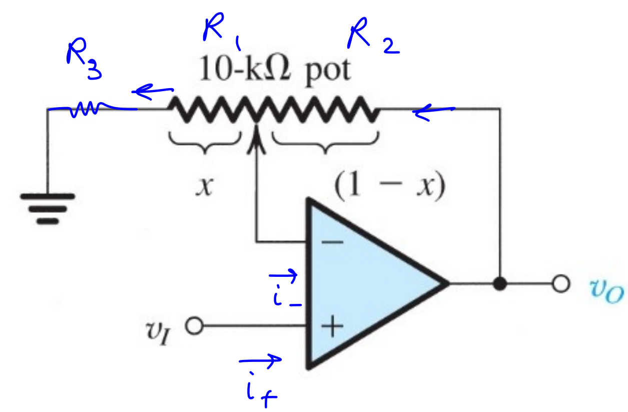
$R_1 = 10x$ and $R_2 = 10(1-x)$

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

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?

Assume an ideal op-amp.



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

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

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

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

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

ECE 65: Components & Circuits Lab

Lecture 4

Diode introduction

and review of circuit theory

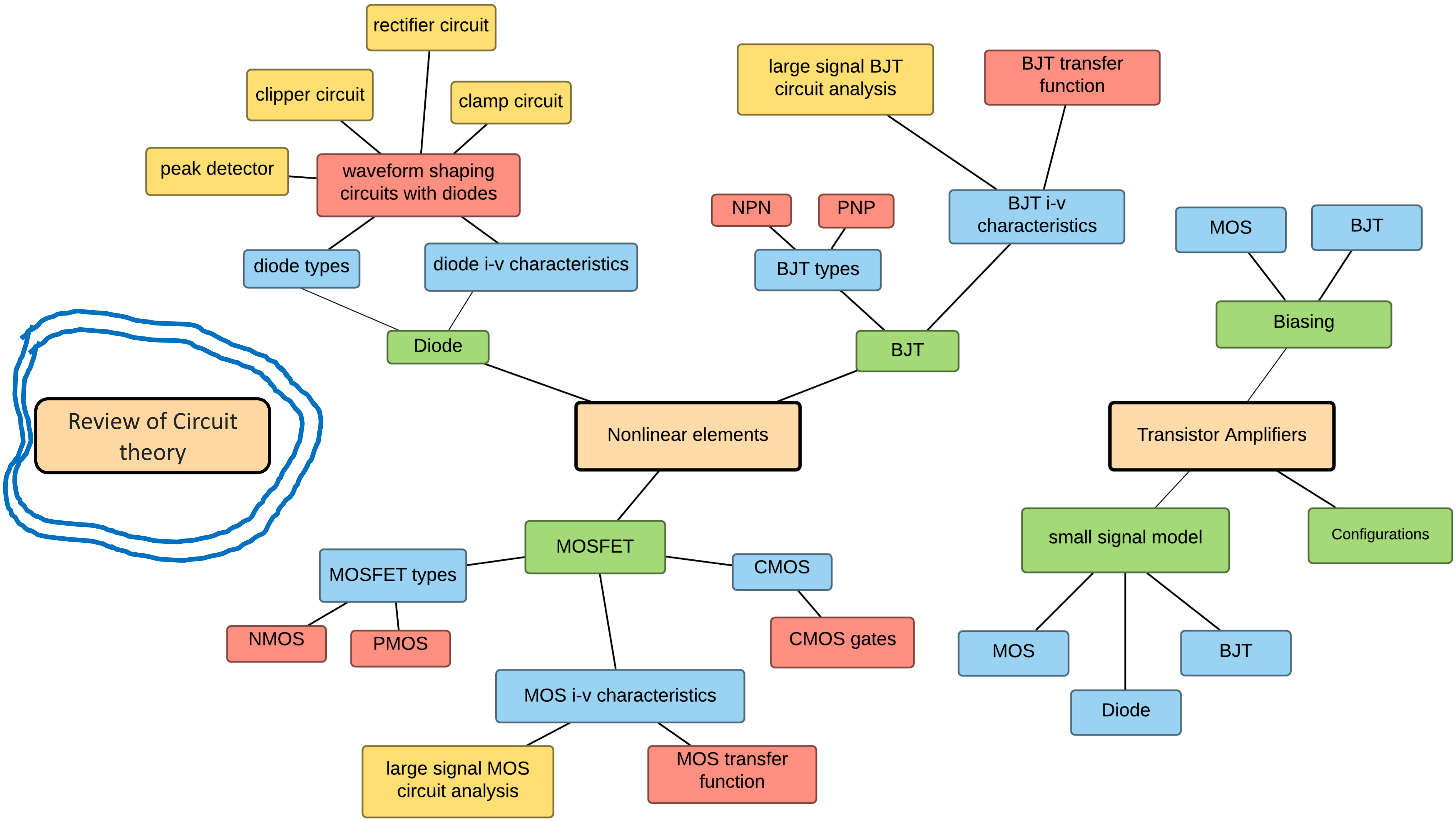
Reference notes: sections 2.1-2.8

Sedra & Smith (7th Ed): sections 4.3-4.4

Saharnaz Baghdadchi

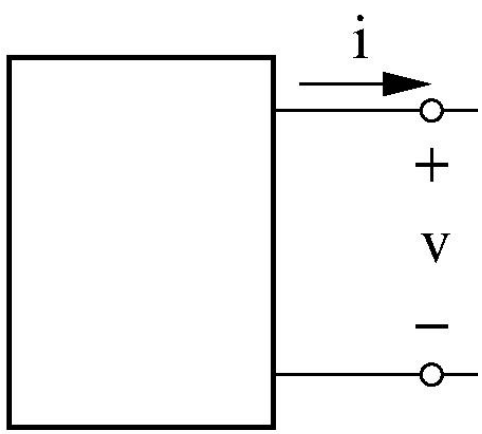
Course map

1. Review of Circuit theory



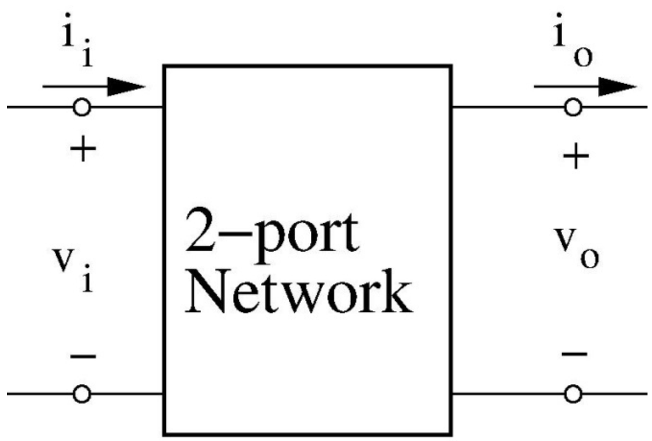
We will analyze many <u>functional circuits</u>

Two-terminal Networks



Function is defined by the iv equation

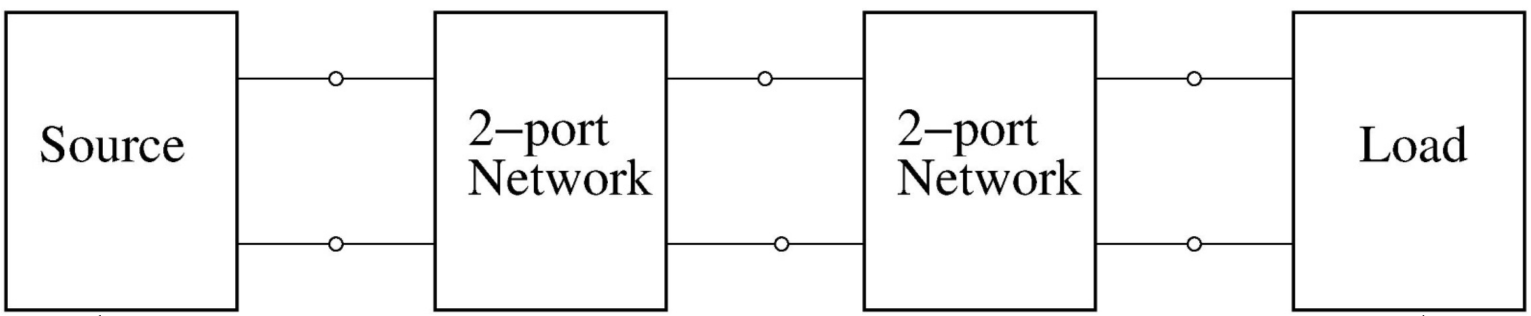
Two-port Networks



Function is defined by the transfer function (e.g., v_o in terms of v_i)

A typical analog circuit contains a load and a source (two-terminal networks) and several two-port networks

We divide the circuit into building blocks to simplify analysis and design



Two-terminal network containing an independent source

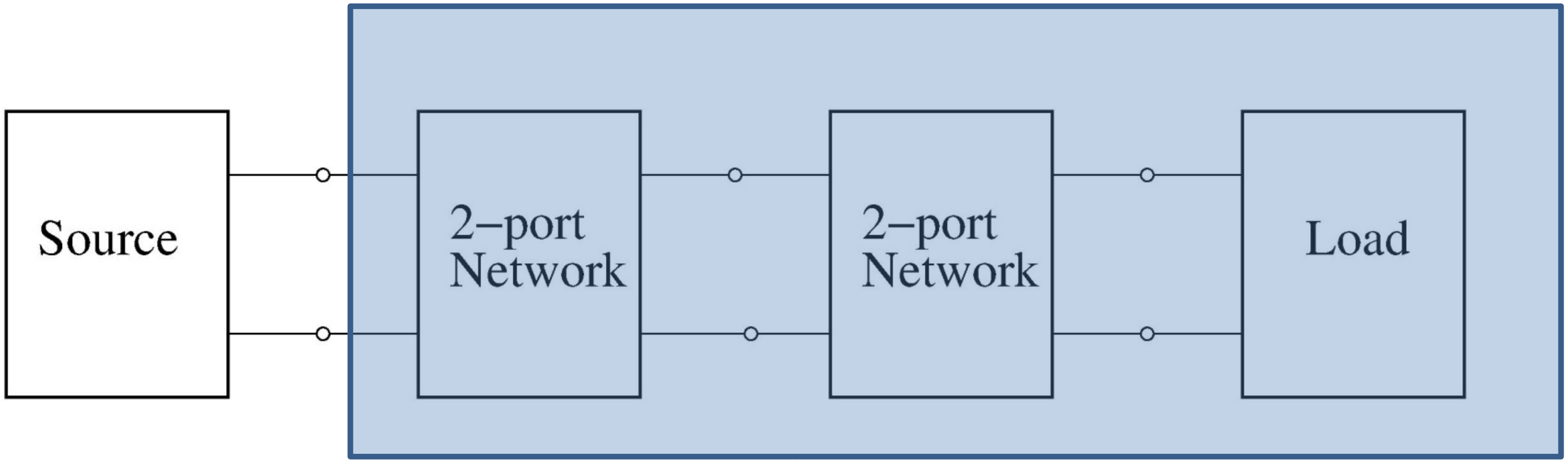
Two-terminal network containing NO independent source

In linear circuits:

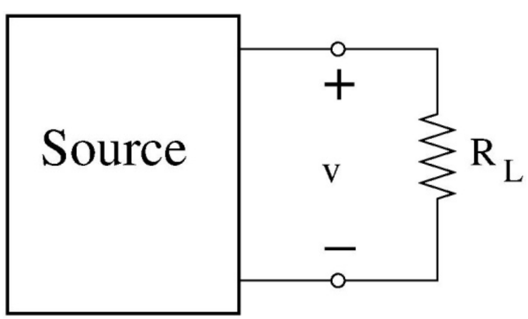
Any two-terminal network can be replaced by its Thevenin equivalent circuit.

If a two-terminal network does not include an “independent source” it will be reduced to a single “impedance” (even if it includes dependent sources).

Source only sees a load resistor

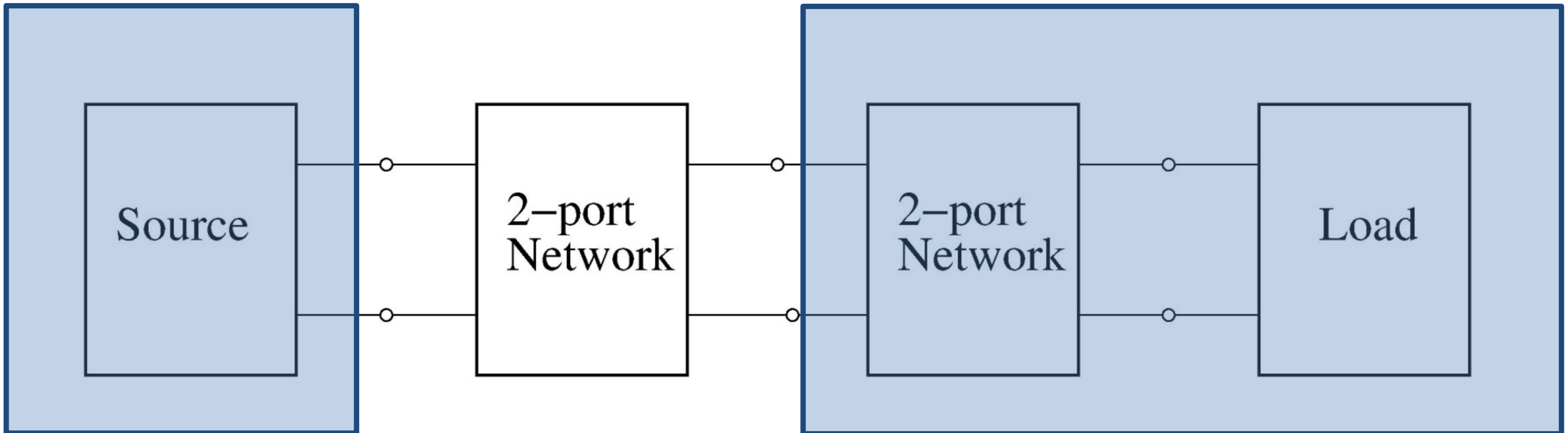


A two-terminal network containing NO independent source



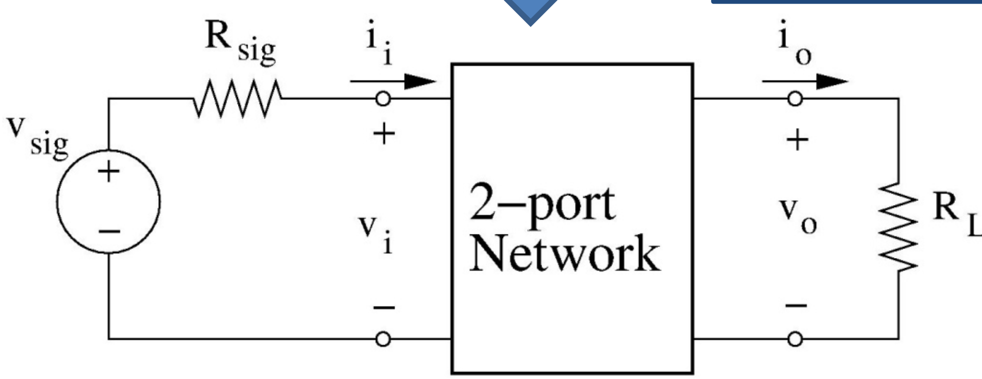
For a linear source, we only find the Thevenin parameters of the source.

Two-port network



A two-terminal network containing an independent source

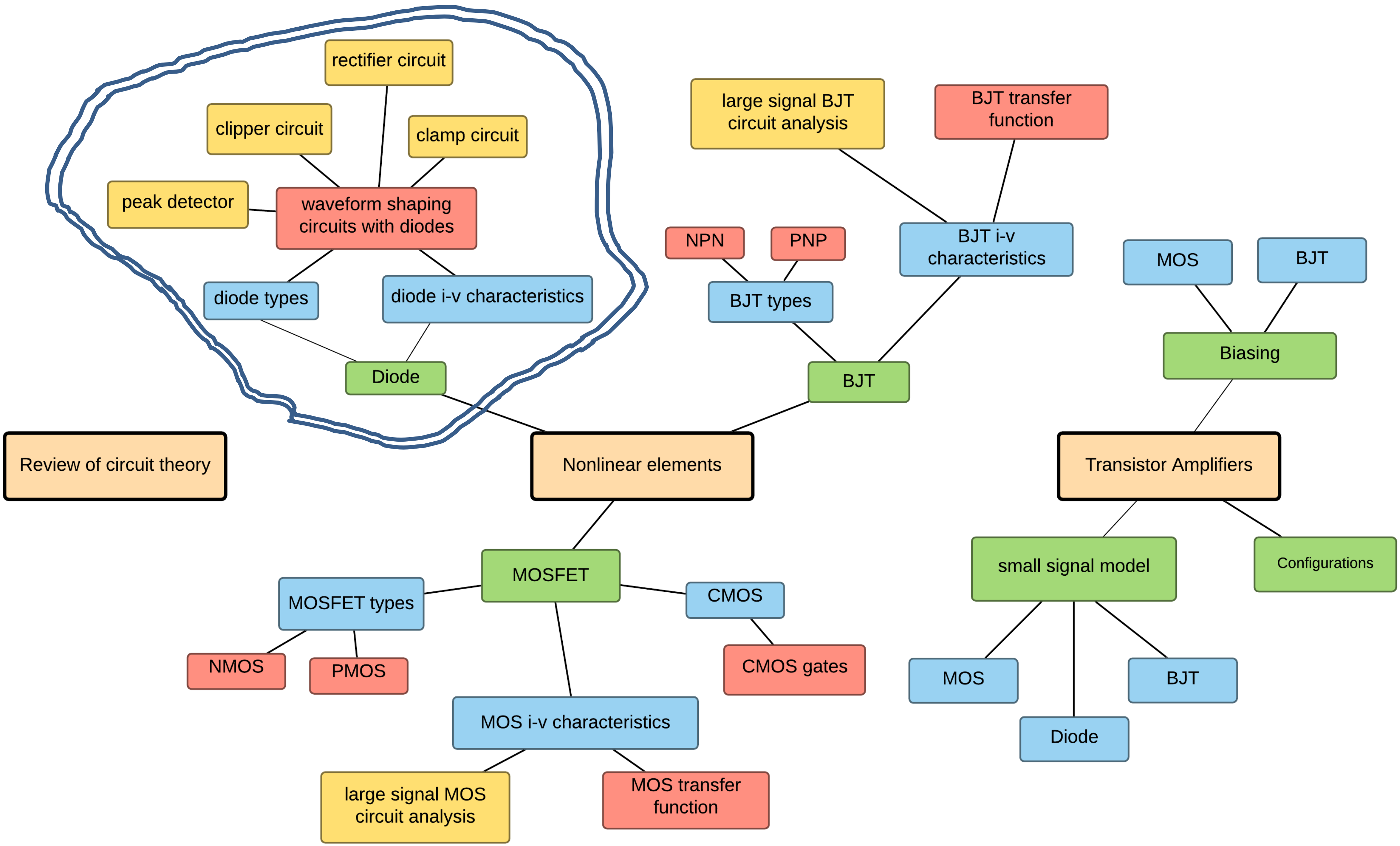
A two-terminal network containing no independent source



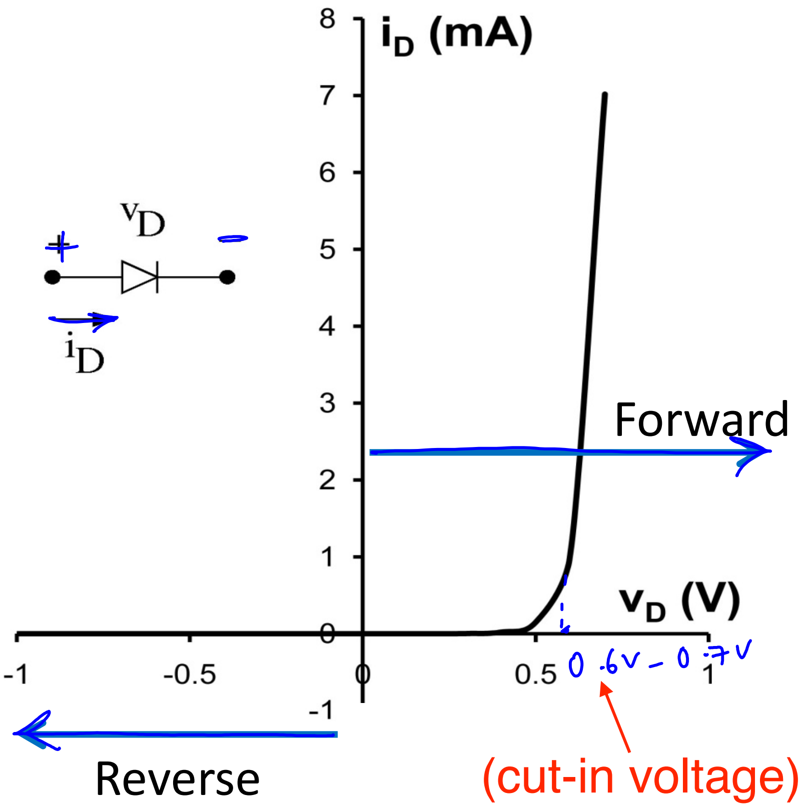
Transfer function of a two-port network can be found by solving the above circuit once.

Course map

2. Diodes



The iv characteristics of a silicon junction diode



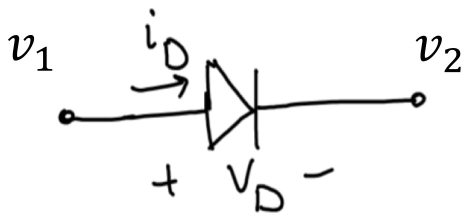
When the diode conducts,
$i_D \gg I_S$ and:

$$\boxed{i_D = I_S\, e^{v_D/V_T}}$$

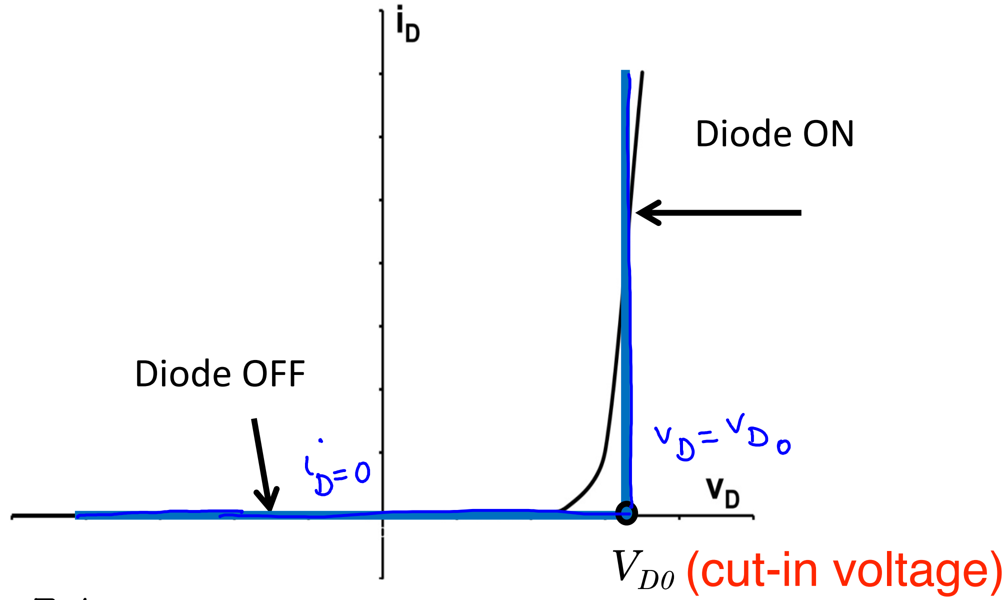
I_S: Saturation Current
(10^{-9} to 10^{-18} A)

V_T: Thermal voltage = 26mV at room temp.

Diode piecewise-linear model:



$v_D = v_1 - v_2$



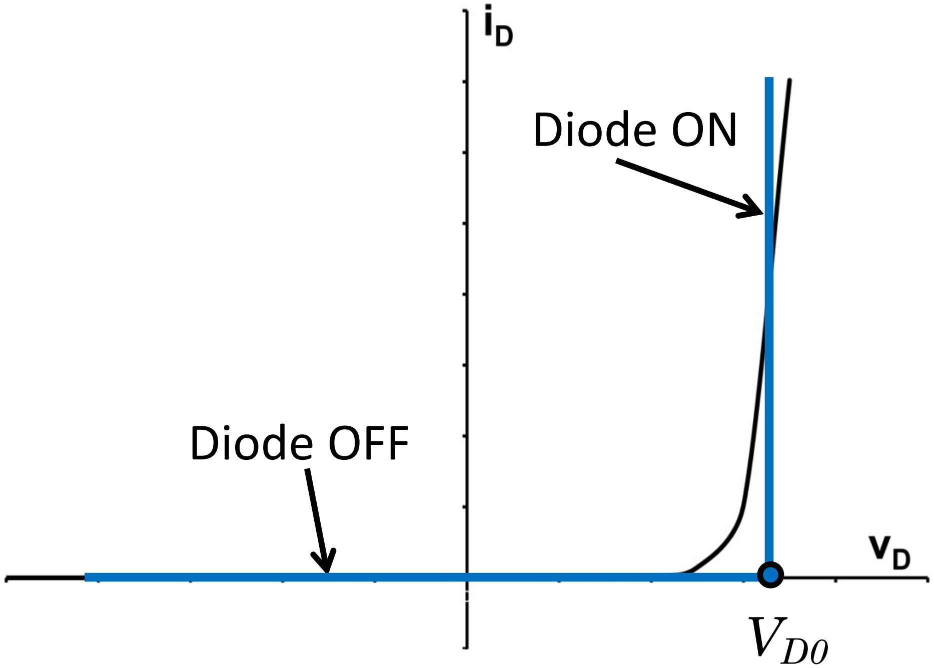
Assume Si Diode with $v_{D_0} = 0.7V$

(A) When $v_1 - v_2 < 0$ → diode is reverse-biased ⇒ $i_D = 0$

(B) When $0 < v_1 - v_2 < 0.7$ → diode is forward-biased, but it is not ON, yet ⇒ $i_D = 0$

(C) When $v_1 - v_2 = 0.7$ → diode is forward biased and it's ON ⇒ $i_D \geq 0$ & $v_D = v_{D_0} = 0.7$

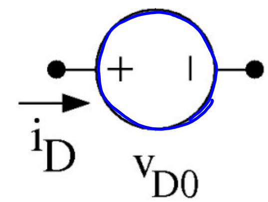
Diode piecewise-linear model:



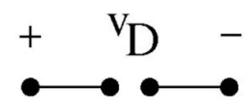
Constant Voltage drop Model:

Circuit Models:

ON:



OFF:

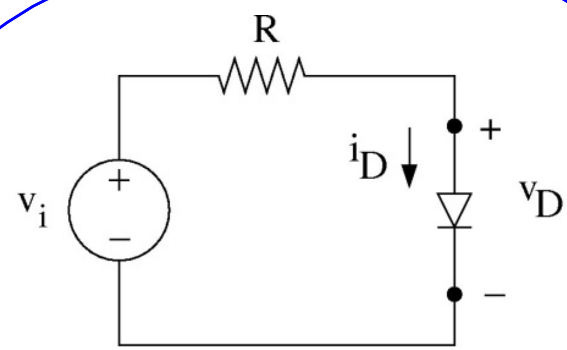


Diode ON: $v_D = V_{D0}$ and $i_D \geq 0$

Diode OFF: $i_D = 0$ and $v_D < V_{D0}$

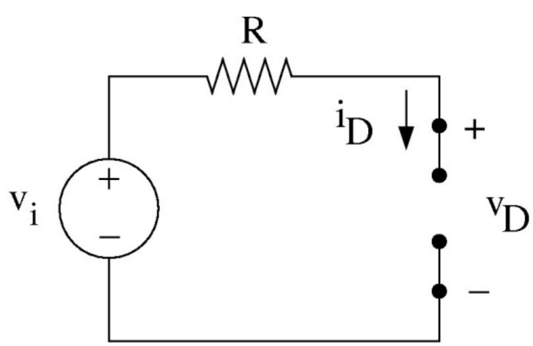
(cut-in voltage) $V_{D0} = 0.6 - 0.7\ V$ for Si

Diode circuit models:



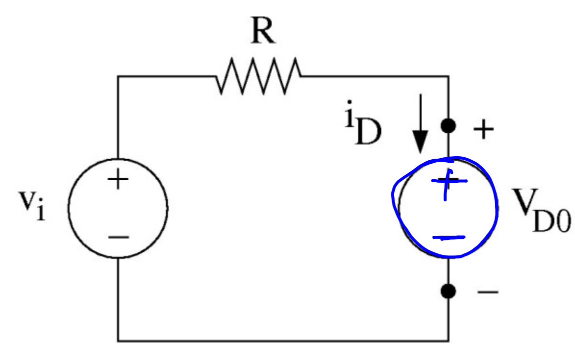
When Diode is OFF:

$i_D = 0$ and $v_D < V_{D0}$



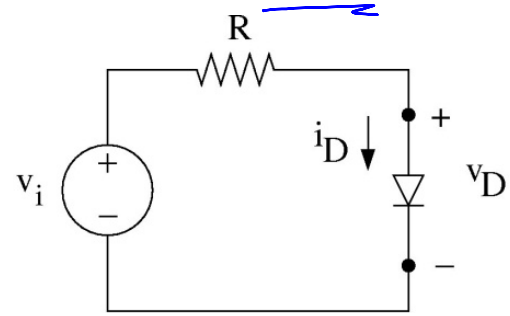
When Diode is ON:

$i_D \geq 0$ and $v_D = V_{D0}$



Example 1:

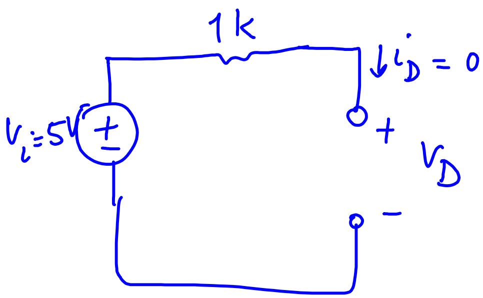
Find i_D and v_D for R = 1k, $V_i = 5$ V, and Si Diode ($V_{D0} = 0.7$ V).



Solution with diode circuit models:

Assume Diode is off

$\boxed{i_D = 0,\ V_D < V_{D_0}}$

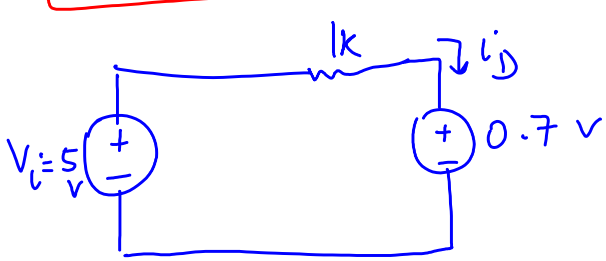


$V_i = 1k \times i_D + V_D$

$V_i = V_D = 5V > 0.7$ → Assumption was wrong.

Assume Diode is ON

$\boxed{i_D > 0}$, $V_D = V_{D_0}$



$V_i = 1k \times i_D + 0.7V$

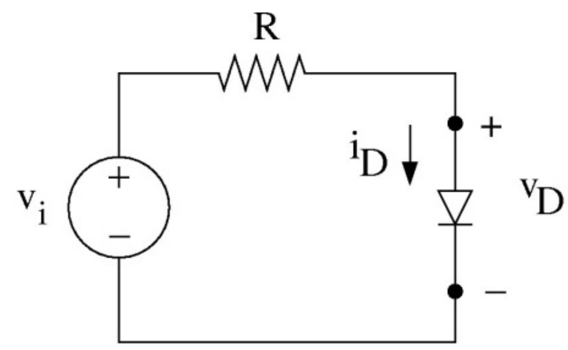
$\rightarrow i_D = \dfrac{5 - 0.7}{1k} = \underline{4.3\,mA > 0}$

The diode is ON.

Example 2 :

For what range of V_i the diode will be ON and for what range it will be OFF?

Find i_D and v_D for each range.



When diode is ON : $i_D \geq 0$, $V_D = V_{D_0}$

$V_i = R\,i_D + V_D = R\,i_D + 0.7$

$i_D = \dfrac{V_i - 0.7}{R} \geq 0 \longrightarrow V_i \geq 0.7\,V$

$\boxed{\text{For } v_i \geq 0.7\,V, \text{ diode is ON}, \; V_D = V_{D_0}, \; i_D \geq 0}$

---

when the diode is off : $i_D = 0$, $V_D < V_{D_0}$

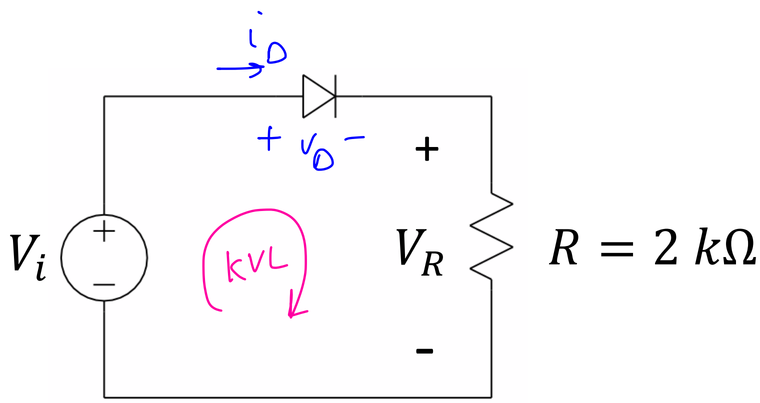
$V_i = R\,i_D + V_D \longrightarrow V_i = V_D, \; V_D < V_{D_0} \longrightarrow V_i < V_{D_0}$

$\boxed{\text{For } v_i < V_{D_0}, \text{ diode is off}, \; i_D = 0, \; V_D < V_{D_0}}$

Lecture 4 reading quiz

In this diode circuit, what is the value of V_R for $V_i = 5\ V$ and $V_i = -5\ V$?

Assume $V_{D0} = 0.7\ V$



when $V_i = 5\,V$:

Assume the diode is off :

$v_D < V_{D_0}$ and $i_D = 0$

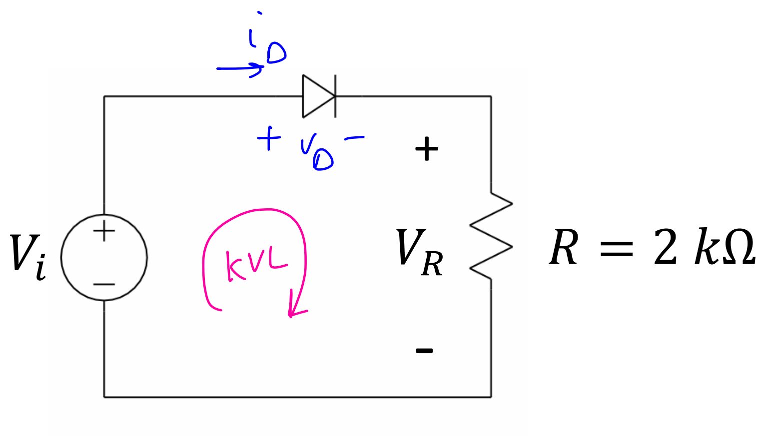
KVL : $-V_i + V_D + R\, i_D = 0 \longrightarrow -V_i + V_D = 0 \longrightarrow V_i = V_D = 5 > V_{D_0}$

$\Rightarrow$ The assumption was wrong.

Lecture 4 reading quiz

In this diode circuit, what is the value of V_R for $V_i = 5\ V$ and $V_i = -5\ V$?

Assume $V_{D0} = 0.7\ V$



when $V_i = 5V$:

Assume the diode is ON :

$V_D = V_{D_0}$ and $i_D \geq 0$

KVL : $-V_i + V_D + R\, i_D = 0 \longrightarrow -V_i + V_{D_0} + 2k\Omega \times i_D = 0$

$\longrightarrow -5V + 0.7V + 2k\Omega \times i_D = 0 \implies i_D = 2.15\ mA > 0$

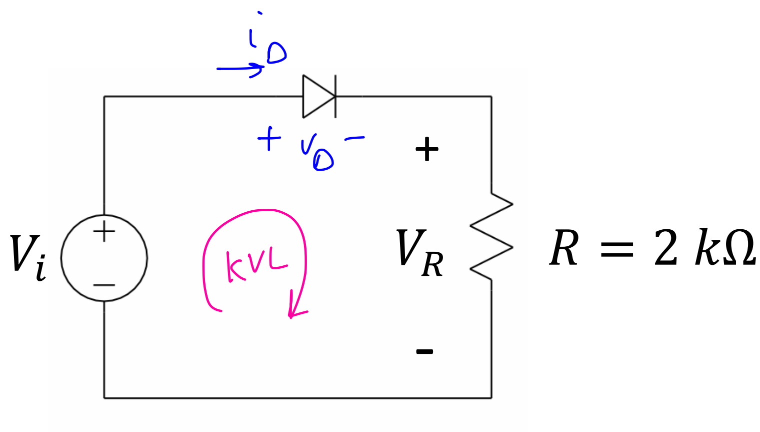
$\implies$ The assumption was correct. The diode is ON, $V_D = V_{D_0}$ and $i_D = 2.15\ mA$.

$V_R = 2k\Omega \times 2.15\ mA = 4.3\ V$

Lecture 4 reading quiz

In this diode circuit, what is the value of V_R for $V_i = 5\ V$ and $V_i = -5\ V$?

Assume $V_{D0} = 0.7\ V$



when $V_i = -5\,V$:

Assume the diode is off :

$v_D < V_{D_0}$ and $i_D = 0$

KVL : $-V_i + V_D + R\, i_D = 0 \longrightarrow -V_i + V_D = 0 \longrightarrow V_i = V_D = -5\,V < V_{D_0}$

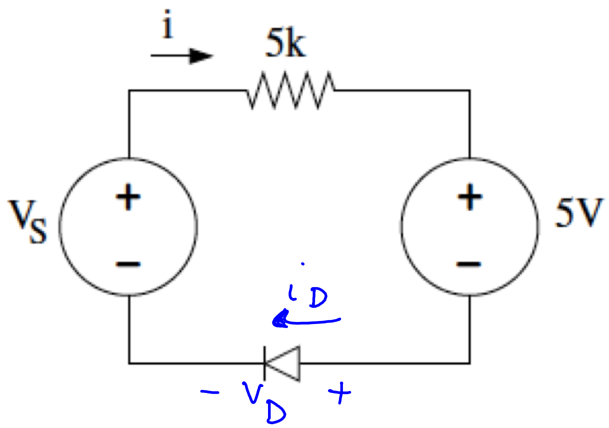
$\Rightarrow$ The assumption was correct. The diode is off. $i_D = 0$ and $V_D = -5\,V$.

$V_R = 2\,k\Omega \times i_D = 0\ V$

Clicker question 1.

For what range of v_s , will the diode in the following circuit be ON??

(Si diodes with $V_{D0} = 0.7\ V$)



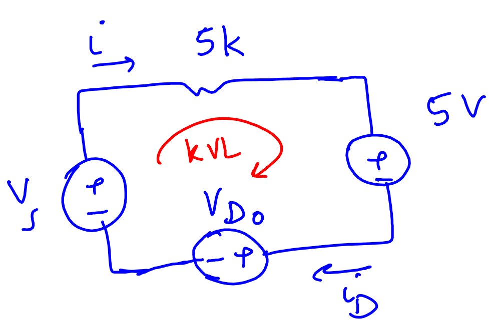
A. $v_s \geqslant 5$ V

B. $v_s \geq 5.7$ V

C. $v_s \geqslant 4.3$ V

Diode ON : $V_D = V_{D_0}$, $\boxed{i_D \geqslant 0}$

replacing the diode with the constant voltage drop model:



KVL : $-V_s + 5k\Omega \times i + 5V + V_{D_0} = 0$

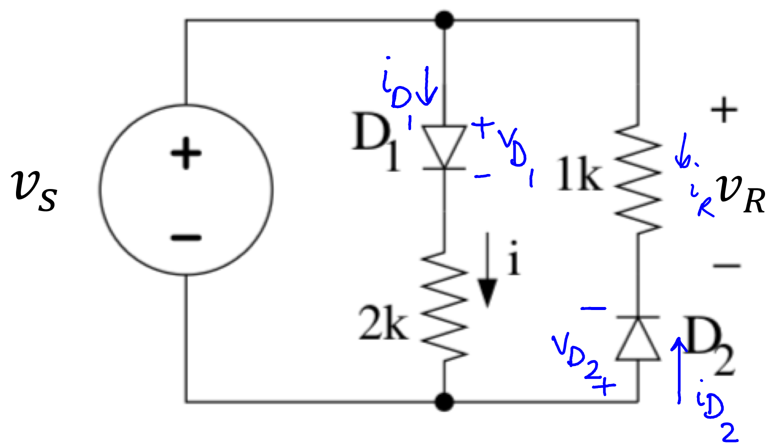
$\Rightarrow i = i_D = \dfrac{V_s - 5.7}{5k\Omega} \geqslant 0$

$\rightarrow V_s \geqslant 5.7V$

Clicker question 3.

Find v_R and i in the below circuit for $v_s = 3V$.

(Assume Si diodes with $V_{D0} = 0.7\ V$)



A. $v_R = 2.3\ V,\quad i = 1.15\ mA$

B. $v_R = 0\ V,\quad i = 1.15\ mA$

C. $v_R = 0.6\ V,\quad i = 0.3\ mA$

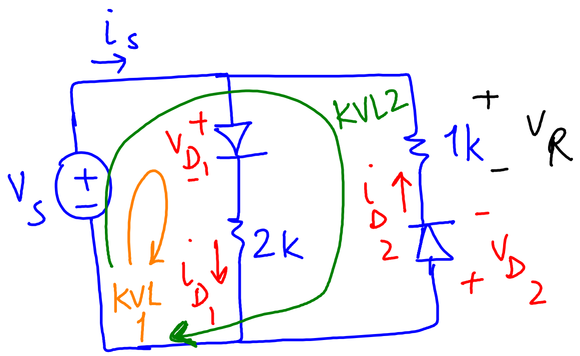
A. $v_R = -2.3\ V,\quad i = 1.15\ mA$

$V_R = 1k\Omega \times i_R$

KCL: $i_R = -i_{D_2}$

$\rightarrow V_R = -1k\Omega \times i_{D_2}$

All the states for D_1 and D_2:



D_1	D_2	
ON	OFF	Case 1
OFF	OFF	Case 2
ON	ON	Case 3
OFF	ON	Case 4

Case 1: Assume D_1 is ON and D_2 is OFF

$$V_{D_1} = V_{D_0} \;\&\; i_{D_1} \geq 0 \quad \& \quad V_{D_2} < V_{D_0} \;\&\; i_{D_2} = 0$$

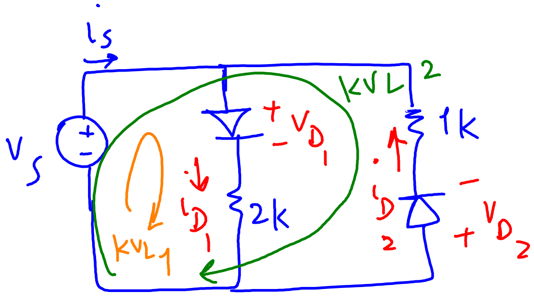
$$\boxed{\begin{aligned} &\text{KVL 1: } -V_s + V_{D_1} + 2k \times i_{D_1} = 0 \longrightarrow -3V + 0.7V + 2k\Omega \times i_{D_1} = 0 \\ &\longrightarrow i_{D_1} = 1.15\ mA \geq 0 \end{aligned}}$$

$$\text{KVL 2: } -V_s + 1k\Omega \times (-i_{D_2}) - V_{D_2} = 0 \longrightarrow -3V + 0 - V_{D_2} = 0 \longrightarrow V_{D_2} = -3V < 0.7V$$

$i_{D_1} \geq 0$ and $V_{D_2} < V_{D_0}$ $\longrightarrow$ the assumption was correct.

$$V_R = -1k\Omega \times i_{D_2} = 0\,V \longrightarrow \boxed{V_R = 0\,V}$$

Let's show that other cases are not valid.



Case 2: Assume D_1 is OFF and D_2 is OFF

$i_{D_1}=0$ & $V_{D_1} < V_{D_0}$ & $i_{D_2}=0$ & $V_{D_2} < V_{D_0}$

KVL1: $V_s = V_{D_1} + 2k \times i_{D_1} \longrightarrow V_{D_1} = V_s = 3V > V_{D_0} \longrightarrow$ Assumption was wrong

---

Case 3: Assume D_1 and D_2 are ON

$V_{D_1} = V_{D_0}$ & $i_{D_1} \geqslant 0$ & $V_{D_2} = V_{D_0}$ & $i_{D_2} \geqslant 0$

KVL2: $V_s = -1k\Omega \times i_{D_2} - V_{D_2} \longrightarrow i_{D_2} = \dfrac{-3-0.7}{1k} = -3.7mA < 0 \longrightarrow$ Assumption was wrong

---

Case 4: Assume D_1 is OFF and D_2 is ON

$V_{D_1} < V_{D_0}$ & $i_{D_1}=0$ & $V_{D_2} = V_{D_0}$ & $i_{D_2} \geqslant 0$

KVL1: $V_s = V_{D_1} + 2k \times i_{D_1} \longrightarrow V_{D_1} = V_s = 3V > V_{D_0} \longrightarrow$ Assumption was wrong

ECE 65: Components & Circuits Lab

Lecture 5

Zener Diode

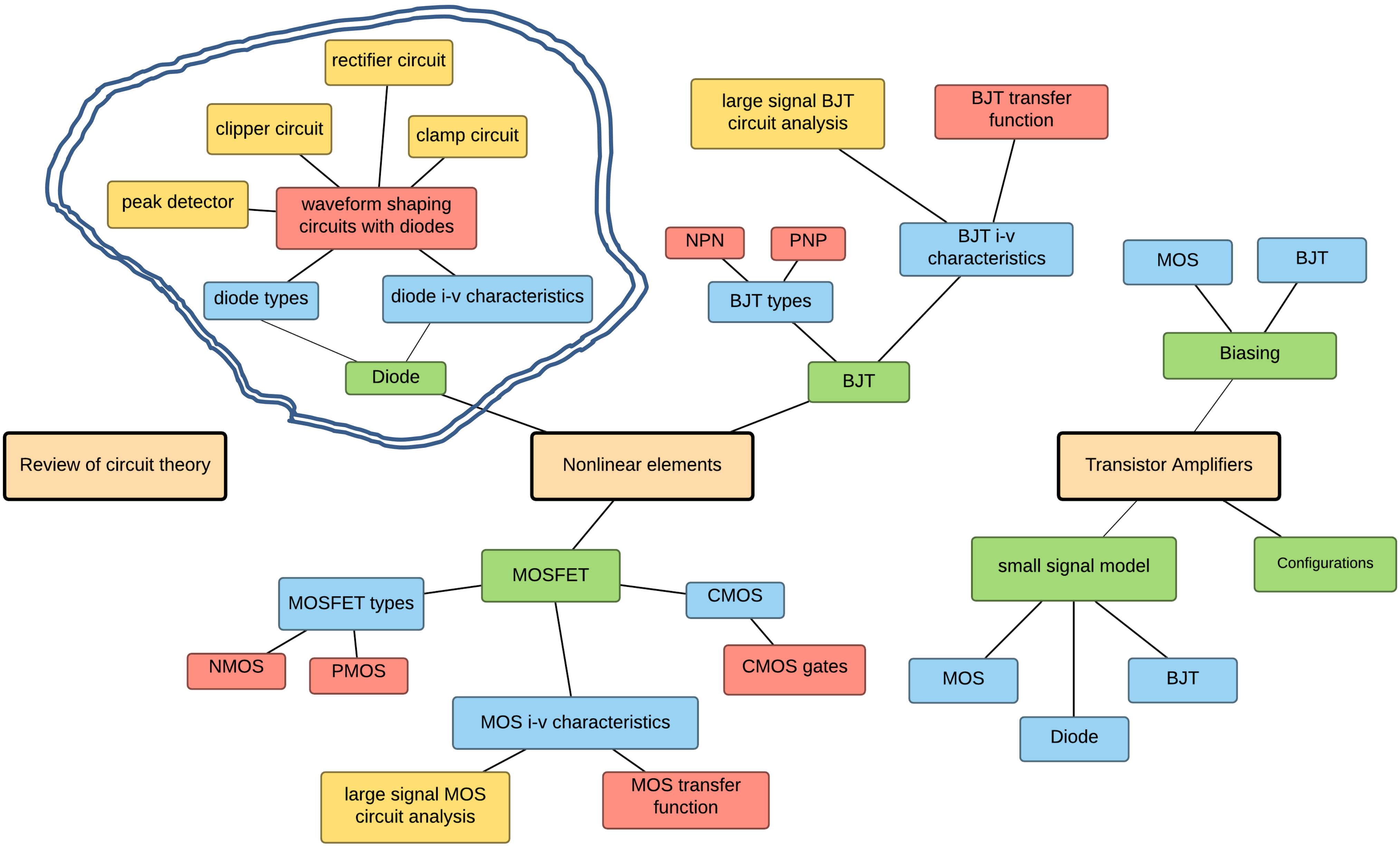
Reference notes: sections 2.1-2.8

Sedra & Smith (7^{th} Ed): sections 4.3-4.4

Saharnaz Baghdadchi

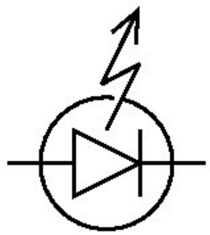
Course map

2. Diodes



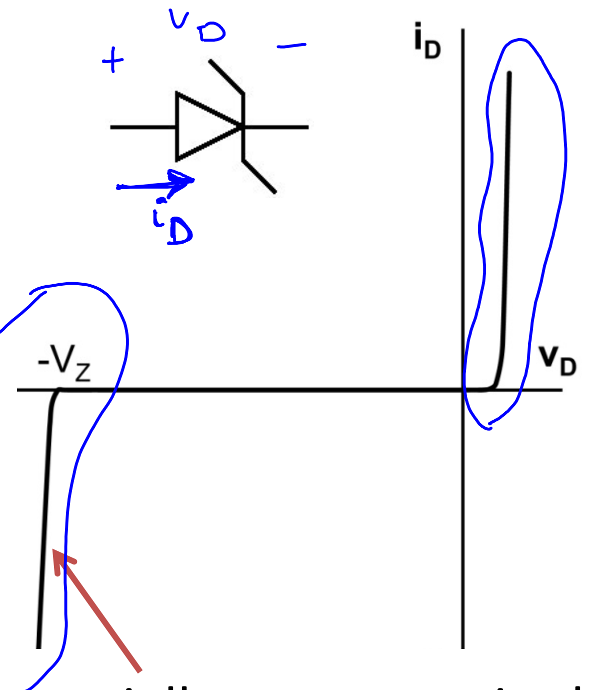
Other types of diodes

Light-emitting diode (LED)



$V_{D0} = 1.7 - 1.9$ V

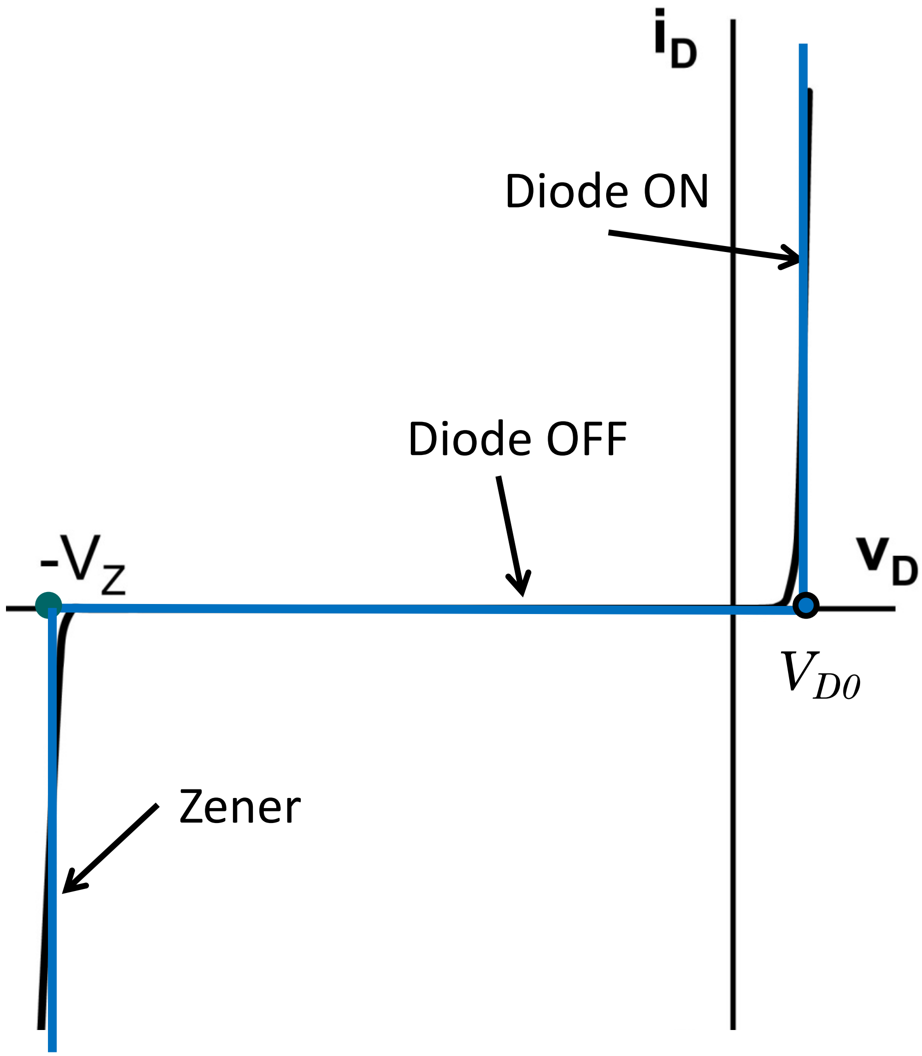
Zener Diode



Made specially to operate in the reverse breakdown region.

Useful as a “reference” voltage in many circuits.

Zener Diode piecewise-linear model



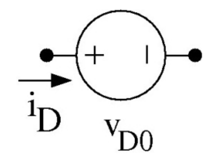
Diode ON: $v_D = V_{D0}$ and $i_D \geq 0$

Diode OFF: $i_D = 0$ and $-V_Z < v_D < V_{D0}$

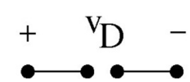
Zener: $v_D = -V_Z$ and $i_D \leq 0$

Circuit Models:

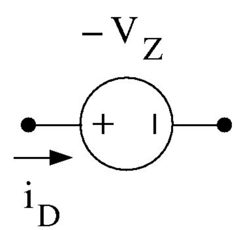
ON:



OFF:

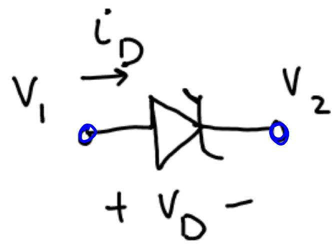


Zener:



Zener Diode piecewise-linear model

Assume Zener diode with $V_D = 0.7\ V$ and $V_Z = 5\ V$.



Ⓐ When $0 < V_1 - V_2 < 0.7$, diode is forward-biased, but it's not ON, yet. $\Rightarrow$ $i_D = 0$

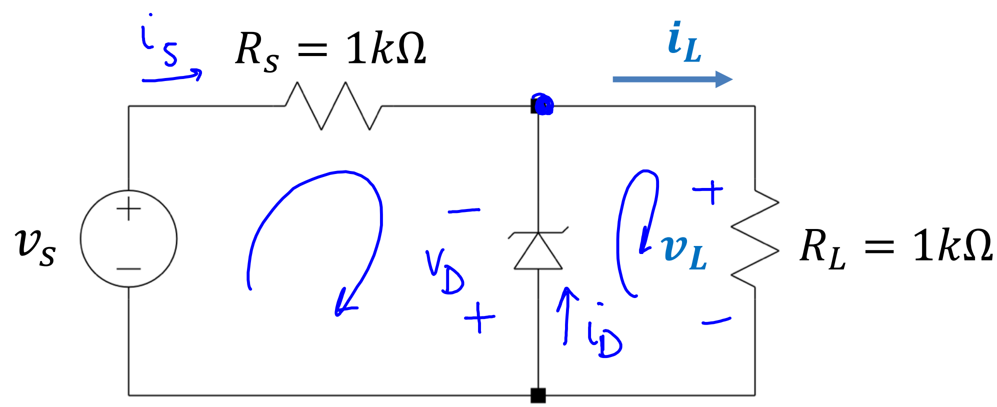
Ⓑ When $-5 < V_1 - V_2 < 0$, diode is reverse-biased, but it's not in the Zener region, so it's off. $\Rightarrow$ $i_D = 0$

Ⓒ When $V_1 - V_2 = 0.7$, diode is forward-biased and it's ON $\Rightarrow$ $i_D \geq 0$ and $V_D = V_{D_0} = 0.7\ V$.

Ⓓ When $V_1 - V_2 = -5\ V$, diode is in Zener region, it conducts, $\Rightarrow$ $i_D \leq 0$ and $V_D = -V_Z = -5\ V$

Example:

In the following circuit, find i_L and v_L for $v_s = 10\ V$. For what range of v_s and R_L the Zener diode will be in the Zener region and the circuit can operate as a voltage regulator? $(V_Z = 3\ V, V_{D0} = 0.7\ V)$



KCL:

$$\boxed{i_s + i_D - i_L = 0}$$

KVL:

$$\boxed{V_s = R_s i_s - V_D}$$

$$V_D + V_L = 0 \rightarrow \boxed{V_L = -V_D}$$

Assume the diode is in the Zener region:

$$\boxed{V_D = -V_Z},\ \boxed{i_D < 0}$$

$$\boxed{V_L = V_Z = 3V}$$

$$i_L = \frac{V_L}{R_L} = \frac{3V}{1k} = 3mA\ ,\ \boxed{i_L = 3mA}$$

$$i_s = \frac{V_s + V_D}{R_s} = \frac{10V - 3V}{1k}$$

$$\boxed{i_s = 7mA}$$

$$i_D = i_L - i_s = 3mA - 7mA$$

$$= -4mA < 0$$

when the diode is in the Zener region, $i_D \leq 0$.

$$i_D = i_L - i_s \leq 0 \longrightarrow \boxed{i_s \geq i_L}$$

$$V_L = V_Z \quad , \quad \boxed{i_L = \frac{V_L}{R_L} = \frac{V_Z}{R_L}}$$

$$\boxed{i_s = \frac{V_s - V_Z}{R_s}}$$

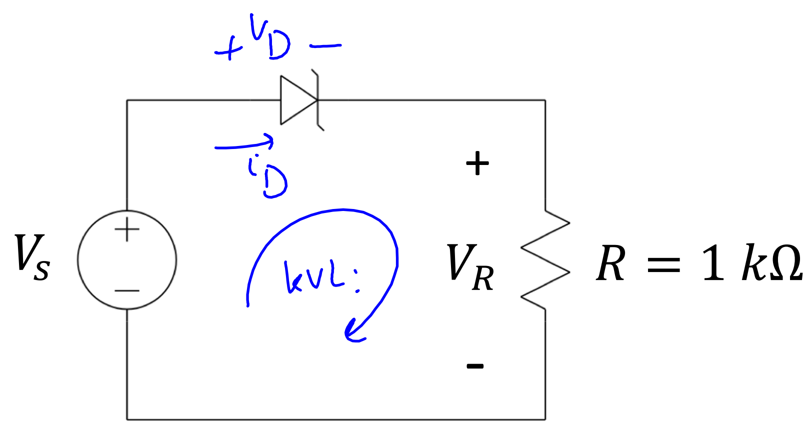
$$\boxed{\frac{V_s - V_Z}{R_s} \geq \frac{V_Z}{R_L}}$$

$$\frac{V_s}{R_s} \geq V_Z \left(\frac{1}{R_L} + \frac{1}{R_s} \right) \longrightarrow V_s \geq \underline{\underline{V_Z \left(1 + \frac{R_s}{R_L} \right)}}$$

$$\frac{V_s/V_Z - 1}{R_s} \geq \frac{1}{R_L} \longrightarrow R_L \geq \boxed{\frac{R_s}{V_s/V_Z - 1}}$$

Lecture 3 reading quiz

In the following circuit, find V_R for $V_s = +5\ V$ and $V_s = -5\ V$. Assume $V_Z = 3\ V$ and $V_{Do} = 0.7\ V$.



$\boxed{V_s = 5V}$

Assume diode is in Zener

$V_D = -V_Z$, $\boxed{i_D < 0}$

KVL: $V_s = V_D + R\, i_D$

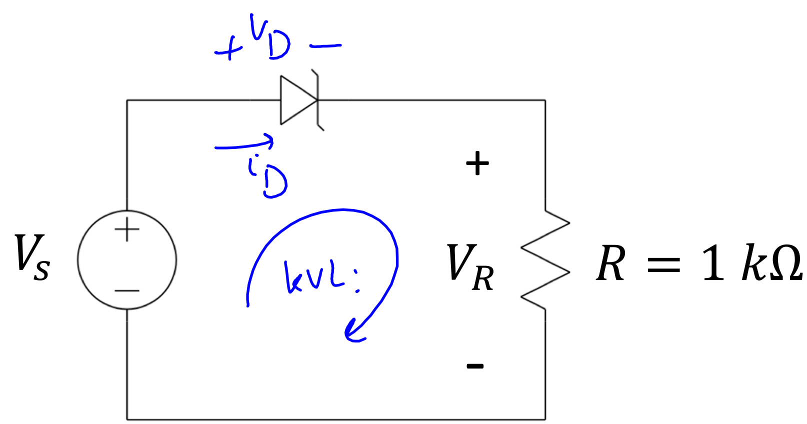
$5 = -3 + 1\,k\Omega \times i_D \longrightarrow i_D = 8mA > 0$

Assumption was wrong.

Lecture 3 reading quiz

In the following circuit, find V_R for $V_s = +5\ V$ and $V_s = -5\ V$. Assume $V_Z = 3\ V$ and $V_{Do} = 0.7\ V$.

$\boxed{V_s = 5V}$



Assume the diode is ON,

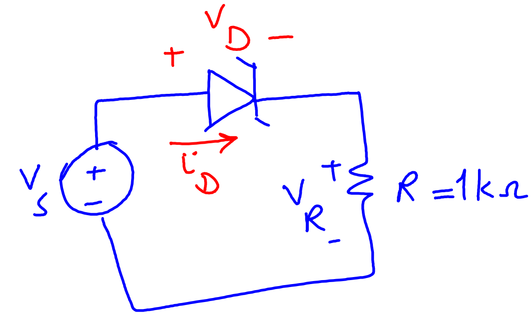
$V_D = V_{D_0}$ and $\boxed{i_D \geq 0}$

Assumption was correct

KVL : $V_s = V_D + R i_D \longrightarrow 5 = 0.7 + 1k\Omega \times i_D \longrightarrow \boxed{i_D = 4.3\ mA > 0}$

$V_R = 1k\Omega \times i_D = 4.3\ V$

For $\boxed{V_s = -5\,V}$,



Assume diode is in zener region:

$V_D = -V_Z$, $\boxed{i_D \leq 0}$

KVL: $V_s = V_D + 1k\Omega \times i_D$

$-5V = -3V + 1k\Omega \times i_D \longrightarrow i_D = -2mA < 0$

Assumption was correct and the diode is in the Zener region.

$V_R = 1k\Omega \times i_D = -2V$

---

what if we assumed the diode was off for $V_s = -5V$

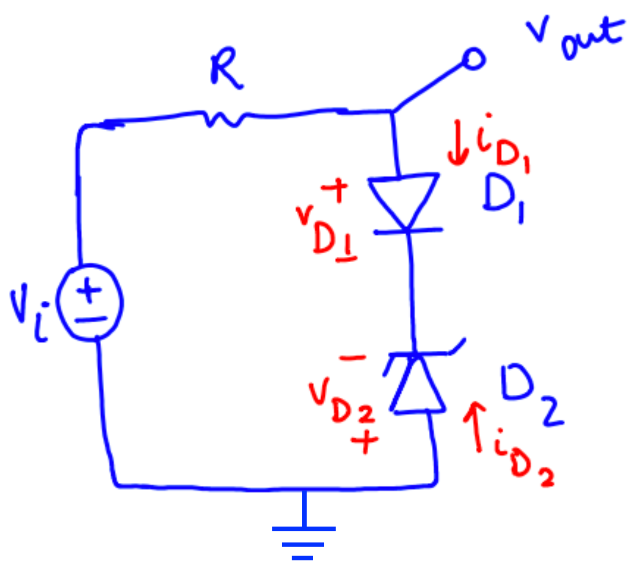
Diode off: $i_D = 0$, $-3V < V_D < 0.7V$

$V_S = V_D + R\,i_D \longrightarrow V_S = V_D = -5V < -3V \Longrightarrow$ Assumption was wrong.

Discussion question 1.

In the below circuit find the range of v_i for which D_1 is ON and D_2 is in the Zener region. Calculate v_{out}.

Are there any other possible states at which D_1 and D_2 can operate? Assume $V_{D0} = 0.7\ V$ and $V_Z = 5\ V$.

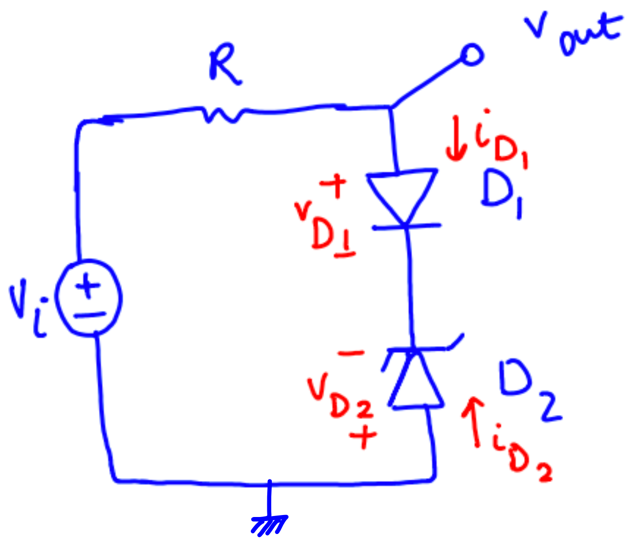


Extra activity: find v_{out} for all ranges of v_i (solve the circuit parametrically).

Discussion question 1.

$V_{D_0} = 0.7\,V \;,\quad V_Z = 5V$

Solve the following circuit parametrically.



	D_1	D_2	
	ON	ON	✗
	ON	OFF	✗ Diodes are in series
A	ON	Zener	✓
	OFF	ON	✗ Diodes are in series
B	OFF	OFF	✓
	OFF	Zener	✗ Diode are in series

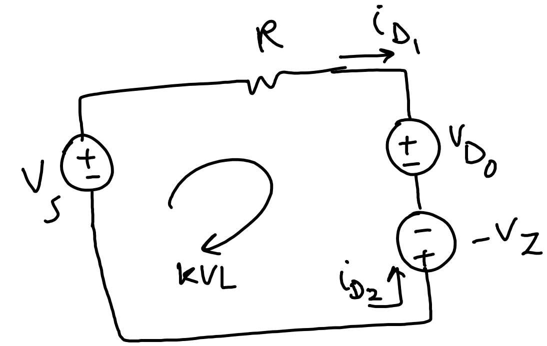
D_1 and D_2 cannot be forward biased and ON, because:

D_1 ON $\longrightarrow i_{D_1} \geq 0 \;,\quad v_{D_1} = 0.7\,V$

D_2 ON $\longrightarrow i_{D_2} \geq 0 \;,\quad v_{D_2} = 0.7\,V$

KCL: $i_{D_1} = -i_{D_2} \Longrightarrow$ both can't be ON at the same time.

(A) when D_1 is ON & D_2 is in zener :



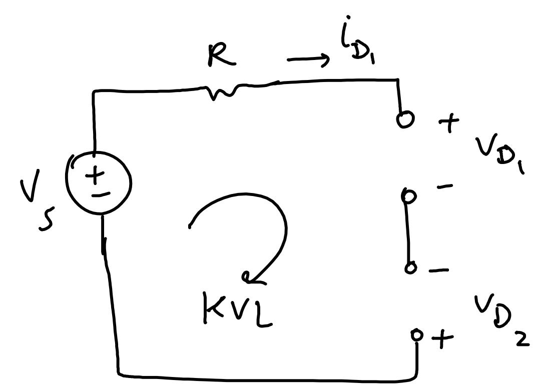
D_1 ON $\longrightarrow$ $i_{D_1} \geq 0$ & $V_{D_1} = V_{D_0} = 0.7V$

D_2 Zener $\longrightarrow$ $i_{D_2} \leq 0$ & $V_{D_2} = -V_Z = -5V$

KVL: $i_{D_1} = \dfrac{V_S - V_{D_0} - V_Z}{R} \geq 0 \longrightarrow V_S \geq V_Z + V_{D_0} \longrightarrow V_S \geq 5.7V$

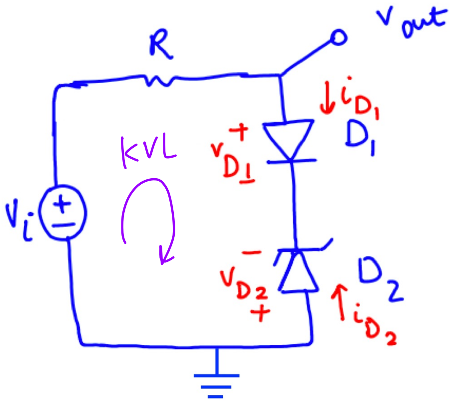
For $V_S \geq 5.7V$ $\longrightarrow$ D_1 is ON and D_2 is in Zener region

(B) when D_1 and D_2 are off :



D_1 off $\longrightarrow$ $i_{D_1} = 0$ & $V_{D_1} < V_{D_0}$

D_2 off $\longrightarrow$ $i_{D_2} = 0$ & $-V_Z < V_{D_2} < V_{D_0}$



when D_1 and D_2 are off:

D_1 off $\longrightarrow$ $i_{D_1}=0$ & $V_{D_1} < V_{D_0}$

D_2 off $\longrightarrow$ $i_{D_2}=0$ & $-V_Z < V_{D_2} < V_{D_0}$

KVL: $V_i = R \times i_{D_1} + V_{D_1} - V_{D_2} \Rightarrow V_i = V_{D_1} - V_{D_2}$

$-V_Z < V_{D_2} < V_{D_0} \longrightarrow -V_{D_0} < -V_{D_2} < V_Z$

also $V_{D_1} < V_{D_0}$. V_{D_1} in this range can have any value from $-\infty$ up to V_{D_0}.

As a result, we can write $-\infty < V_{D_1} < V_{D_0}$

* note: this is a theoretical range. There is a limit on negative V_D values.

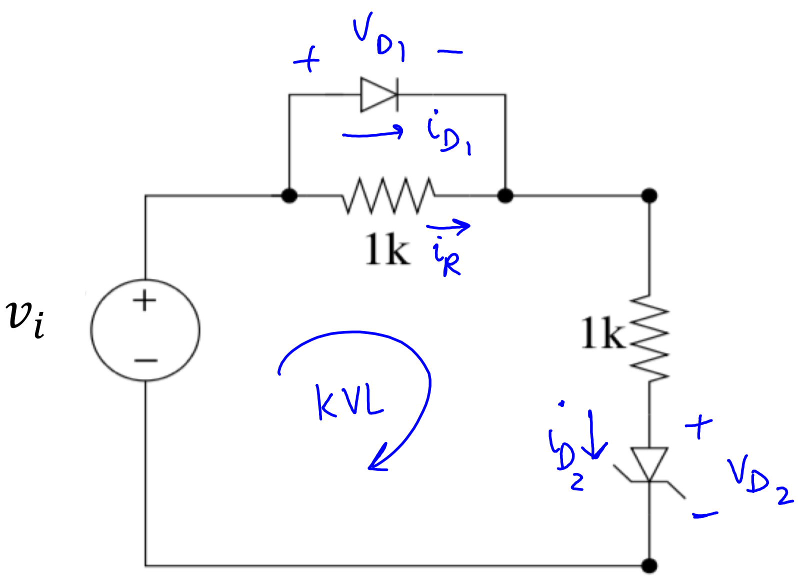
$\Rightarrow$ $-V_{D_0} < -V_{D_2} < V_Z$

$-\infty < V_{D_1} < V_{D_0}$

$\longrightarrow -\infty < \underbrace{\boxed{V_{D_1} - V_{D_2}}}_{V_i} < V_Z + V_{D_0}$ or $V_i < V_Z + V_{D_0}$

Clicker question 1:

What is the range of v_i for which both diodes are ON? Assume $V_Z = 4\ V$ and $V_{Do} = 0.7\ V$.



A. $v_i \geq 2.1$ V

B. $v_i \geq 1.4$ V

C. $v_i \geq 0.7$ V

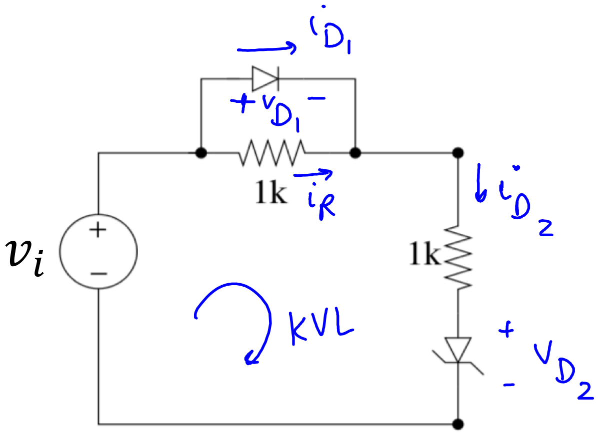
D. Both diodes cannot be ON simultaneously.

D_1 ON : $i_{D_1} \geq 0$

$V_{D_1} = V_{D_o}$

D_2 ON : $i_{D_2} \geq 0$

$V_{D_2} = V_{D_o}$



KCL: $i_{D_2} = i_{D_1} + i_R$, $i_{D_1} \geq 0$ and $i_{D_2} \geq 0$

Both current inequalities must be true when D_1 and D_2 are ON.

$$i_R = \frac{v_{D_1}}{1k} = \frac{0.7\,V}{1k\Omega} = 0.7\,mA$$

$$i_{D_2} = i_{D_1} + 0.7\,mA$$

KVL: $v_i = v_{D_1} + 1k \times i_{D_2} + v_{D_2} \longrightarrow v_i = 0.7V + 1k\Omega \times (i_{D_1} + 0.7mA) + 0.7V$

$$v_i = 2.1\,V + 1k\Omega \times i_{D_1} \longrightarrow i_{D_1} = \frac{v_i - 2.1V}{1k\Omega} \geq 0 \longrightarrow v_i \geq 2.1V$$

ECE 65: Components & Circuits Lab

Lecture 6

Diode waveform shaping circuits

Rectifier circuits

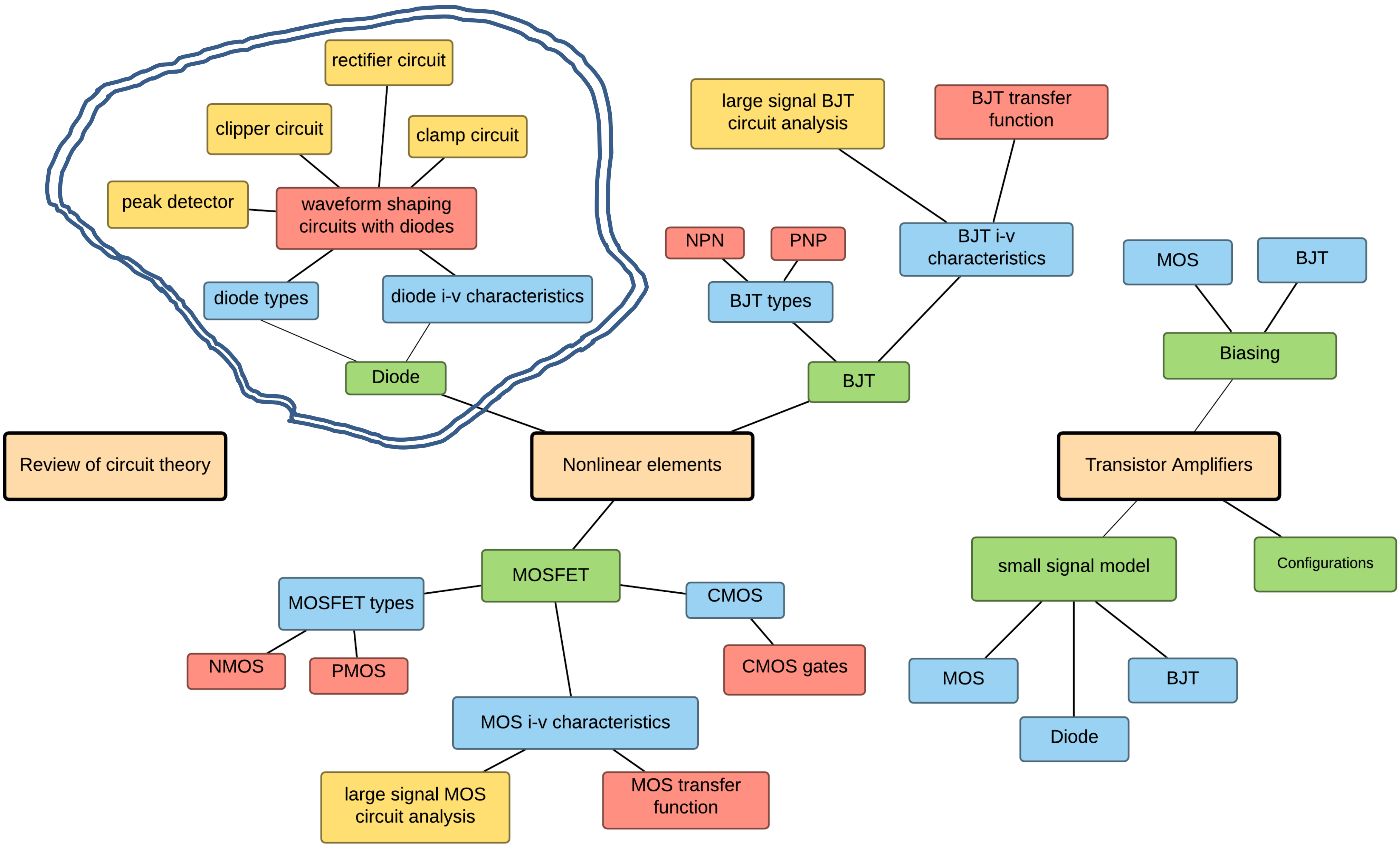
Reference notes: sections 2.9

Sedra & Smith (7th Ed): sections 4.4-4.6

Saharnaz Baghdadchi

Course map

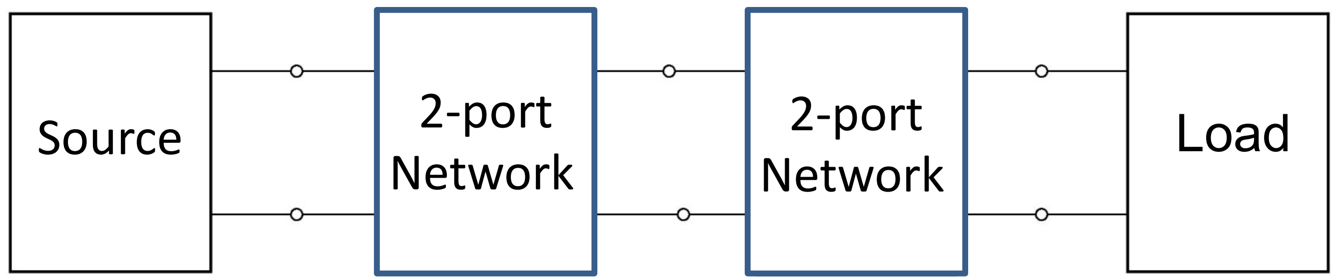
2. Diodes

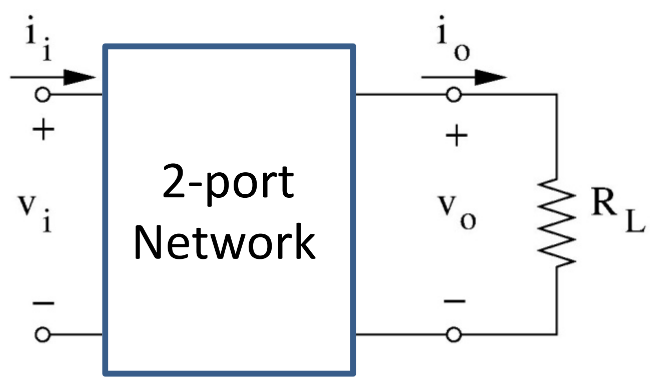


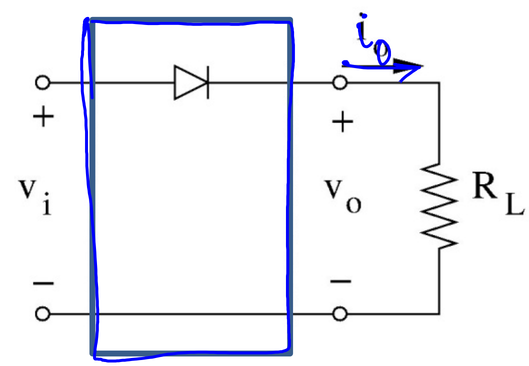
Diodes Waveform shaping Circuits

1. Rectifier Circuit
2. Clipper Circuit
3. Peak Detector
4. Clamp Circuit

Diode waveform shaping circuits as two-port networks







We would like to find the transfer function, v_o vs v_i

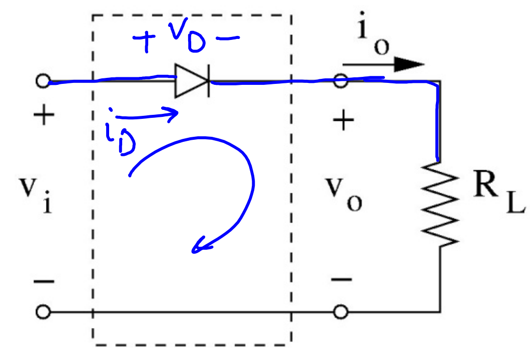
"Open-loop" Transfer function is v_o vs v_i when $R_L \to \infty$ or $i_o = 0$.

Rectifier Circuit

KVL: $v_i = v_D + v_o \rightarrow v_o = v_i - v_D$

Ohm's law: $i_D = v_o/R_L$

$i_D = i_o$



Diode OFF: $i_D = 0$ & $v_D < V_{D0}$

$v_o = R_L i_D = 0$

$v_i = v_D + v_o \Rightarrow v_i = v_D < V_{D0} \longrightarrow v_i < V_{D0}$

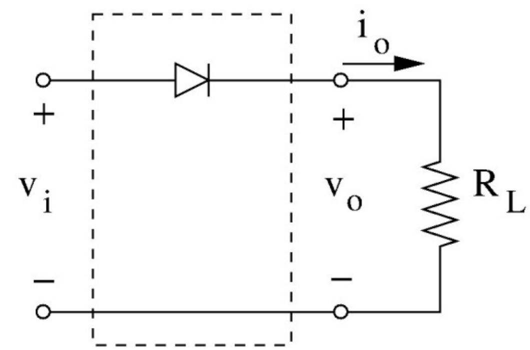
Diode ON: $v_D = V_{D0}$ & $i_D \geq 0$

$v_o = v_i - V_{D0}$

$i_D = \dfrac{v_i - v_D}{R} = \dfrac{v_i - V_{D0}}{R} \geq 0 \longrightarrow v_i \geq V_{D0}$

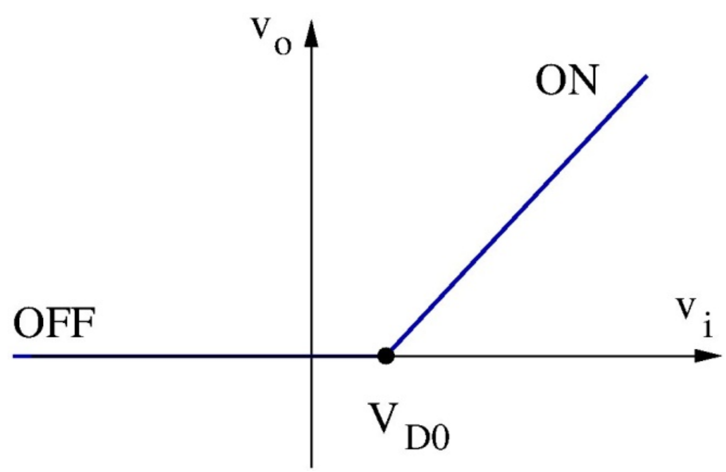
Rectifier Circuit

Transfer Function is non-linear:

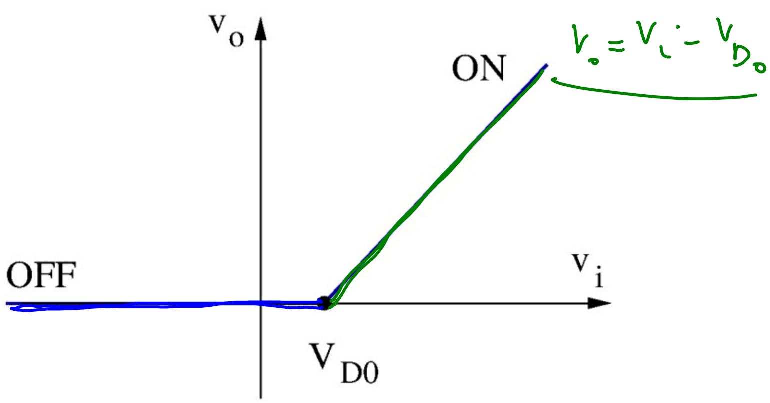


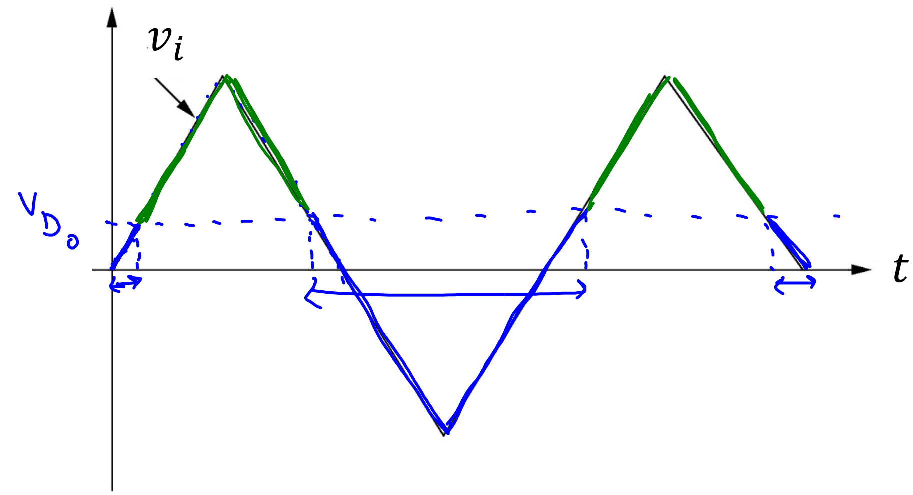
For $v_i \geq V_{D0}$, $v_o = v_i - V_{D0}$ (Diode is ON)

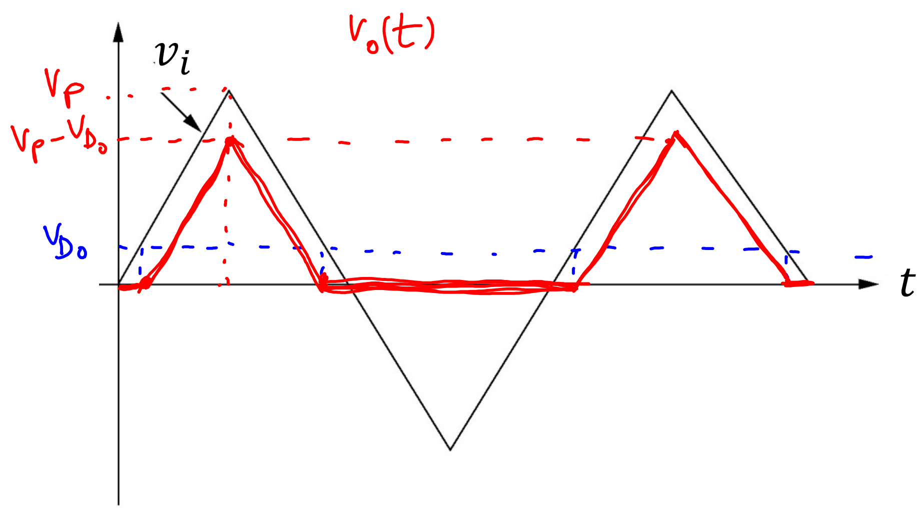
For $v_i < V_{D0}$, $v_o = 0$ (Diode is OFF)

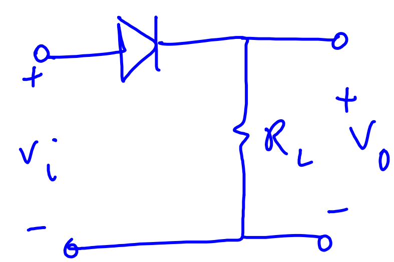


Rectifier Circuit:
example input - output waveforms



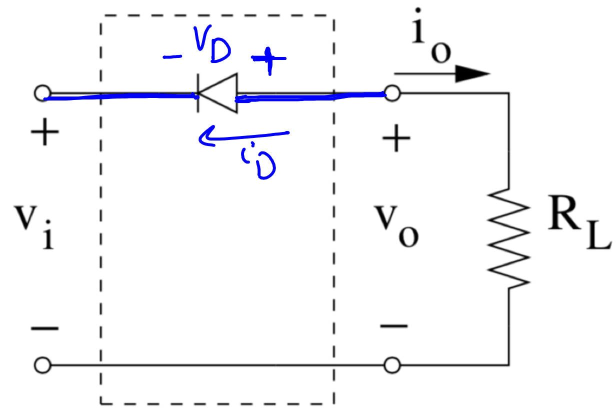






Rectifier Circuit for the negative part of v_i

Transfer Function is non-linear:



For $v_i \leq -V_{D0}$, $\underline{v_o = v_i + V_{D0}}$ (Diode is ON)

For $v_i > -V_{D0}$, $v_o = 0$ (Diode is OFF) → $i_D = 0$

Diode ON: $i_D \geq 0$, $V_D = V_{D_0}$

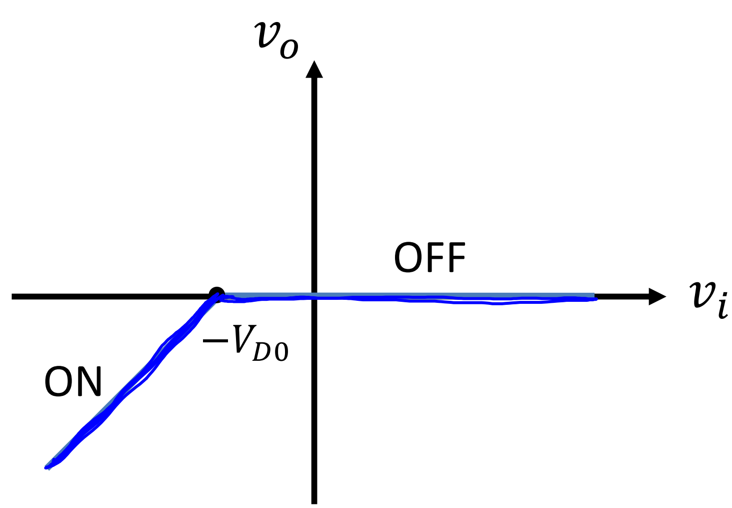
KVL:

$v_i = -V_D - R_L i_D$

$\rightarrow i_D = \dfrac{-V_D - v_i}{R_L}$

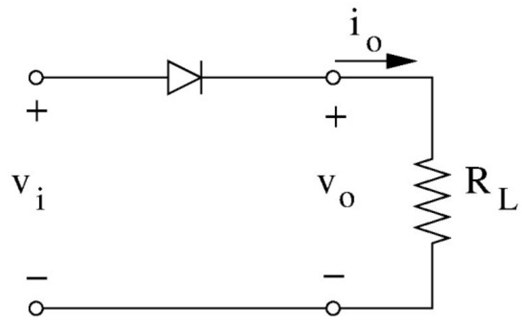
$i_D = \dfrac{-V_{D_0} - v_i}{R_L} \geq 0$

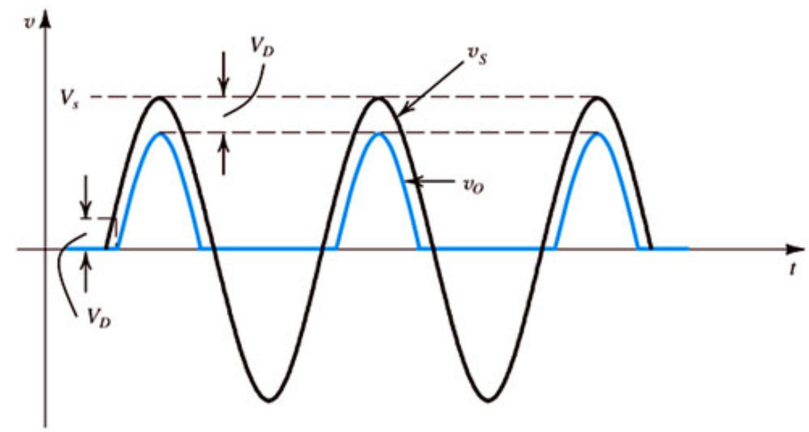
$\rightarrow v_i \leq -V_{D_0}$



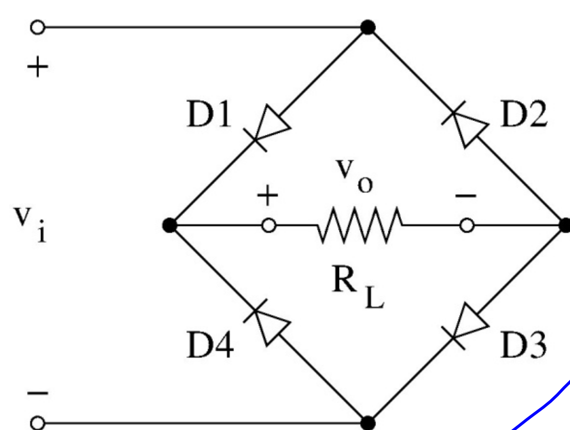
Application of Rectifier Circuit: AC to DC convertor for power supply

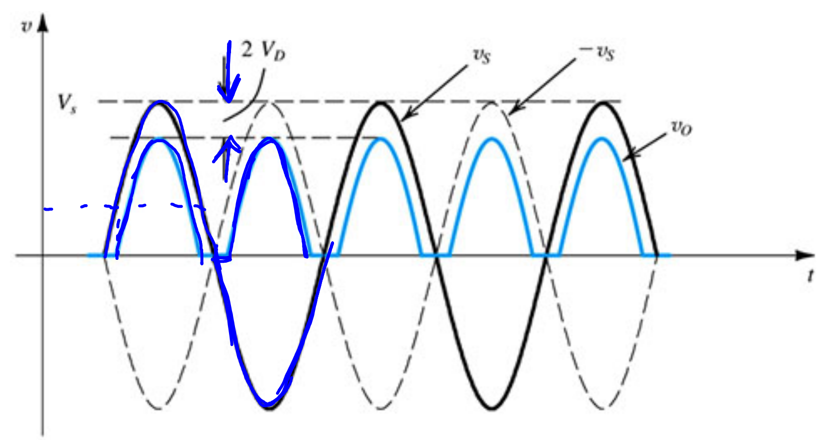
Half-wave rectifier



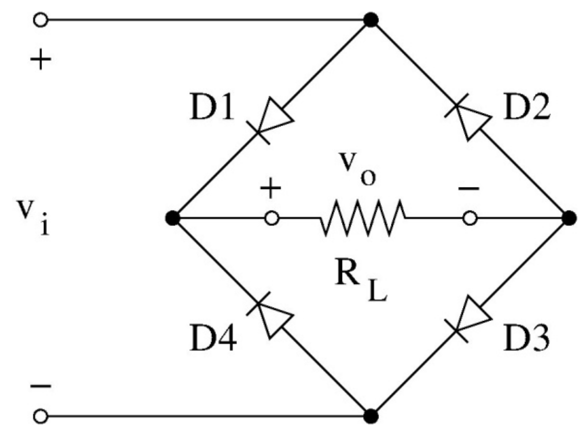


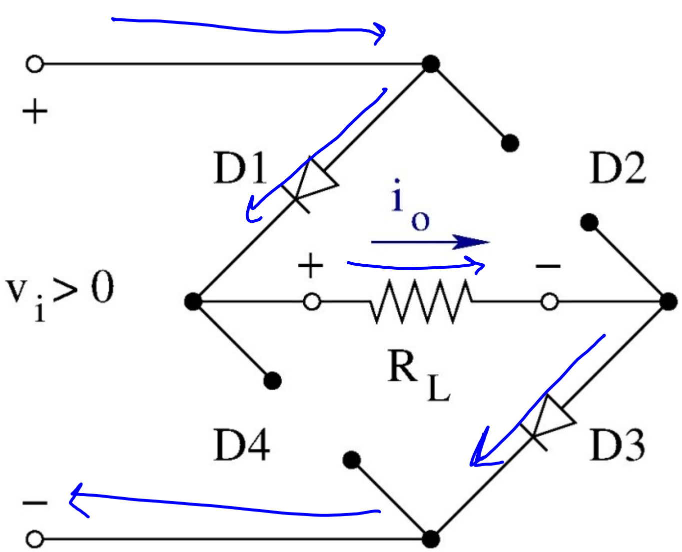
Full-wave rectifier

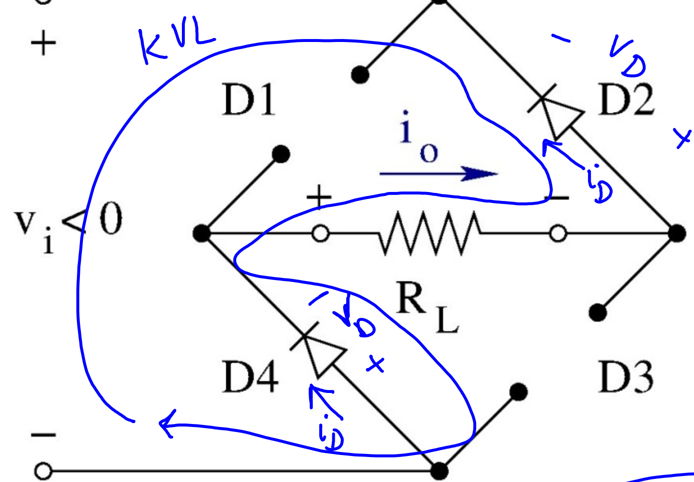




Each pair of diodes conduct only for half of the cycle







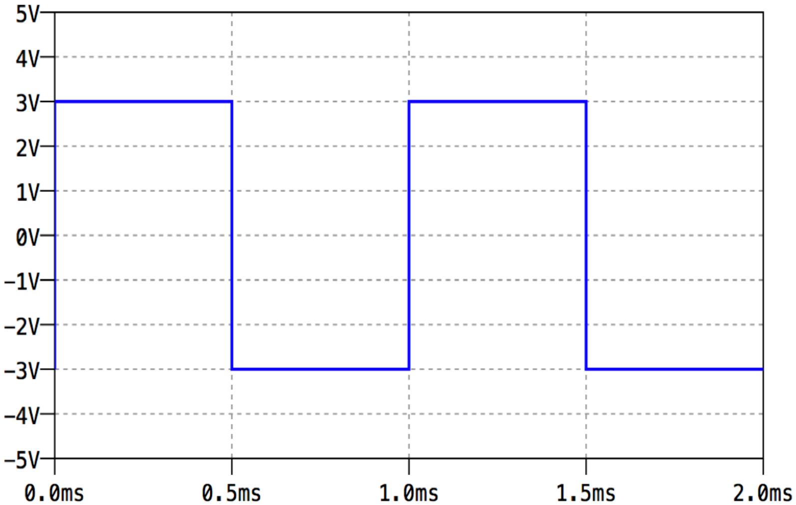
$-V_i - V_{D_o} - V_o - V_{D_o} = 0 \rightarrow V_o = \boxed{-V_i - 2V_{D_o}}$

$V_i \le -2V_{D_o}$

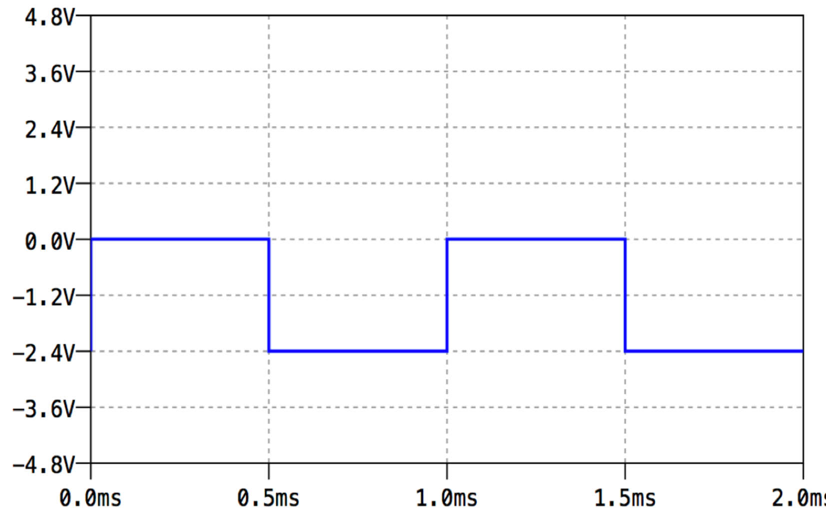
Lecture 6 reading quiz

Which one of the circuits in the provided options could produce the shown output waveform for the given input signal?

$v_i(\mathrm{t})$

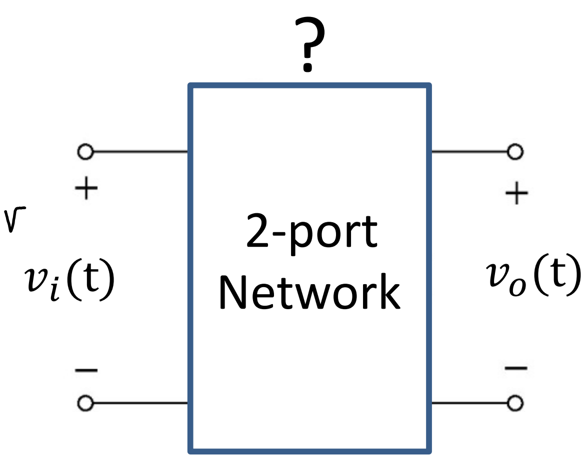


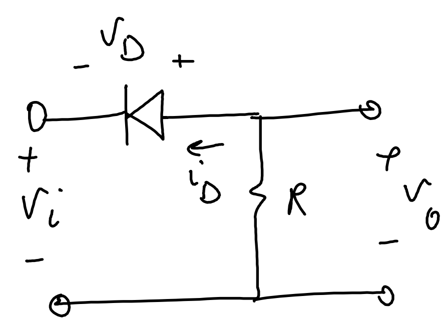
$v_o(\mathrm{t})$



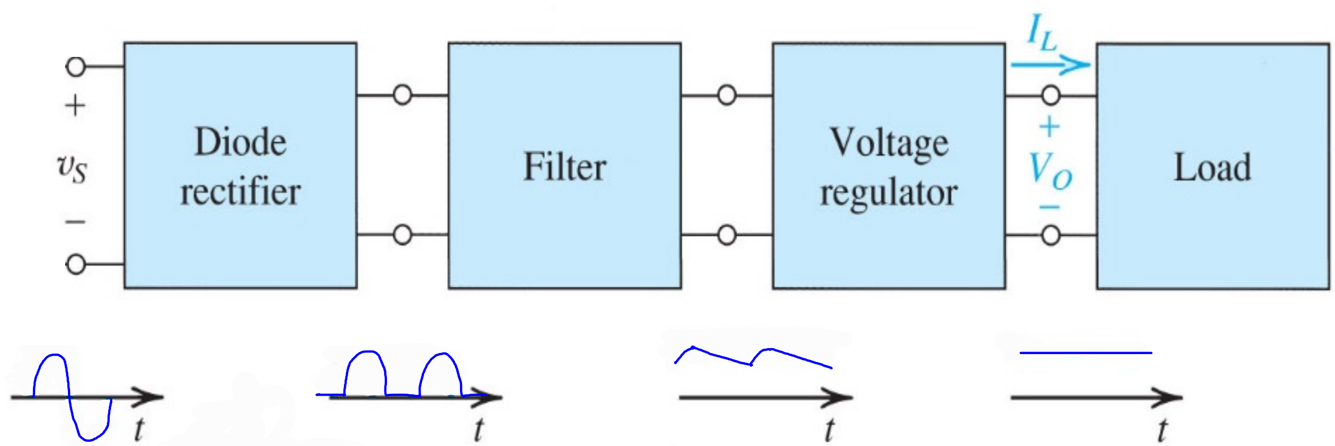
for $V_i = +3V \longrightarrow V_o = 0$

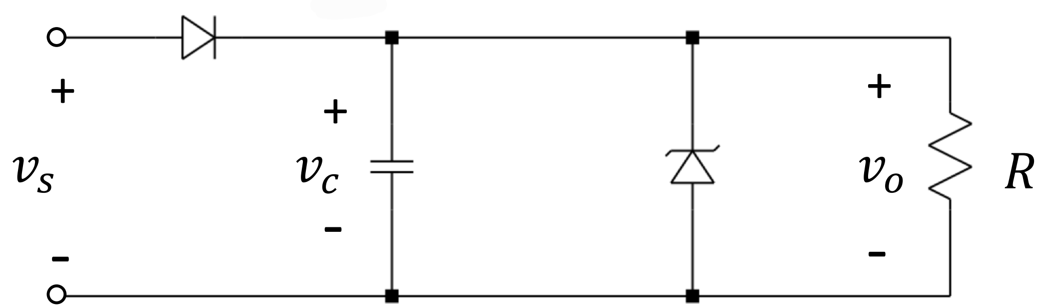
for $V_i = -3V \longrightarrow V_o = V_i + 0.6V$





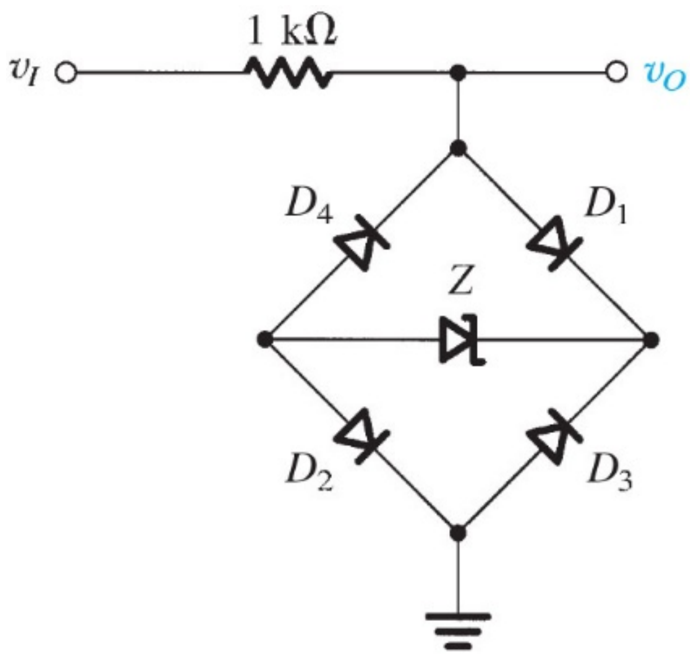
Block Diagram of a DC Power Supply





Discussion question 1.

Plot the transfer function of the following circuit. Find v_o for different ranges of v_i and plot a graph that shows the relationship between v_i and v_o. Assume $V_{D0}= 0.7\ V$, $V_Z= 4\ V$.



Case 1:
D1 and D2 ON, D5 in the Zener mode, D3 and D4 off

Case 2:
D1 and D2 Off, D5 in the Zener mode, D3 and D4 ON

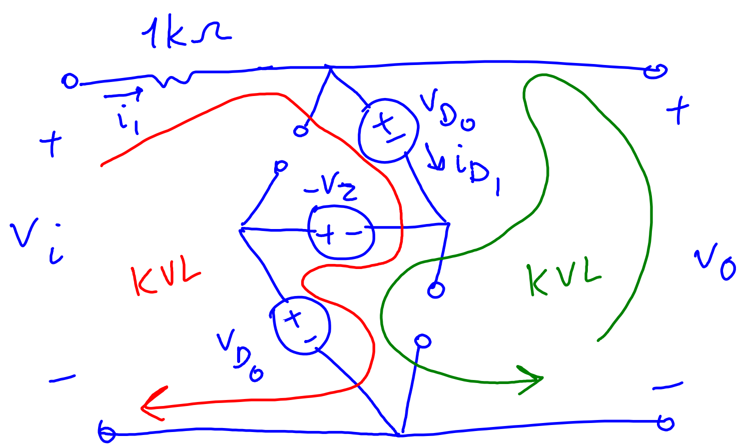
Case 3:
D1, D2, D5, D3, and D4 all off

Extra activity:

Draw the output voltage waveform if $v_i = 2\sin(\omega t)$.

There are three possible cases for the operation of the diodes:

$\boxed{\text{Case 1:}}$ D_1 and D_2 are ON and D_5 is in Zener region. D3 and D4 are off



KVL: $-V_i + 1k\Omega \times i_1 + V_{D_0} - (-V_Z) + V_{D_0} = 0$

$i_1 = i_{D_1}$

D_1 is ON $\longrightarrow$ $i_{D_1} \geq 0$

$\longrightarrow$ $i_{D_1} = \dfrac{V_i - 2V_{D_0} - V_Z}{R} \geq 0$

$\Rightarrow$ $V_i \geq 2V_{D_0} + V_Z$

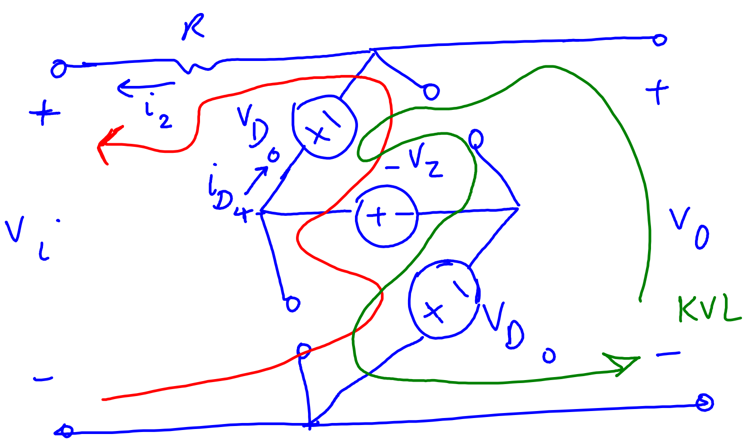
KVL:

$$-V_0 + V_{D_0} - (-V_Z) + V_{D_0} = 0$$

$\Rightarrow$ $V_0 = 2V_{D_0} + V_Z$

$\boxed{\text{Case 2:}}$ D_3 and D_4 are ON and D_5 is in Zener region.

D1 and D2 are off



KVL: $+V_{D_0} - (-V_Z) + V_{D_0} + R i_2 + V_i = 0$

$i_2 = i_{D_4}$

D_4 is ON $\rightarrow i_{D_4} \geq 0$

$$\rightarrow i_{D_4} = \frac{-V_i - 2V_{D_0} - V_Z}{R} \geq 0$$

$$\Rightarrow V_i \leq -2V_{D_0} - V_Z$$

KVL:

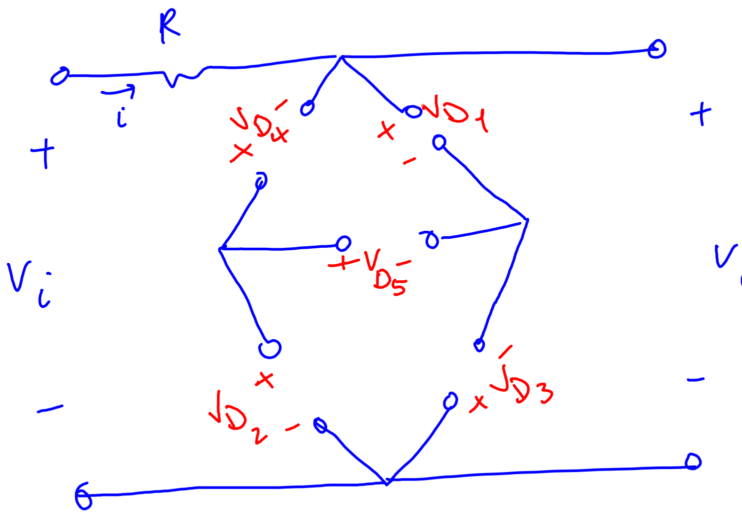
$$-V_0 - V_{D_0} + (-V_Z) - V_{D_0} = 0$$

$$V_0 = -2V_{D_0} - V_Z$$

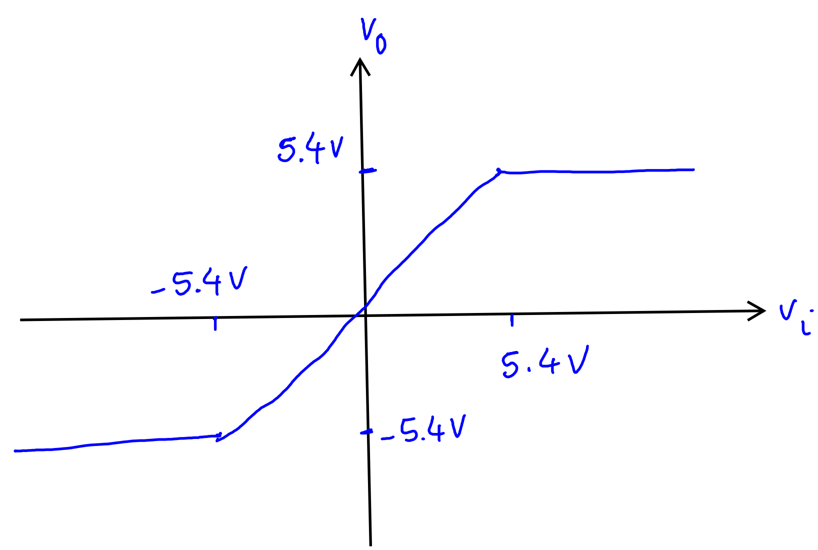
Case 3 : All the diodes are off.

$i = 0$

$V_o = -Ri + V_i \longrightarrow V_o = V_i$



$-2V_{D_0} - V_Z < V_i < 2V_{D_0} + V_Z$

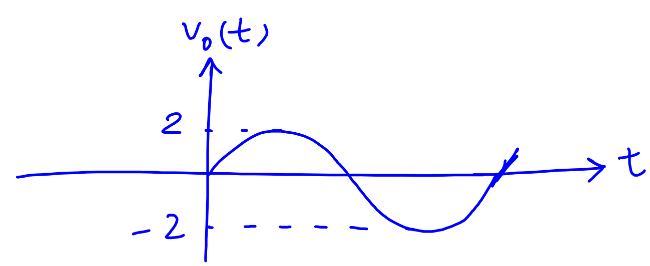


we will use the transfer function to draw the output of the circuit for

$v_i(t) = 2\sin(\omega t)$

Amplitude of v_i changes between $+2V$ and $-2V$

$\Rightarrow V_o = 2\sin(\omega t)$



ECE 65: Components & Circuits Lab

Lecture 7

Diode waveform shaping circuits

Clipper circuits

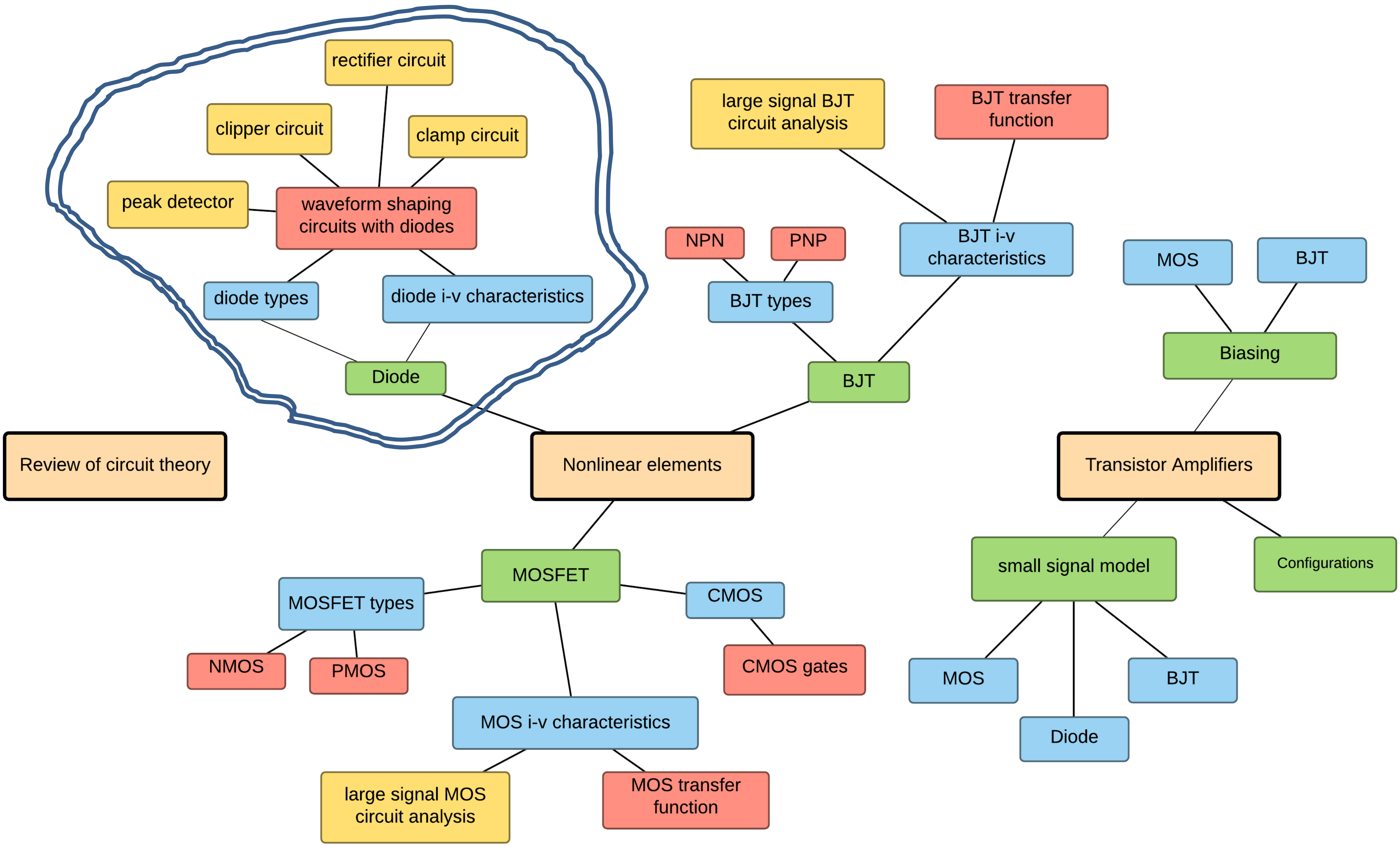
Reference notes: sections 2.9

Sedra & Smith (7th Ed): sections 4.4-4.6

Saharnaz Baghdadchi

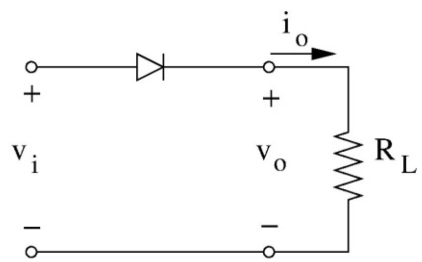
Course map

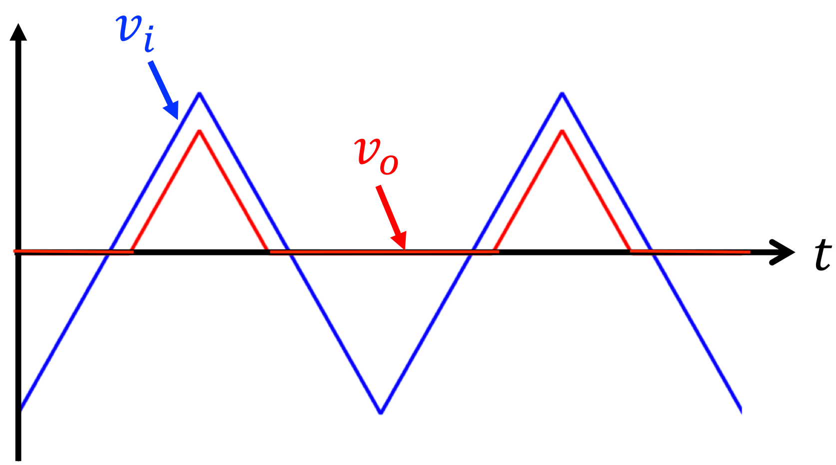
2. Diodes



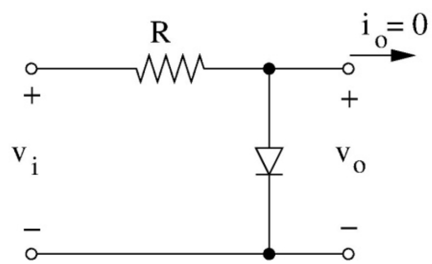
Rectifier & clipper circuits

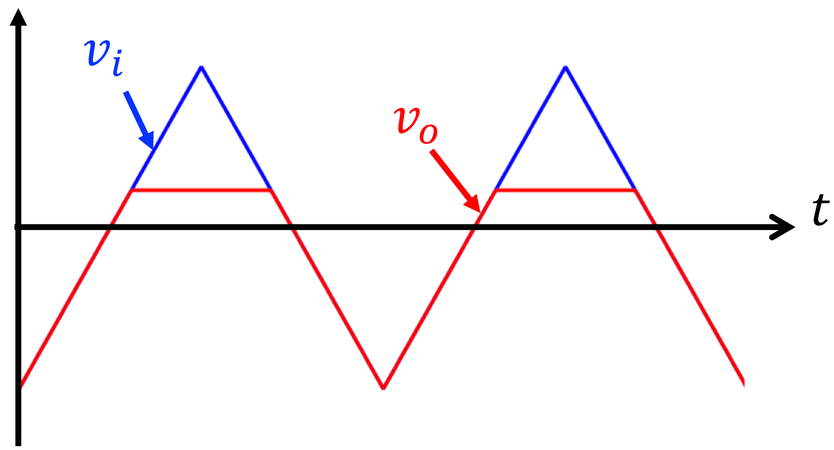
Half-wave Rectifier





Clipper



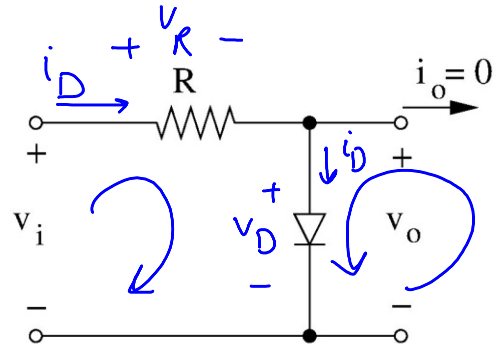


Clipper or Limiter Circuit

KVL: $v_i = v_R + v_D$ ✓

KVL: $v_o = v_D$ ✓

Ohm's law: $i_D = v_R/R$



$-v_o + v_D = 0$

$v_o = v_D$

Diode OFF: $i_D = 0$ & $\boxed{v_D < V_{D0}}$

$v_i = v_R + v_D = v_R + v_o = R \times i_D + v_o \longrightarrow v_i = v_o$

$v_i = v_R + v_D \longrightarrow v_i = v_D < V_{D0} \longrightarrow v_i < V_{D0}$

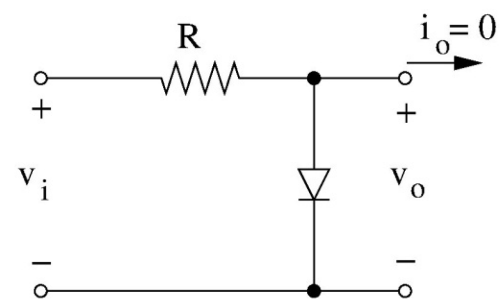
Diode ON: $v_D = V_{D0}$ & $\boxed{i_D \geq 0}$

$v_o = v_D = V_{D0}$, $v_o = V_{D0}$

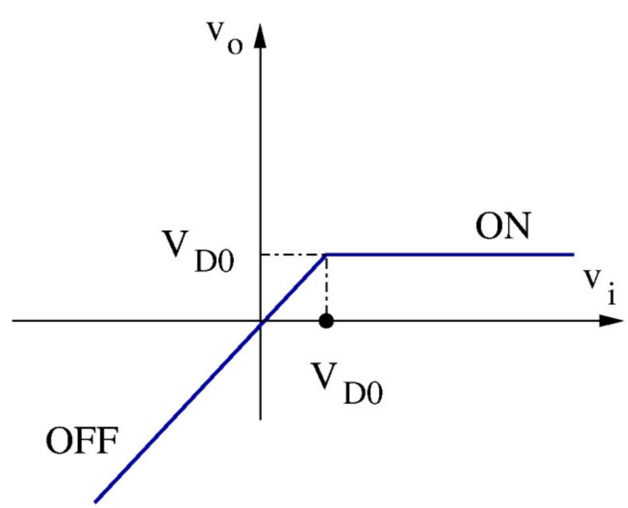
$i_D = \frac{v_i - V_{D0}}{R} \geq 0 \longrightarrow v_i \geq V_{D0}$

Clipper Circuit
open loop transfer function

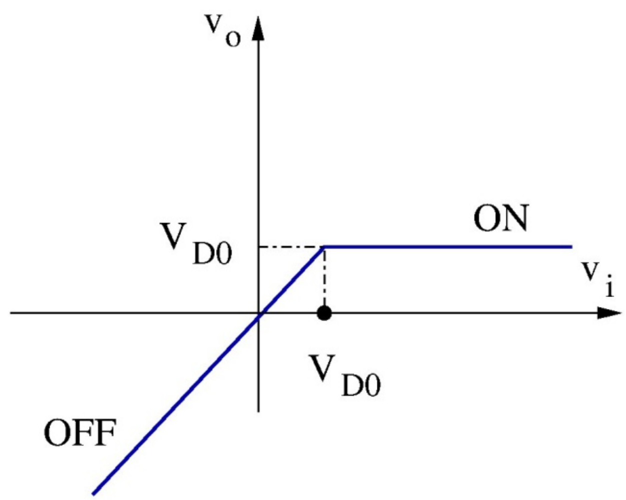
Transfer Function is non-linear:

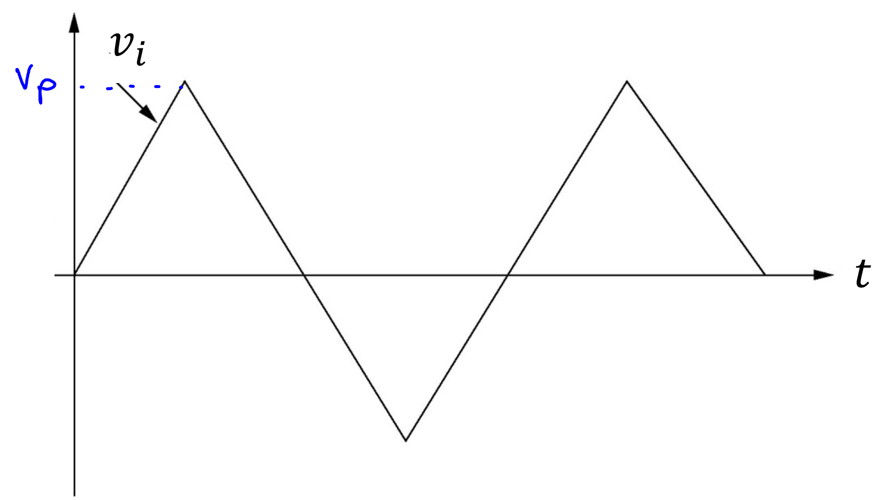


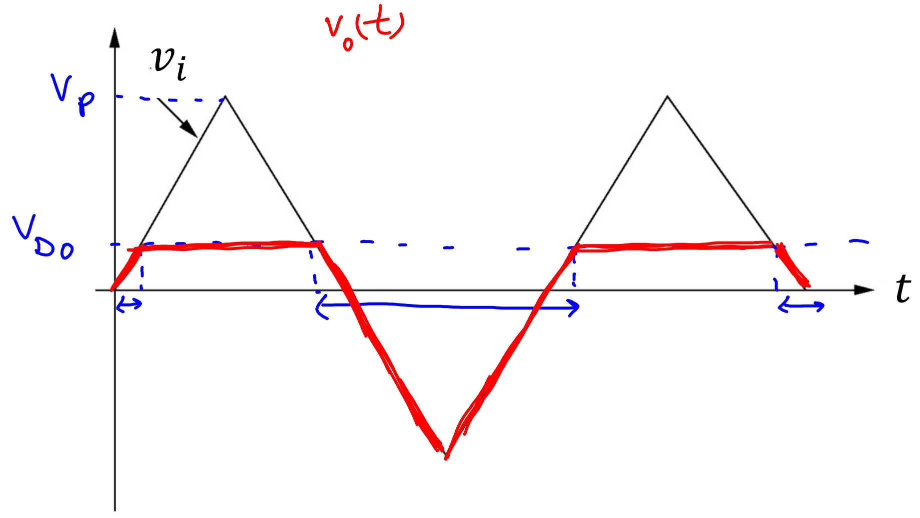
$$\begin{cases} \text{For } v_i \geq V_{D0}\,, \quad v_o = V_{D0} & \text{(Diode is ON)} \\ \text{For } v_i < V_{D0}\,, \quad v_o = v_i & \text{(Diode is OFF)} \end{cases}$$



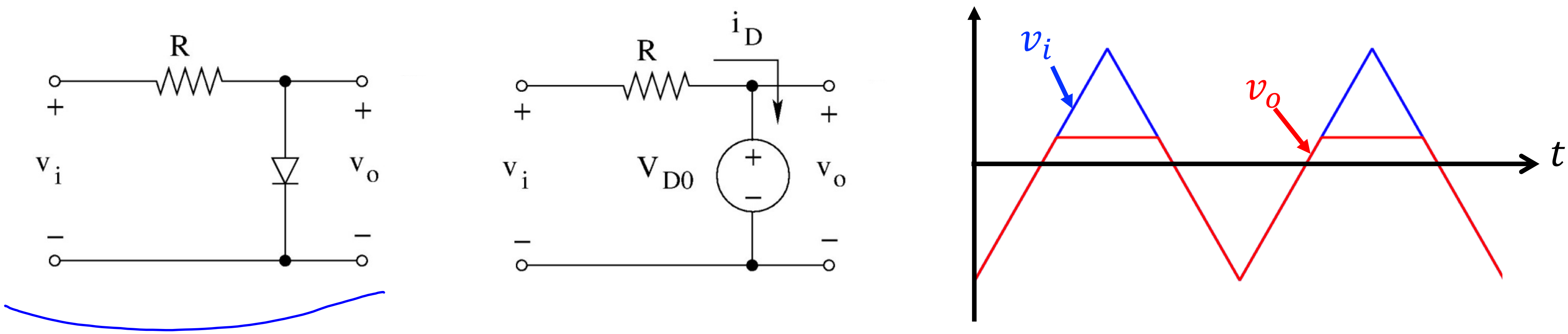
Clipper Circuit: example input-output waveforms

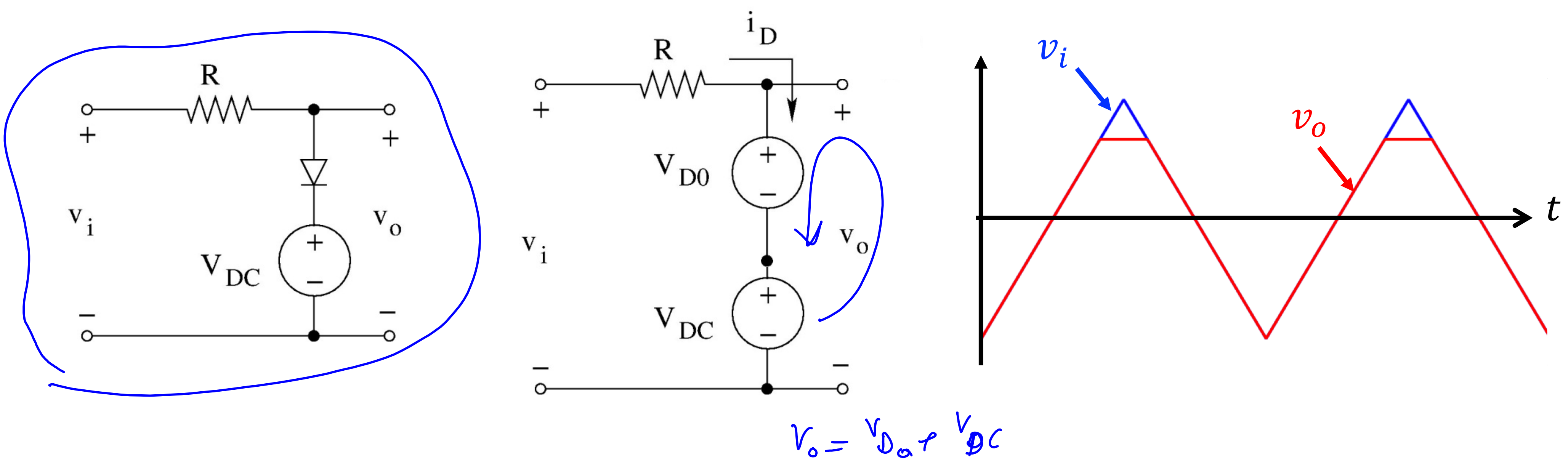




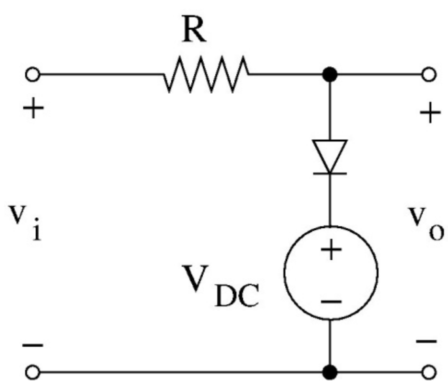


Adjusting the limiting voltage in the clipper circuit

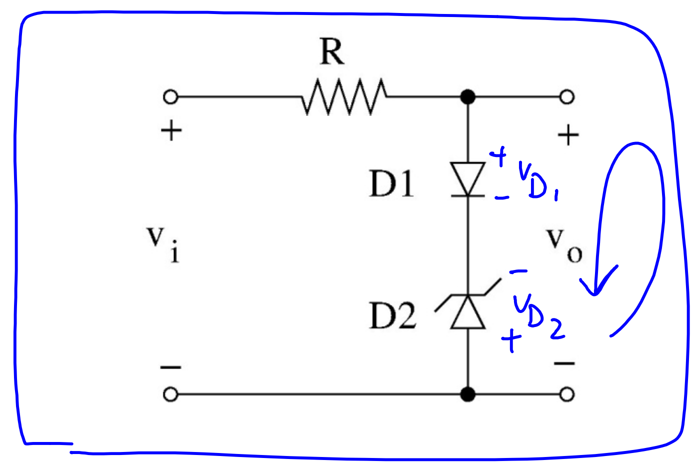




Using Zener diodes to adjust the limiting voltage in the clipper circuit



v_o **limited to ≤** $V_{D0} + V_Z$



D₁ is ON

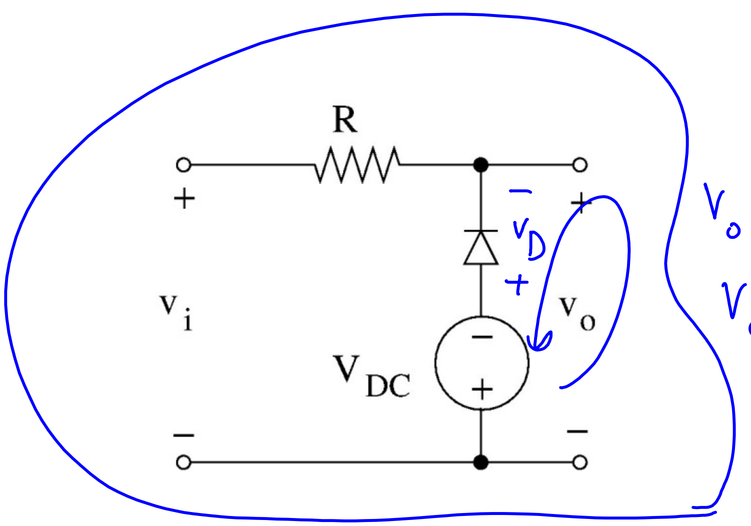
D₂ is Zener

$V_{D_1} = V_{D_0}$

$V_{D_2} = -V_Z$

$V_o = V_{D_1} - V_{D_2}$

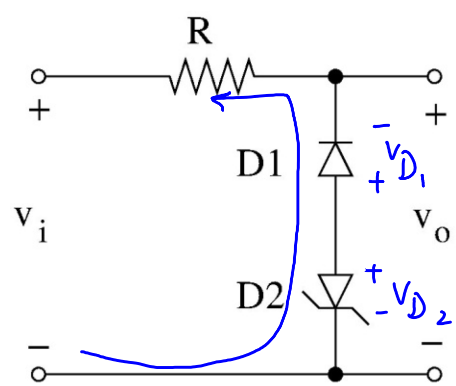
$V_o = V_{D_0} + V_Z$



$V_o = -V_D - V_{DC}$

$V_o = -V_{D_0} - V_{DC}$

v_o **limited ≥** $-V_{D0} - V_Z$



$V_{D_1} = V_{D_0}$

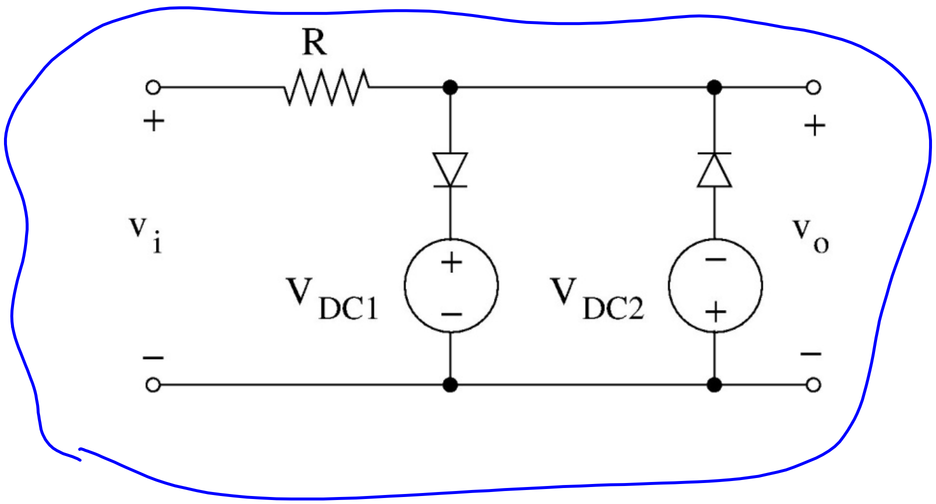
$V_{D_2} = -V_Z$

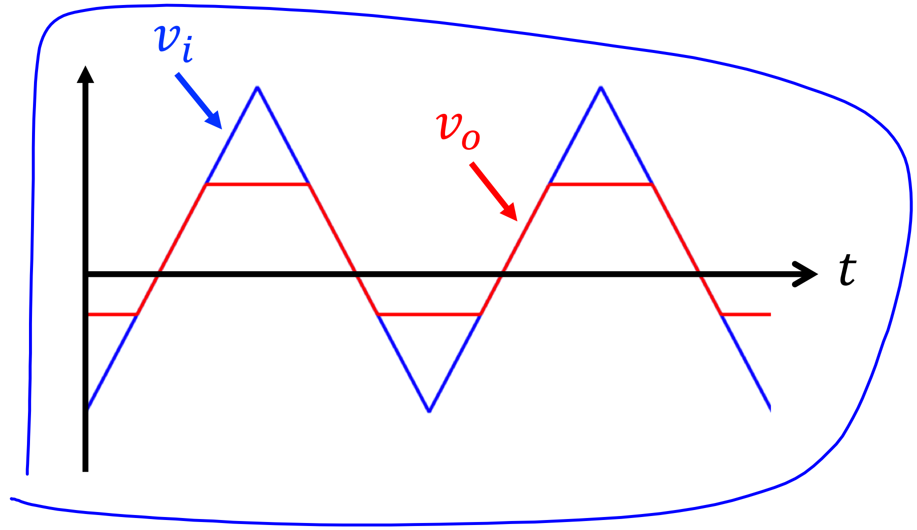
$v_o = -V_{D_0} - V_Z$

$V_o = -V_{D_1} + V_{D_2}$

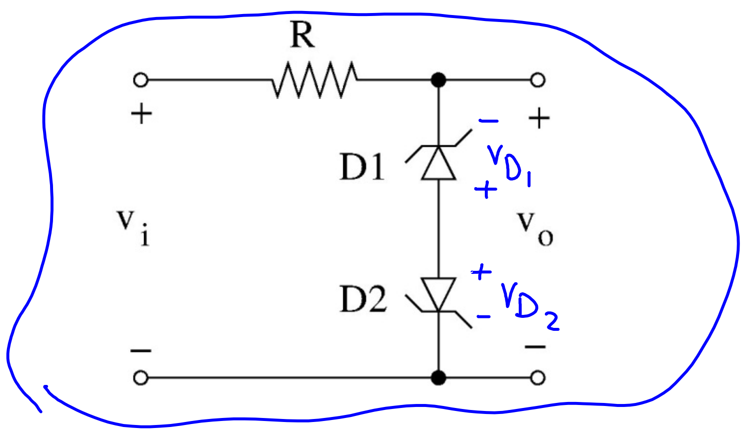
Clipping both the top & bottom portions of the signal simultaneously

v_o **limited to** $\leq V_{D0} + V_{DC1}$ **and** $\geq - V_{D0} - V_{DC2}$



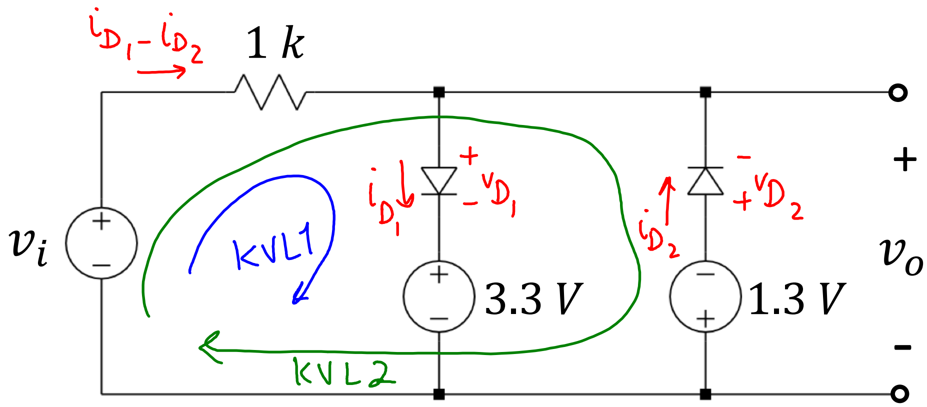


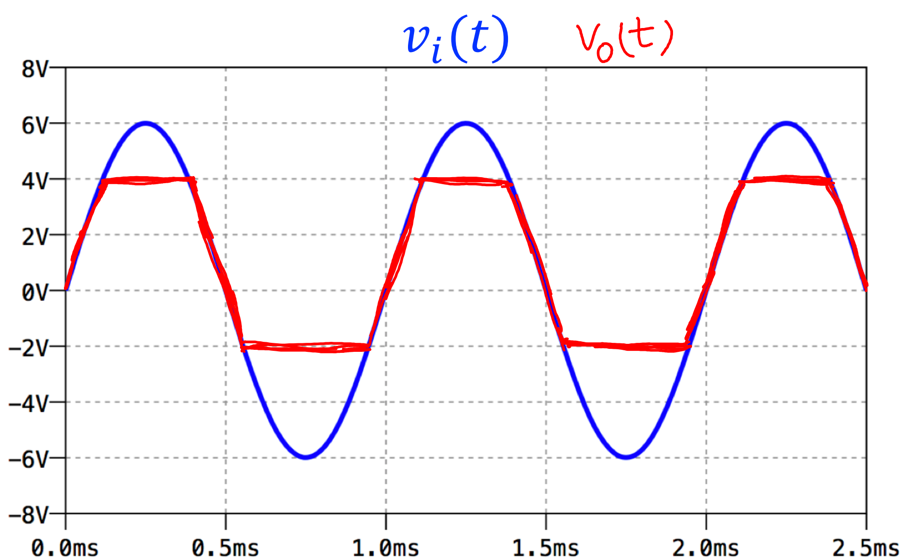
v_o **limited to** $\leq V_{D0} + V_{Z1}$ **and** $\geq - V_{D0} - V_{Z2}$



Lecture 5 reading quiz

Calculate and draw the output of the following two-port network for the given input signal. Assume $V_{D_0} = 0.7\,V$





Case 1: D_1 ON, D_2 off

Case 2: D_2 ON, D_1 off

Case 3: D_1 and D_2 off

Case 1: $i_{D_1} \geq 0, \; V_{D_1} = 0.7$

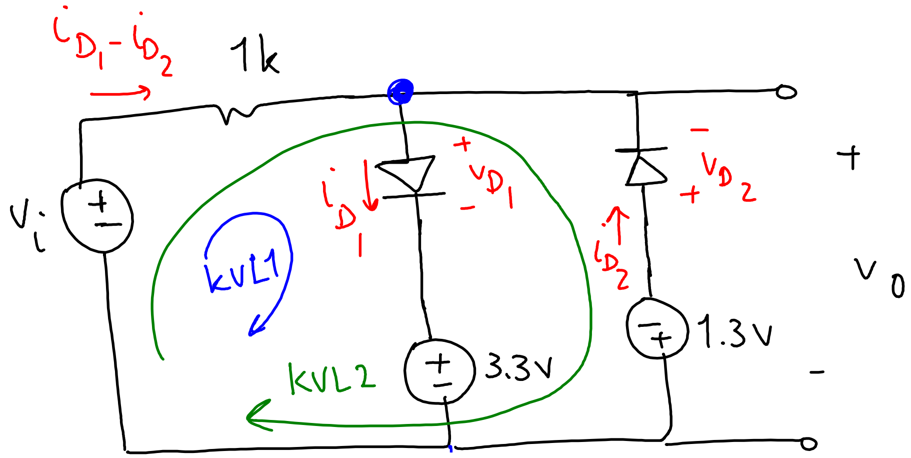
$i_{D_2} = 0, \; V_{D_2} < 0.7\,V$

KVL1:

$$V_i = 1k\Omega \times i_{D_1} + 0.7V + 3.3V$$

$$\rightarrow i_{D_1} = \frac{V_i - 4V}{1k\Omega} \geq 0$$

$$\boxed{V_i \geq 4V}$$



Case 1. Continue:

$V_o = V_{D_o} + 3.3 = 4V$

For $V_i \geq 4V \rightarrow \boxed{V_o = 4V}$

Case 2: $V_{D_2} = V_{D_o}$, $i_{D_2} \geq 0$, $i_{D_1} = 0$, $V_{D_1} < 0.7$

KVL 2: $V_i = 1k(-i_{D_2}) - 0.7 - 1.3V \rightarrow i_{D_2} = \dfrac{-V_i - 2V}{1k} \geq 0 \rightarrow \boxed{V_i \leq -2V}$

$V_o = -0.7 - 1.3V \rightarrow \boxed{V_o = -2V}$

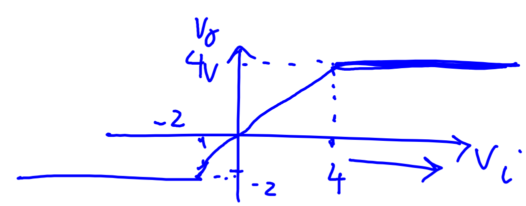
Case 3: $i_{D_1} = i_{D_2} = 0$, $V_{D_1} < 0.7$, $V_{D_2} < 0.7$

KVL1: $V_i = 0 + V_{D_1} + 3.3V \rightarrow V_{D_1} = V_i - 3.3V < 0.7V \rightarrow V_i < 4V$

KVL2: $V_i = 0 - V_{D_2} - 1.3V \rightarrow V_{D_2} = -V_i - 1.3V < 0.7 \rightarrow V_i > -2V$

$\Rightarrow -2 < V_i < 4$

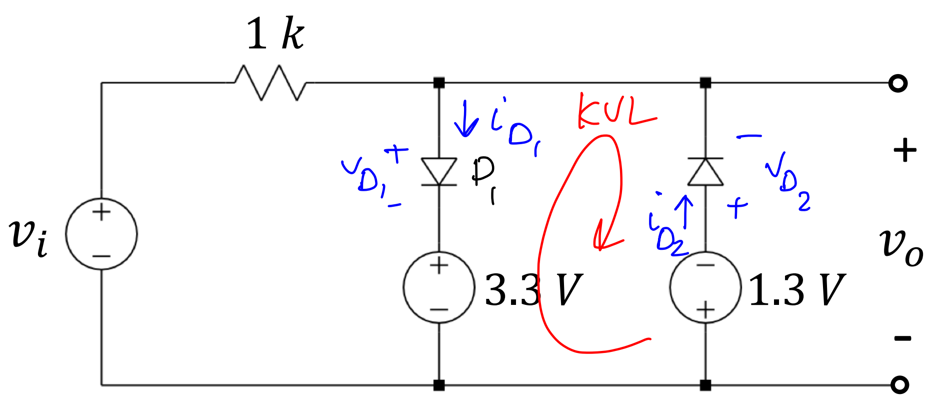
$V_o = 1k\Omega \times (i_{D_2} - i_{D_1}) + V_i \rightarrow \boxed{V_o = V_i}$



Lecture 7 reading quiz

Calculate and draw the output of the following two-port network for the given input signal.

Assume: D_1 and D_2 are ON

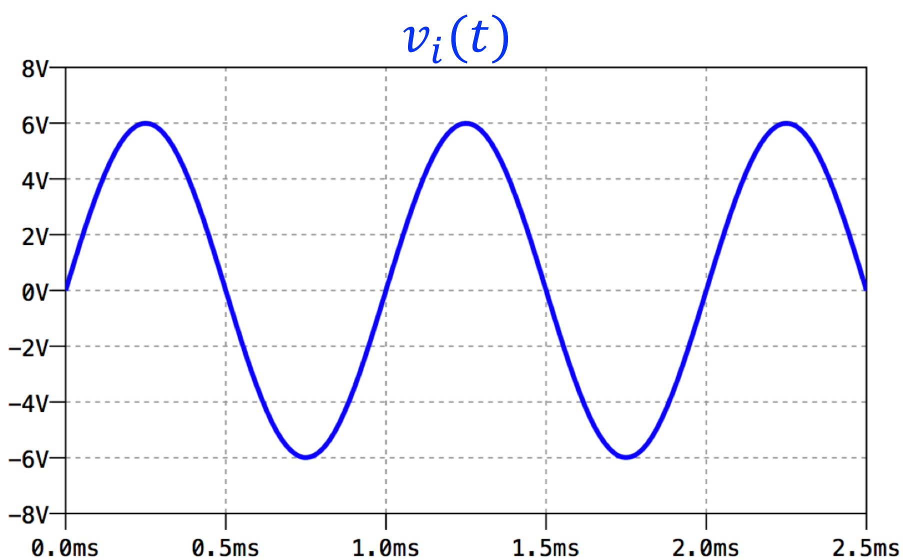


D_1 is ON : $V_{D_1} = V_{D_0} = 0.7\,V$

& $i_{D_1} \geq 0$

D_2 is ON : $V_{D_2} = V_{D_0} = 0.7\,V$

& $i_{D_2} \geq 0$



KVL: $-3.3\,V - V_{D_1} - V_{D_2} - 1.3\,V = 0$

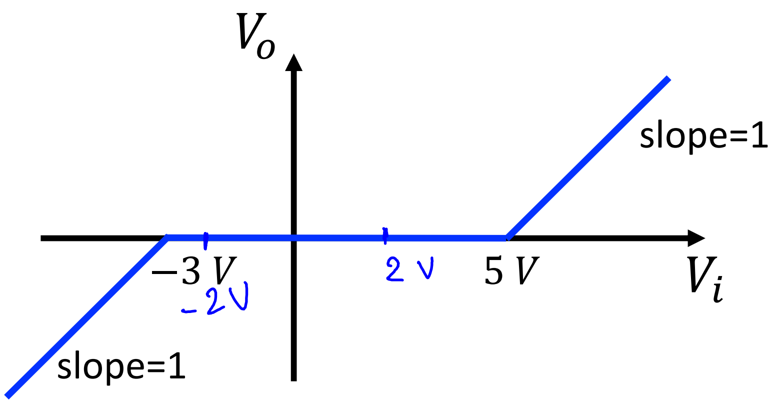
$V_{D_1} + V_{D_2} = -4.6\,V$

$0.7 + 0.7 \neq -4.6\,V \Rightarrow$

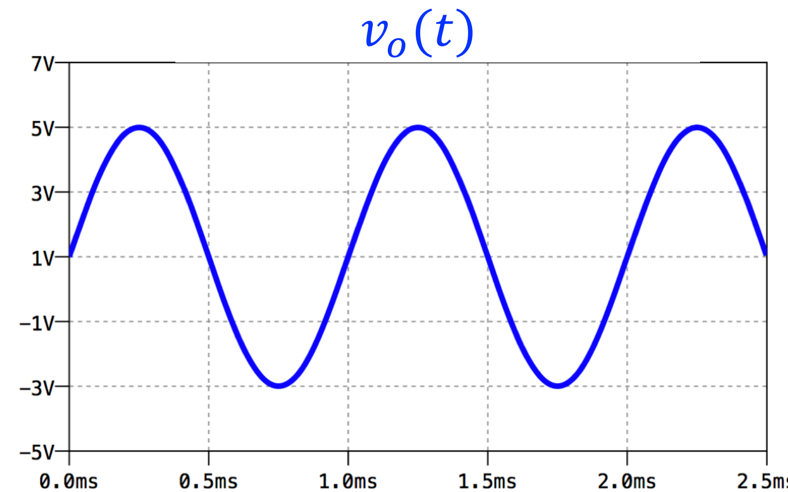
Assumption was incorrect

Clicker question 1

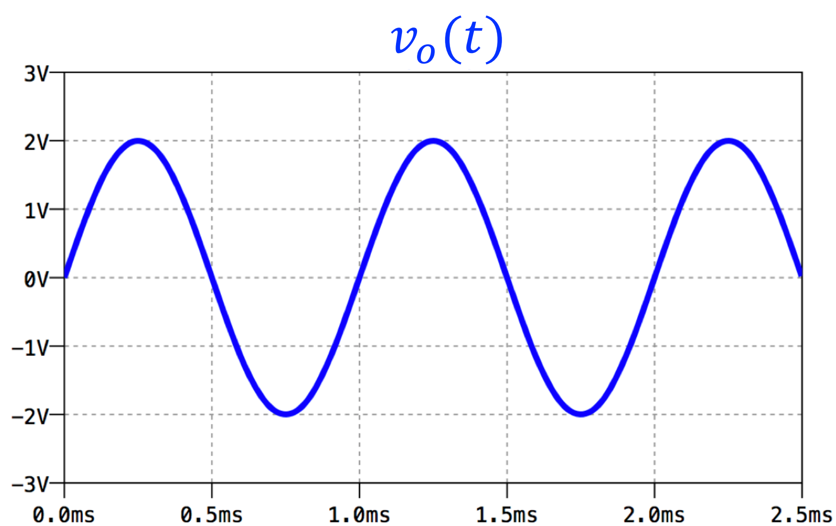
Which one of the waveforms could be the output of a two-port network with the below transfer function for the input $v_i(t) = 2\sin(\omega t)$?



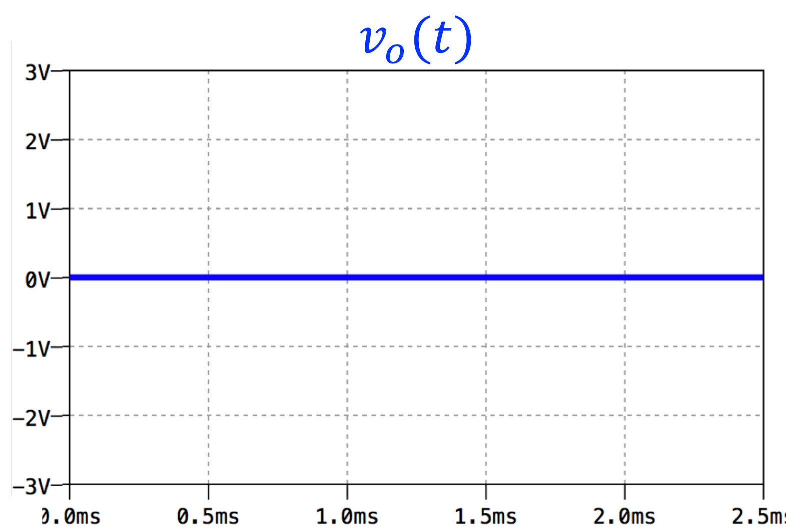
A.



B.

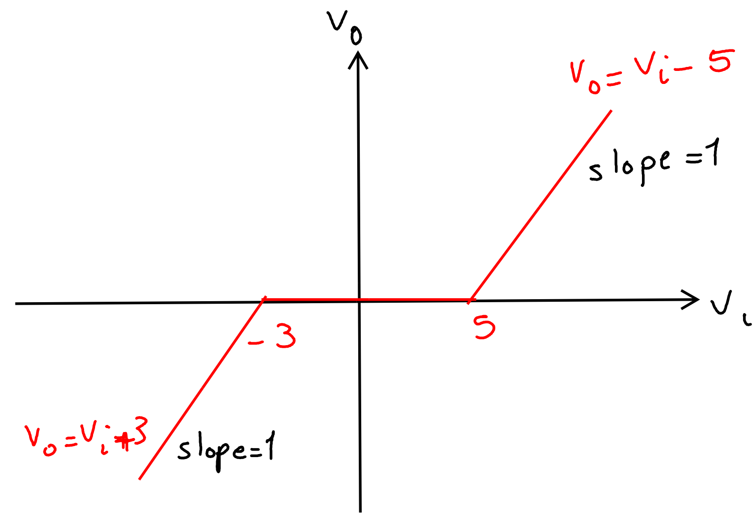


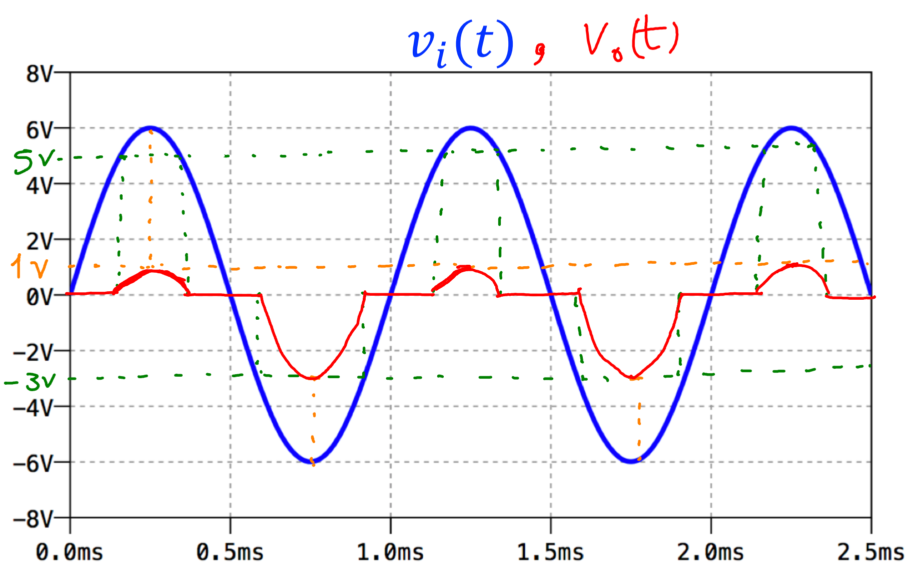
C.



Discussion Question 1.

Draw the output of a two-port network with the shown transfer to the below input signal



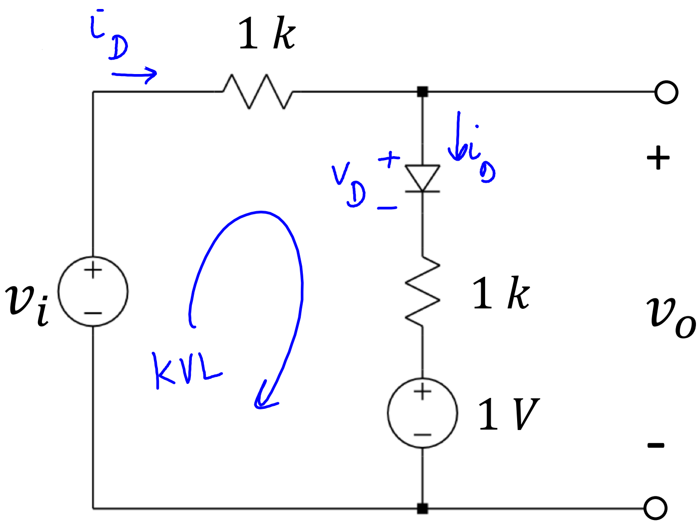


Discussion question 2

Calculate and draw the transfer function for the following two-port network.

$(V_{D0} = 0.7V)$

Case 1. Diode off , $V_D < V_{D0}$, $i_D = 0$



$V_i = 1k\Omega \times i_D + V_D + 1k\Omega \times i_D + 1V$

$V_i = V_D + 1V \longrightarrow V_D = V_i - 1V < V_{D0}$

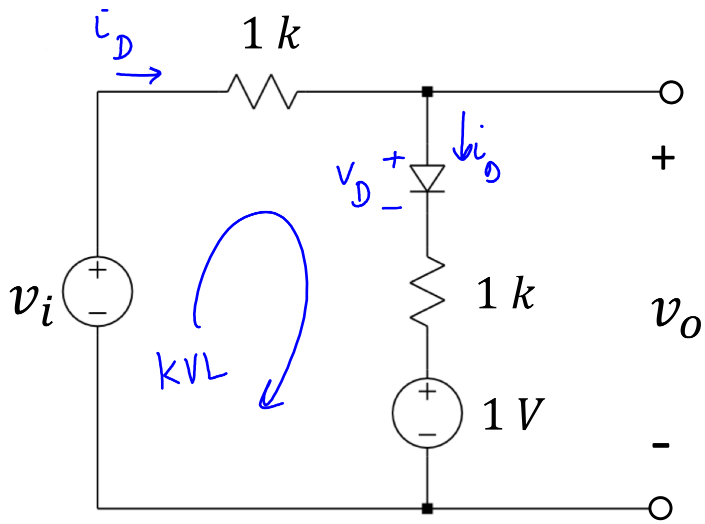
$\longrightarrow V_i < 1 + 0.7 \longrightarrow \boxed{V_i < 1.7V}$

$i_D = 0 \longrightarrow V_o = -i_D \times 1k\Omega + V_i \Longrightarrow \boxed{V_o = V_i}$

Discussion question 2

Calculate and draw the transfer function for the following two-port network.

$(V_{D0} = 0.7V)$



Case 1. Diode off , $V_D < V_{D_0}$, $i_D = 0$

$V_i = 1k\Omega \times i_D + V_D + 1k\Omega \times i_D + 1\,V$

$V_i = V_D + 1V \longrightarrow V_D = V_i - 1V < V_{D_0}$

$\longrightarrow V_i < 1 + 0.7 \longrightarrow \boxed{V_i < 1.7\,V}$

$i_D = 0 \longrightarrow V_o = -i_D \times 1k\Omega + V_i \Longrightarrow \boxed{V_o = V_i}$

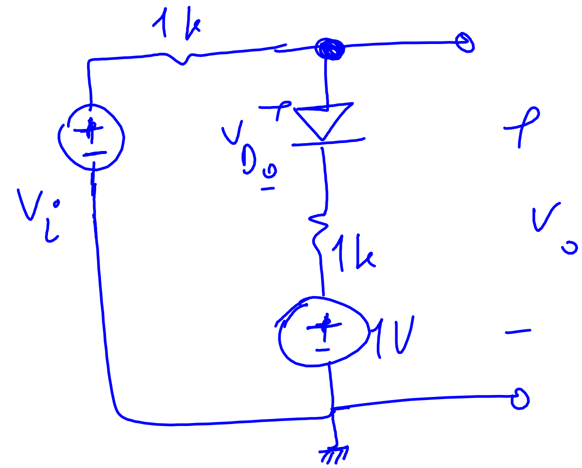
Case 2. Diode ON : $i_D \geq 0$, $V_D = V_{D_0}$

$V_i = (1k\Omega + 1k\Omega)\, i_D + V_D + 1V \longrightarrow V_i = 2k\Omega \times i_D + 1.7V$

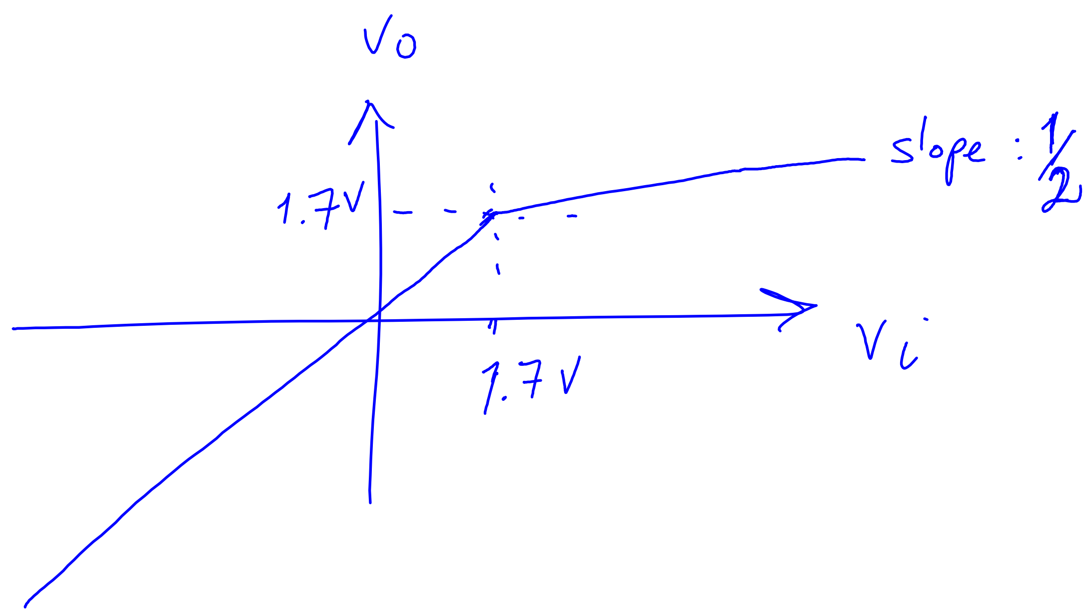
$i_D \geq 0 \longrightarrow (V_i - 1.7)/2k\Omega \geq 0 \longrightarrow \boxed{V_i \geq 1.7V}$

$$V_o = V_{D_0} + 1k\Omega \times i_D + 1V$$

$$\boxed{i_{D_1} = \frac{V_i - 1.7V}{2k\Omega}}$$



$$V_o = 1.7V + \frac{1k\Omega}{2k\Omega}\left(V_i - 1.7V\right) \Rightarrow V_o = \frac{1}{2}V_i + \frac{1.7V}{2}$$



ECE 65: Components & Circuits Lab

Lecture 9

Diode waveform shaping circuits

Clamp circuits

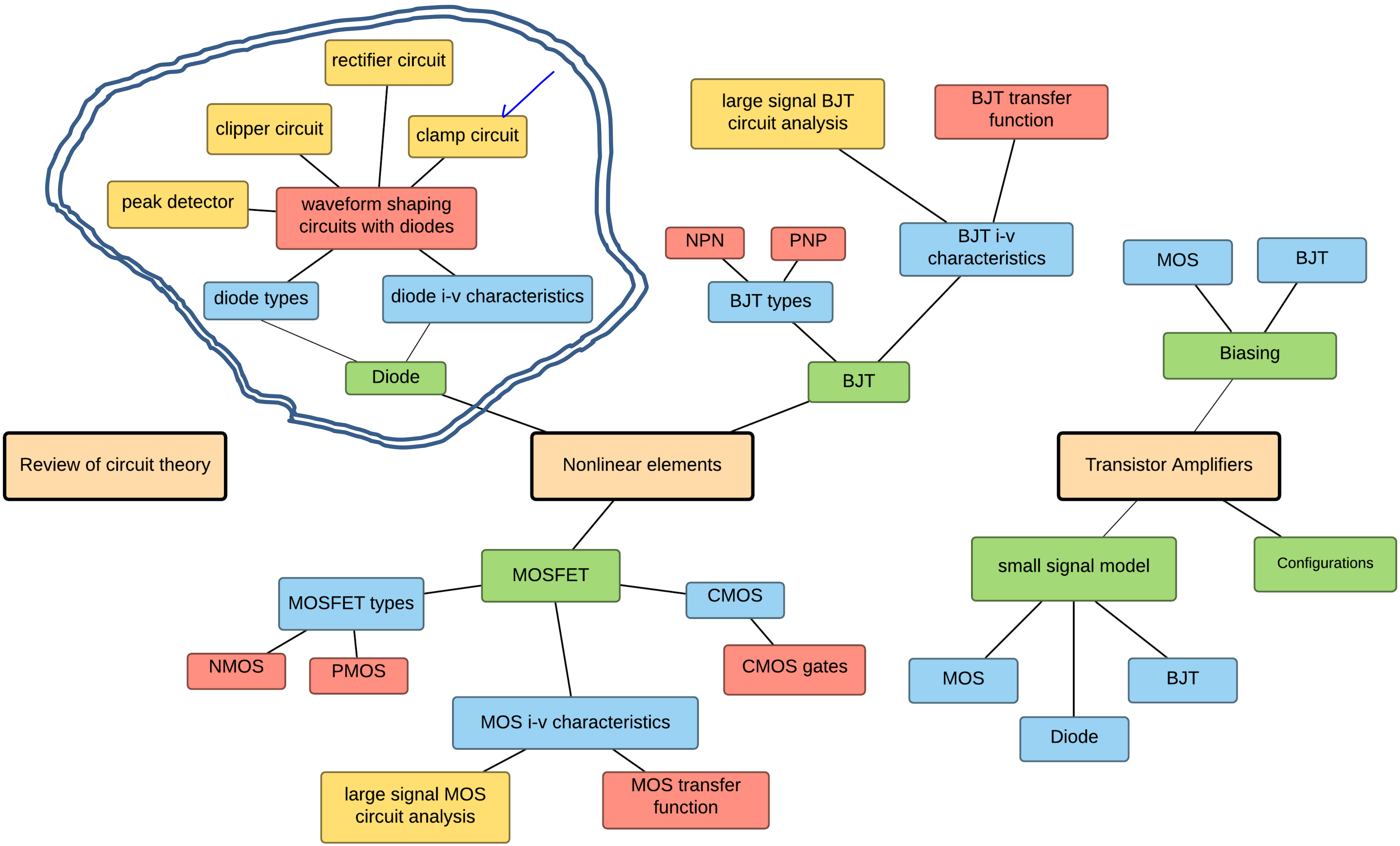
Reference notes: sections 2.9

Sedra & Smith (7th Ed): sections 4.4-4.6

Saharnaz Baghdadchi

Course map

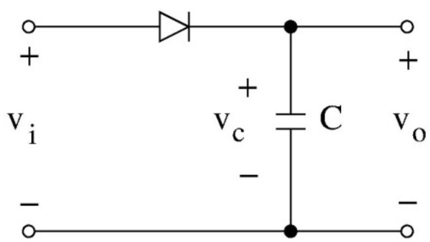
2. Diodes

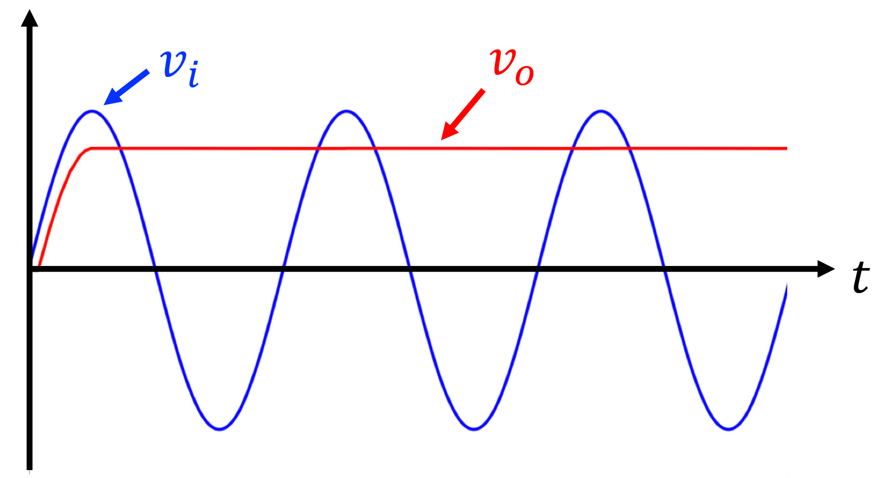


Clamp circuit and peak detector circuit

Ideal peak detector:

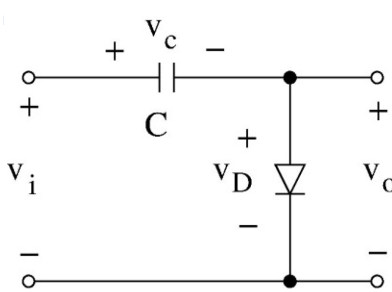
$$v_o = V_p - V_{D0}$$

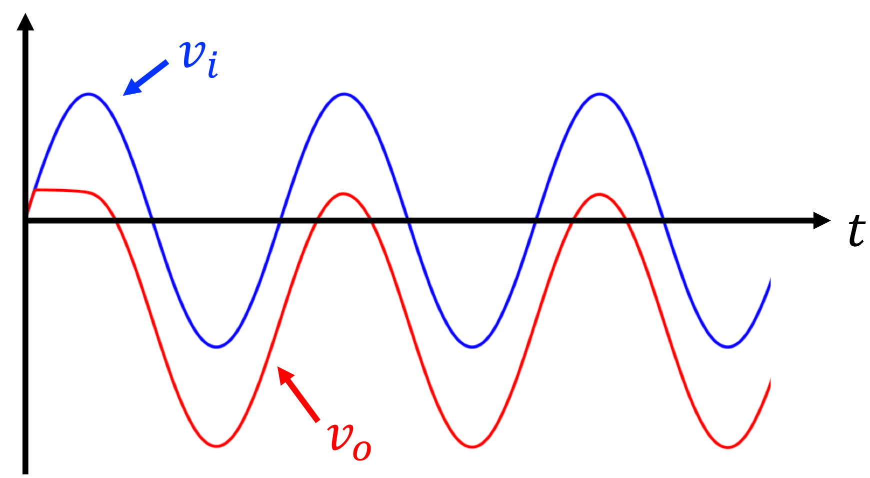




Clamp circuit:

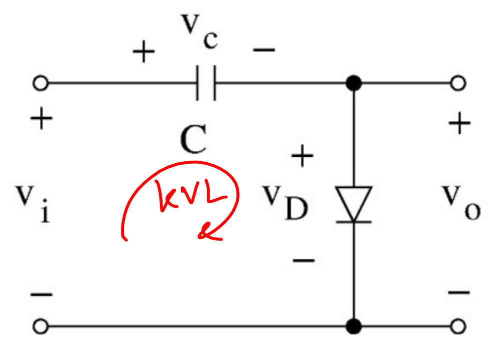
$$v_o = v_i - (V_p - V_{D0})$$



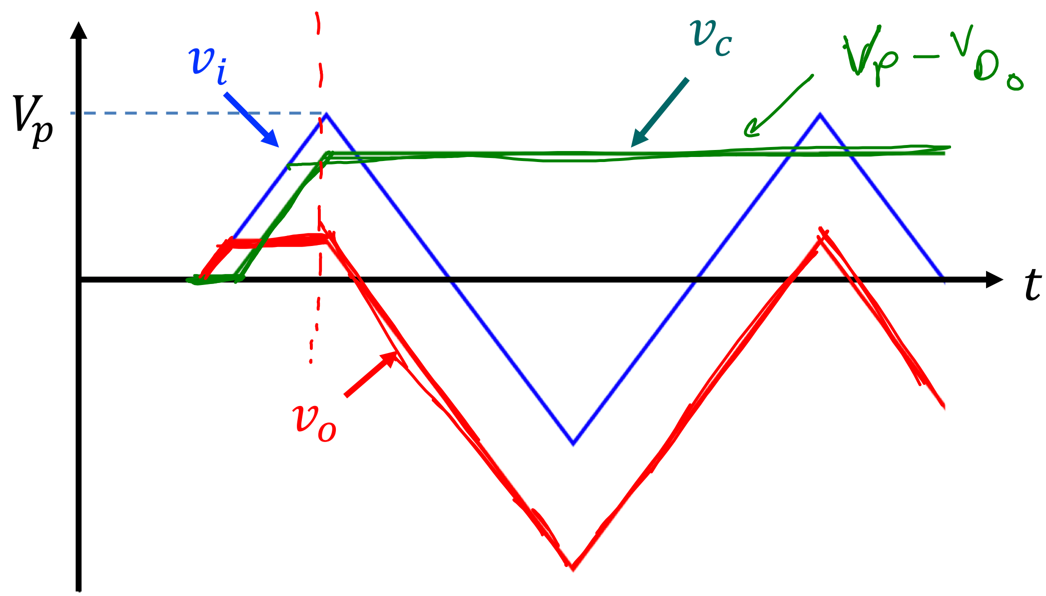


Clamp Circuit

$v_D = -v_c + v_i$



The diode turns OFF when the capacitor is charged to $v_c = \boxed{V_p - V_{D0}}$



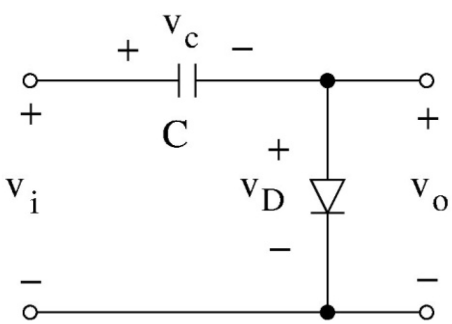
$$v_o = v_D = v_i - v_c$$

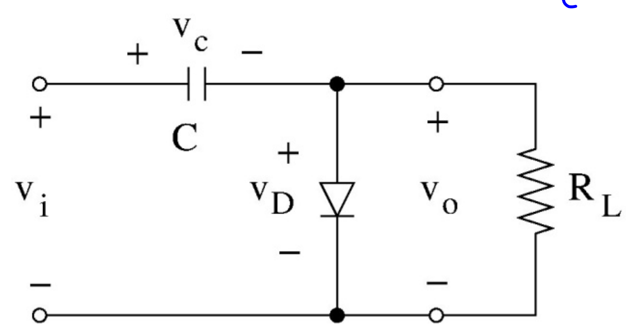
Diode off:

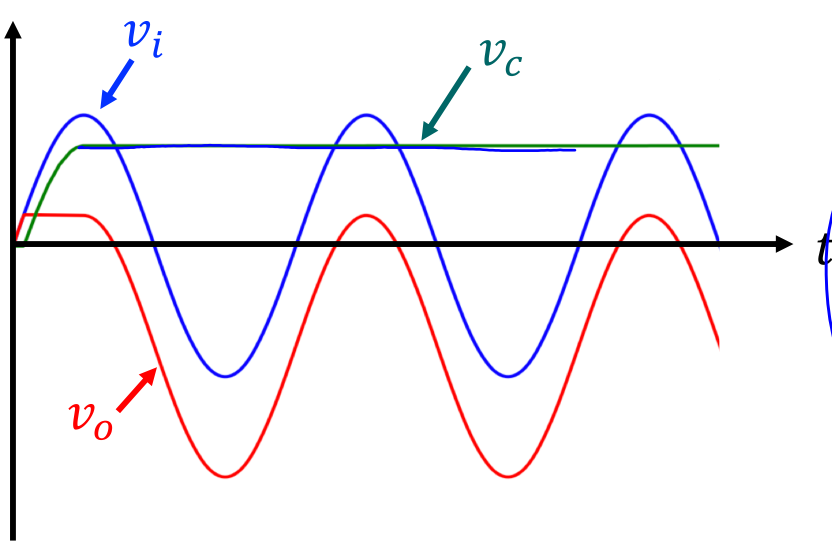
$$v_o = v_i - (V_p - V_{D0})$$

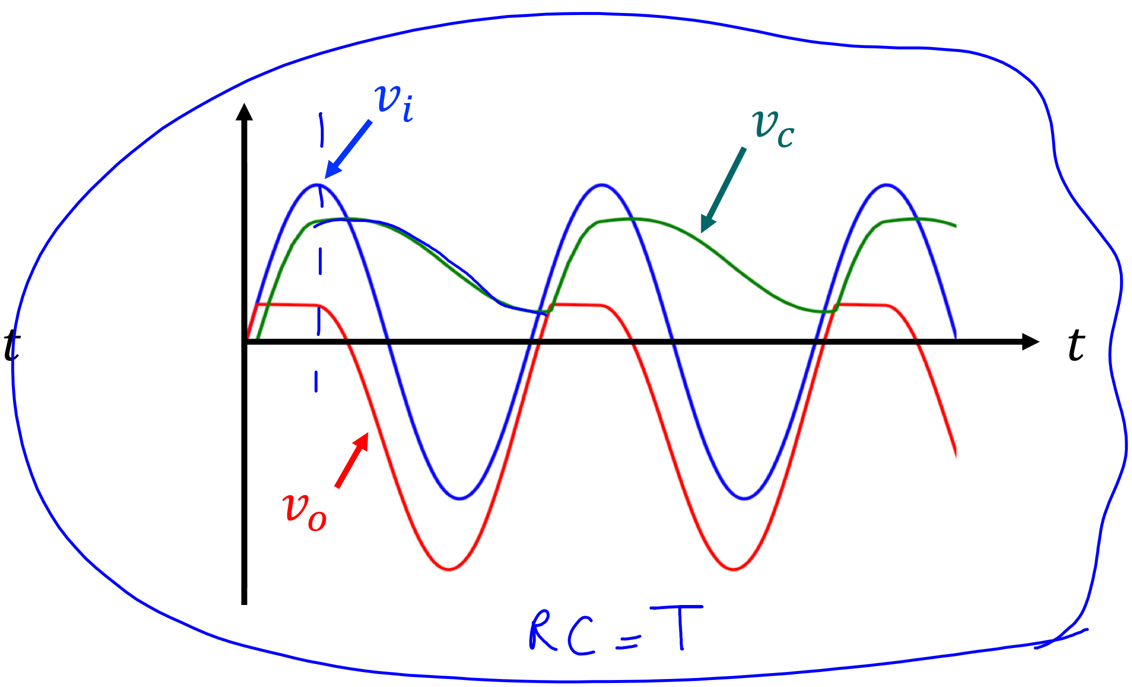
Clamp Circuit with a Load

$\tau = CR_L$



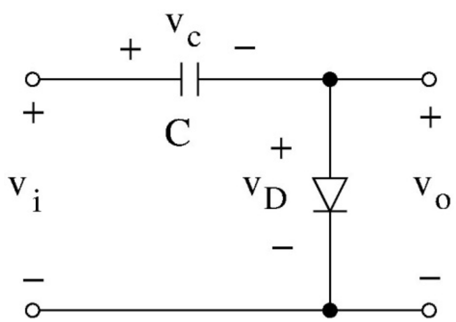






If $\tau = R_L C >> T$ capacitor does not discharge substantially and clamp circuits works fine

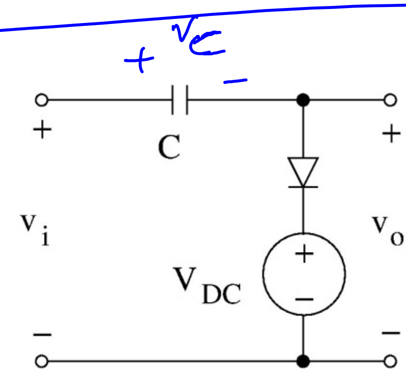
Voltage shift in a clamp circuit can be adjusted



$V_C = V_p - V_{D_0}$

$V_o = -V_C + V_i$

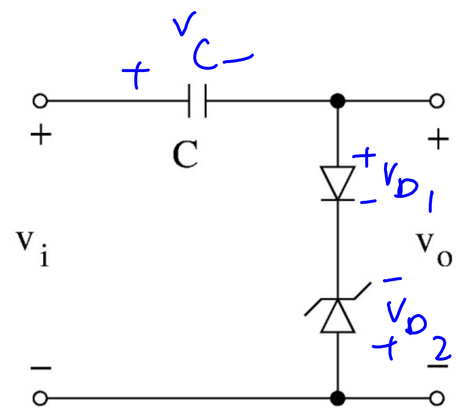
$V_o = V_i - \boxed{(V_p - V_{D_0})}$



$V_C = V_p - (V_{D_0} + V_{DC})$

$V_o = -V_C + V_i$

$= V_i - \boxed{(V_p - V_{D_0} - V_{DC})}$

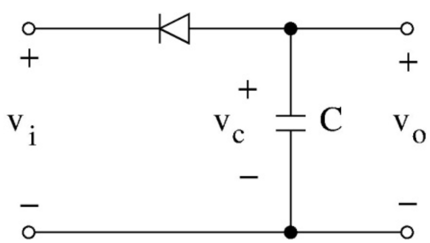


$V_o = -V_C + V_i$

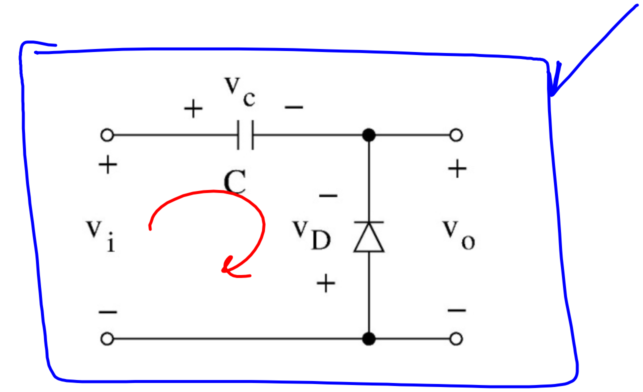
$= V_i - (V_p - V_{D_0} - V_Z)$

Clamp circuit can introduce a "positive" shift by reversing the diode terminals

Peak detector (diode is reversed):



Clamp circuit (diode reversed):



$V_o = -V_c + V_i$

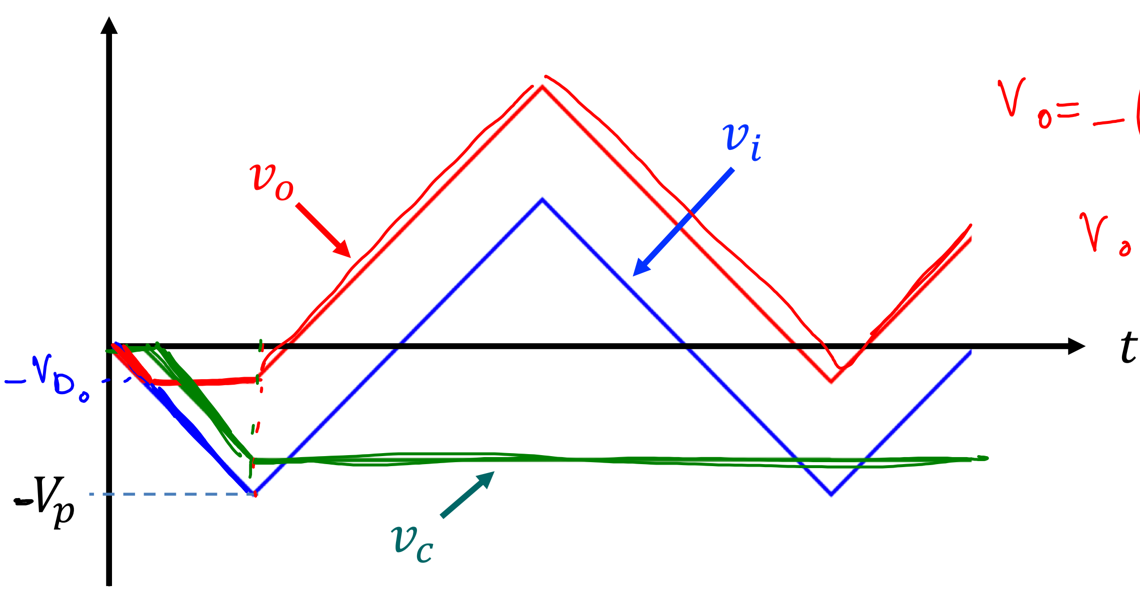
$V_D = -V_i + V_c = -V_i$

$V_o = -(-V_p + V_{D_o}) + V_i$

$V_o = -V_D$

$V_o = V_i + (V_p - V_{D_o})$

$\Rightarrow V_o = +V_i$



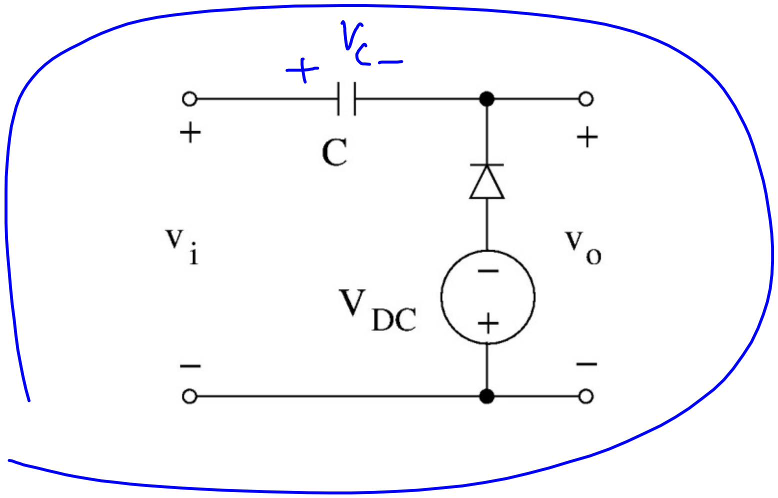
$V_o = -V_{D_o}$

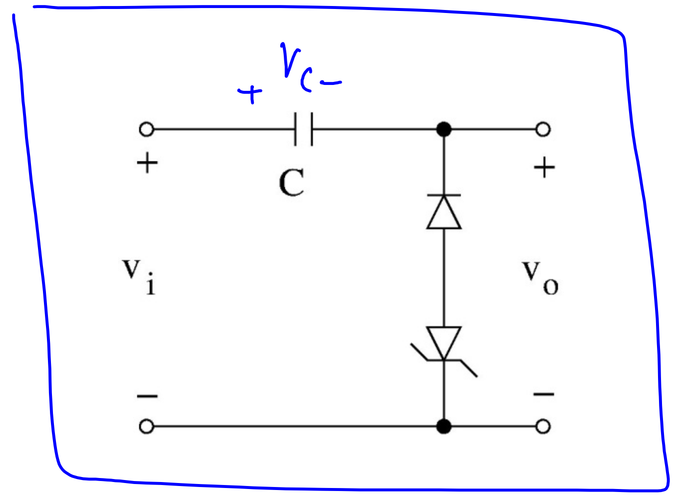
$V_c = V_i + V_{D_o}$

After the diode turned off

$\boxed{V_c = -V_p + V_{D_o}}$

The positive shift can also be adjusted.





$$V_C = -V_p + V_{DC} + V_{D_0}$$

$$V_o = V_i + (V_p - V_{DC} - V_{D_0})$$

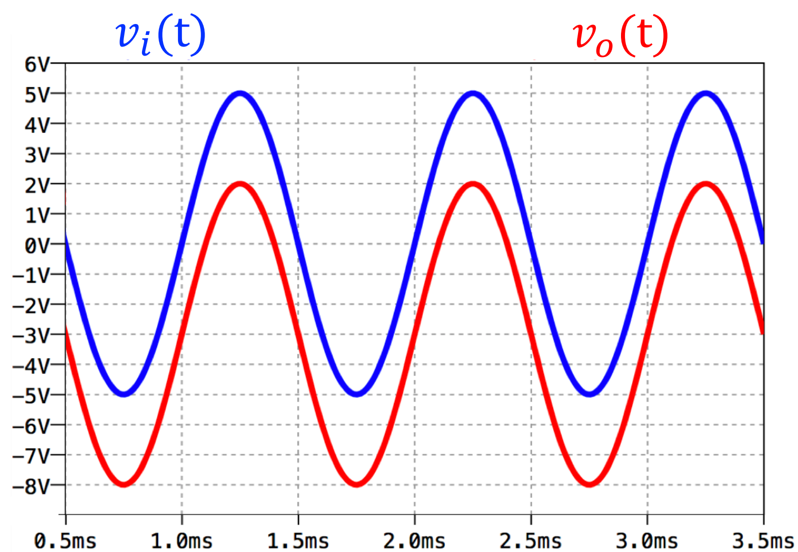
$$V_o = V_i + (V_p - V_Z - V_{D_0})$$

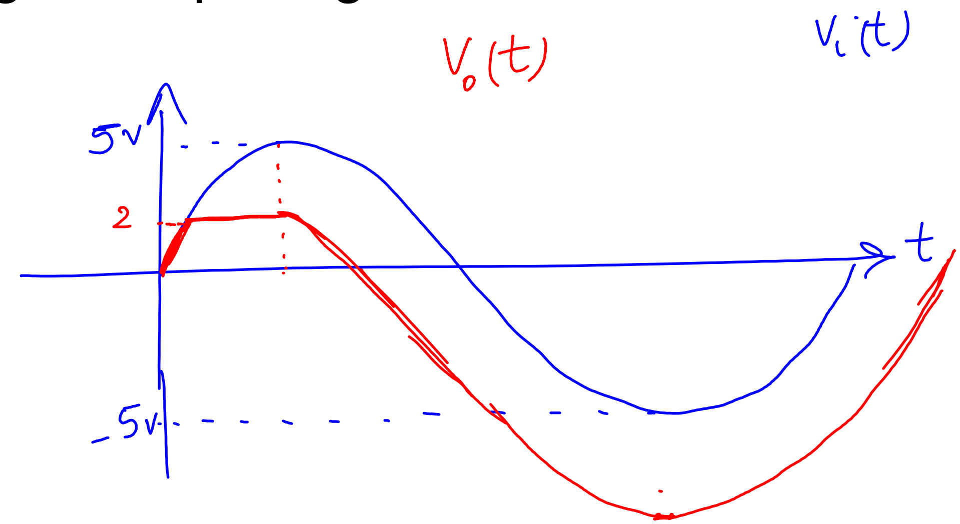
For $0 < V_i < 2$, the diode is off & $V_c = 0$

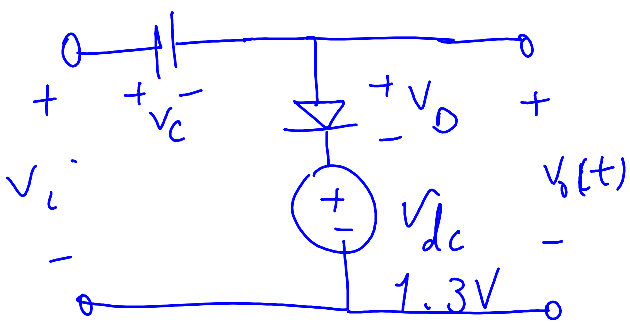
$V_o = -V_c + V_i = 0 + V_i = V_i$

Lecture 9 reading quiz

Which one of the circuits in the provided options could produce the shown output waveform for the given input signal?







When the cap is charging:

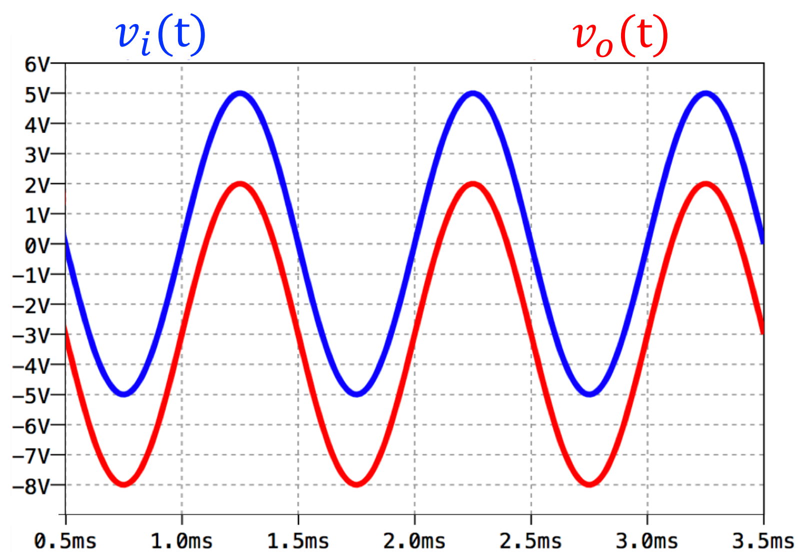
$$\overset{3}{V_c(t)} = \overset{5}{V_i(t)} - \overset{-1.3}{V_{dc}} - V_D = V_i(t) - V_{dc} - V_{D_0}$$

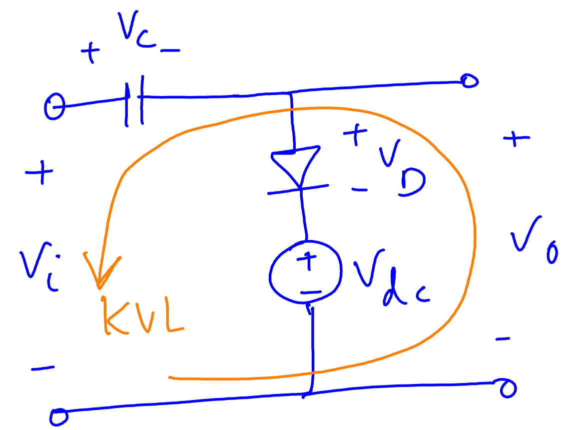
When the diode turns off:

$$\boxed{V_c = V_p - V_{dc} - V_{D_0}}$$

Lecture 9 reading quiz

Which one of the circuits in the provided options could produce the shown output waveform for the given input signal?





after the diode turns off:

$$V_C = \boxed{V_p - V_{dc} - V_{D_0}}$$

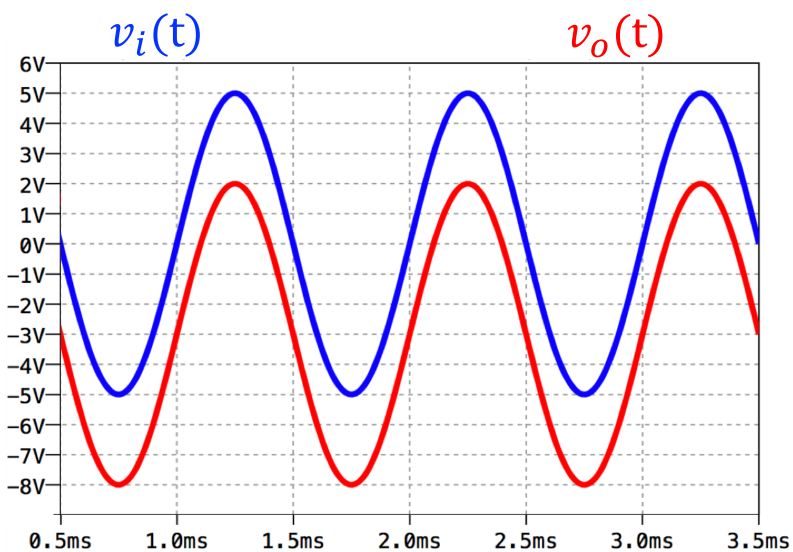
KVL: $V_o = V_i - \boxed{V_C}$

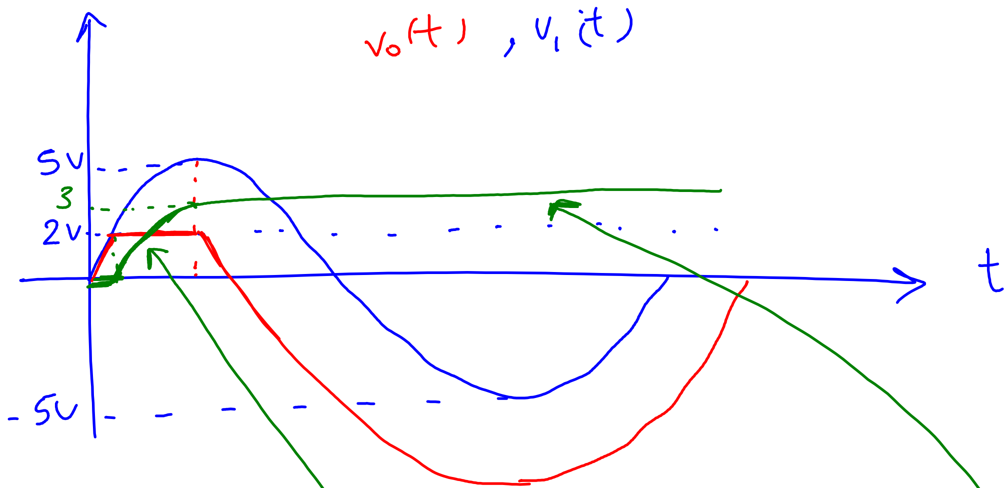
$$V_o = V_i - (V_p - V_{dc} - V_{D_0}) = V_i - 3V \Longrightarrow V_p - V_{dc} - V_{D_0} = 3V \rightarrow 5 - V_{dc} - 0.7 = 3$$

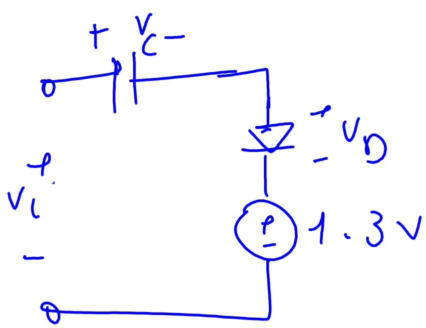
$$\rightarrow \boxed{V_{dc} = 1.3V}$$

Lecture 9 reading quiz

Which one of the circuits in the provided options could produce the shown output waveform for the given input signal?





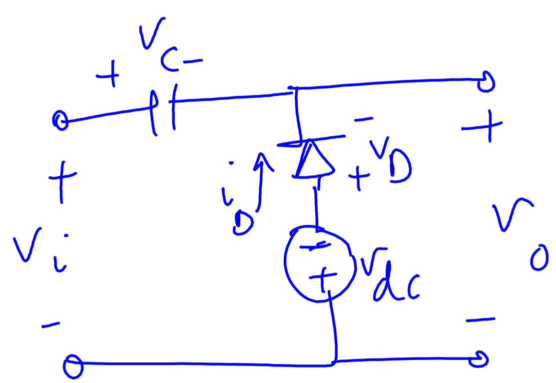


when the cap is charging : $\boxed{V_c(t) = V_i - V_{dc} - V_{D_0}}$

when the diode turns off : $\boxed{V_c(t) = V_p - V_{dc} - V_{D_0}}$

Discussion question 1

Consider a sinusoidal source $v_i(t) = 10\sin(\omega t)\,V$. Using a DC power supply, design a clamp circuit that adds a DC offset of 5V to $v_i(t)$. Draw two cycles of the input and output voltage waveforms.



KVL: $V_C = V_i + V_{dc} + V_D$

when the diode is ON

$V_C(t) = V_i(t) + V_{dc} + V_{D_0}$

when $V_i(t)$ reaches its negative peak

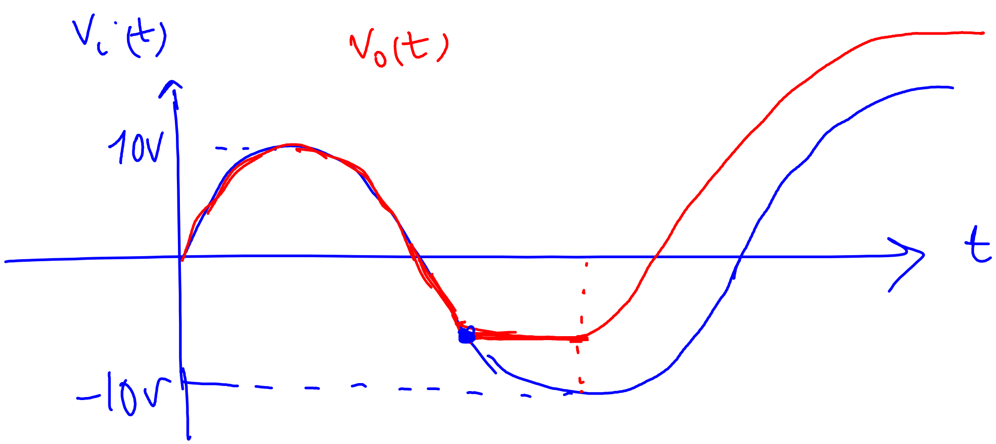
$$\boxed{V_C = -V_p + V_{dc} + V_{D_0}}$$

$V_{dc} = 4.3V$

$V_o = -V_C + V_i = V_i - (-V_p + V_{D_0} + V_{dc})$

$= V_i - \underbrace{(-10 + 0.7 + V_{dc})}_{-5}$

$V_0 = V_i + 5V$



before the diode turns ON : $V_c = 0$, $V_o = -V_c + V_i = V_i$

ECE 65: Components & Circuits Lab

Lecture 8

Diode waveform shaping circuits

Peak detector circuits

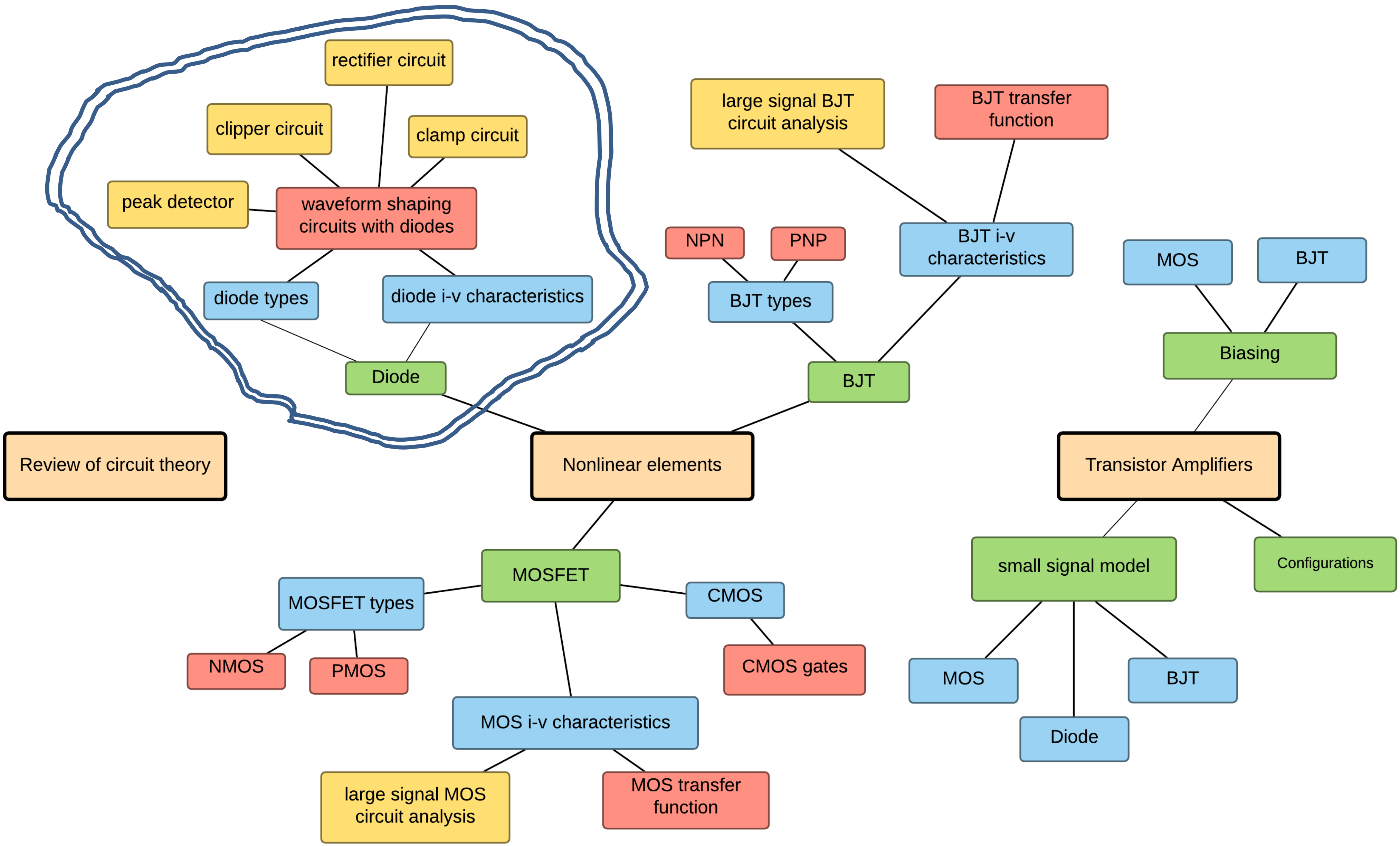
Reference notes: sections 2.9

Sedra & Smith (7th Ed): sections 4.4-4.6

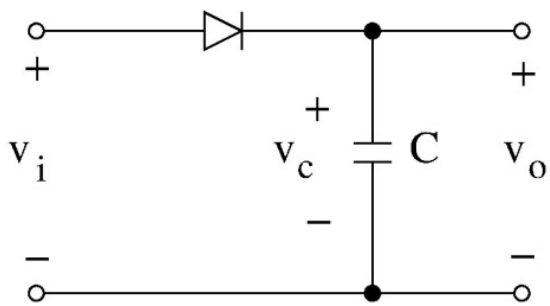
Saharnaz Baghdadchi

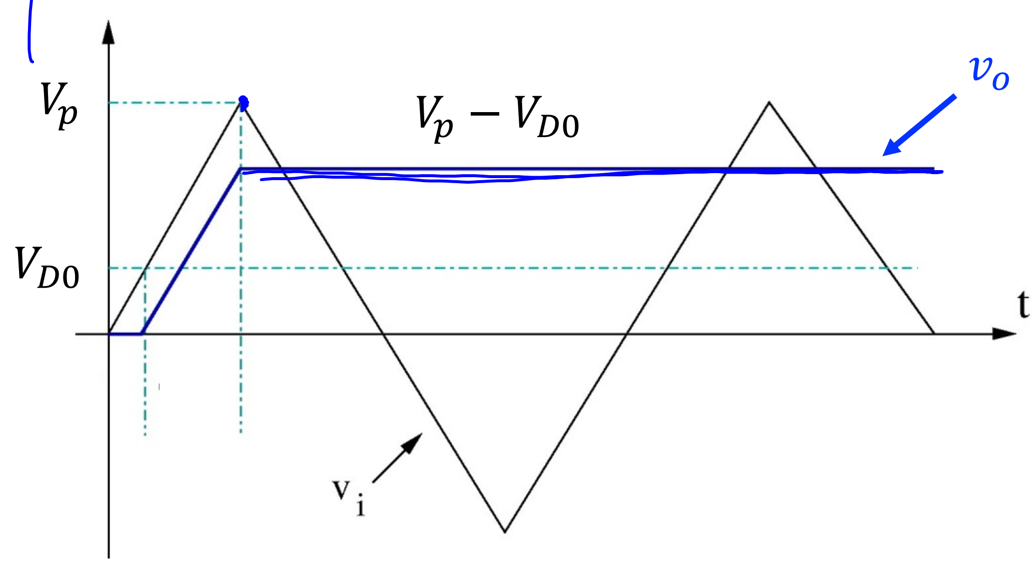
Course map

2. Diodes

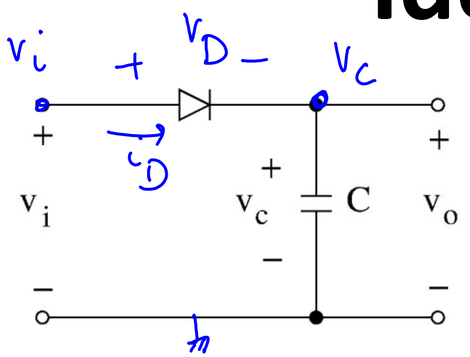


Ideal Peak Detector Circuit

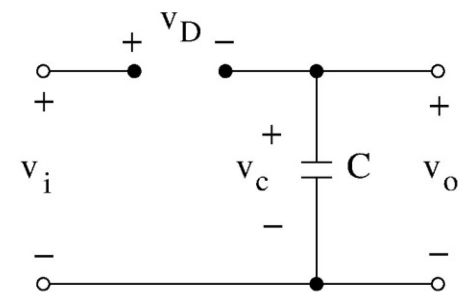




Ideal Peak Detector Circuit



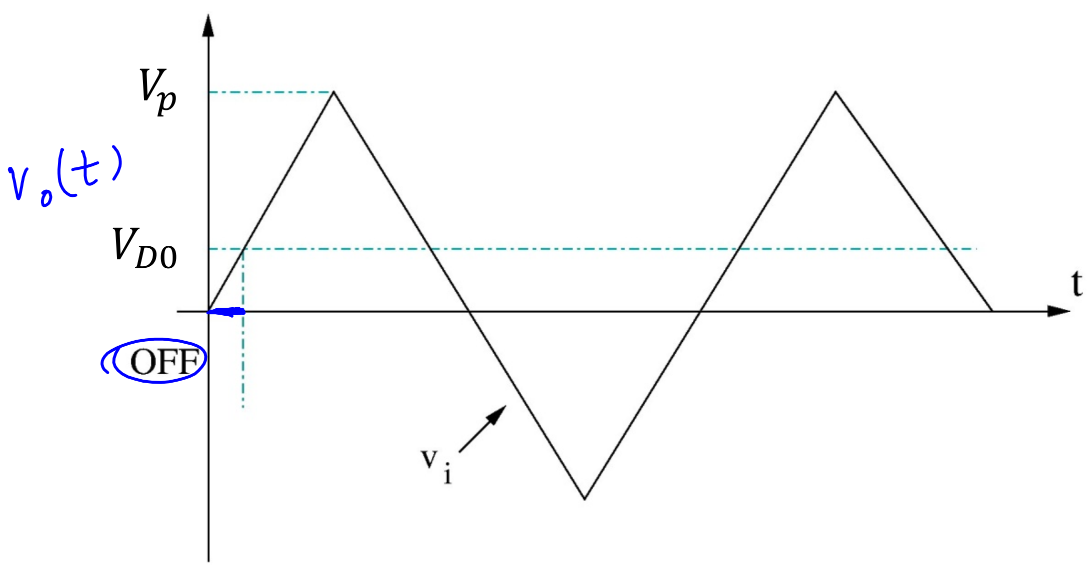
When the Diode is initially OFF:



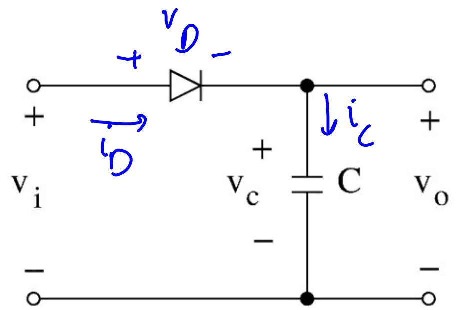
$$v_D = v_i - v_c = v_i$$

$$i_D = 0, \quad v_D < V_{D0}$$

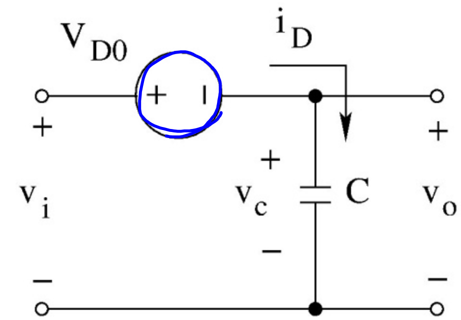
$$\Rightarrow v_i < V_{D0}$$



Ideal Peak Detector Circuit



When the Diode is ON:



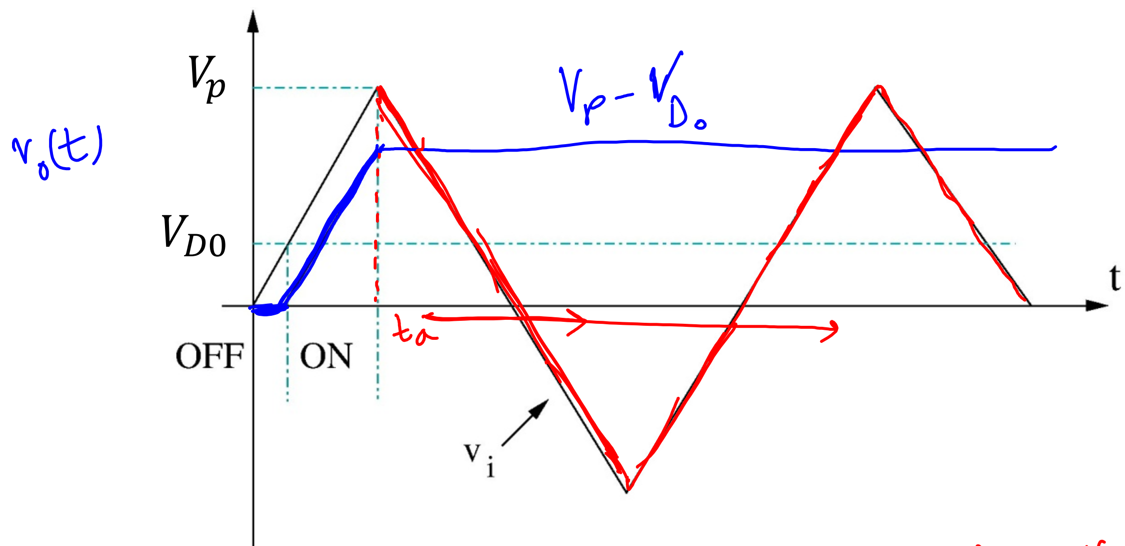
$V_D = V_{D_0}$

$i_D \geq 0$

$V_o = -V_D + V_i = -V_{D_0} + V_i$

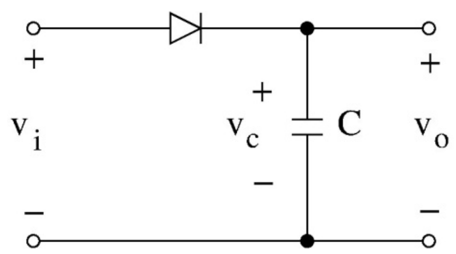
, $i_D = i_C = C\frac{dv_C}{dt} = C\frac{d(v_i - V_{D_0})}{dt}$

$= C\frac{dv_i}{dt}$

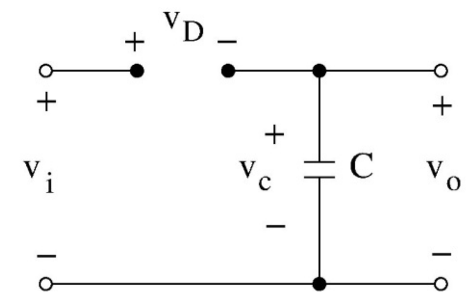


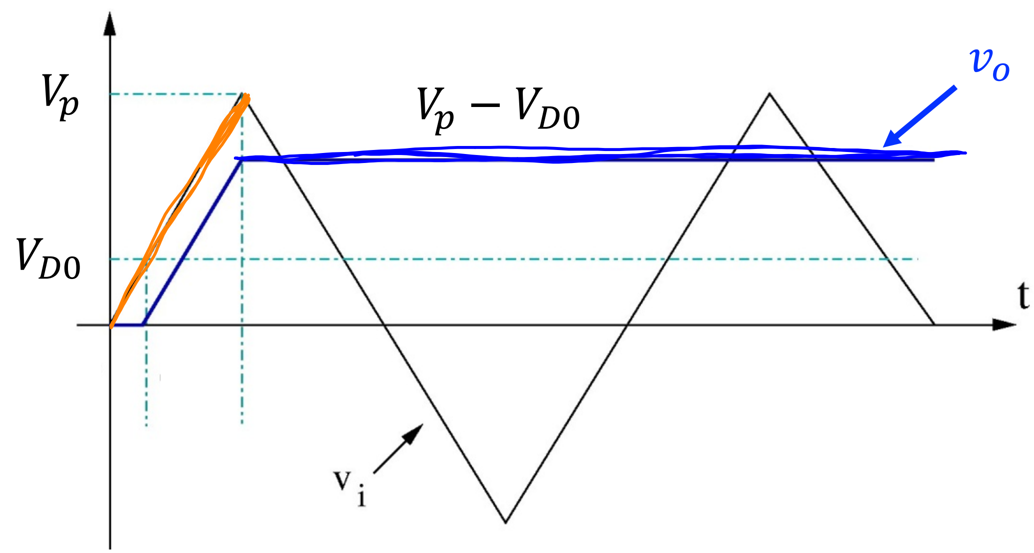
at $t = t_a$, $V_i = V_p$, $V_C = V_p - V_{D_0}$, $V_D = V_i - V_C = V_i - (V_p - V_{D_0})$

Ideal Peak Detector Circuit

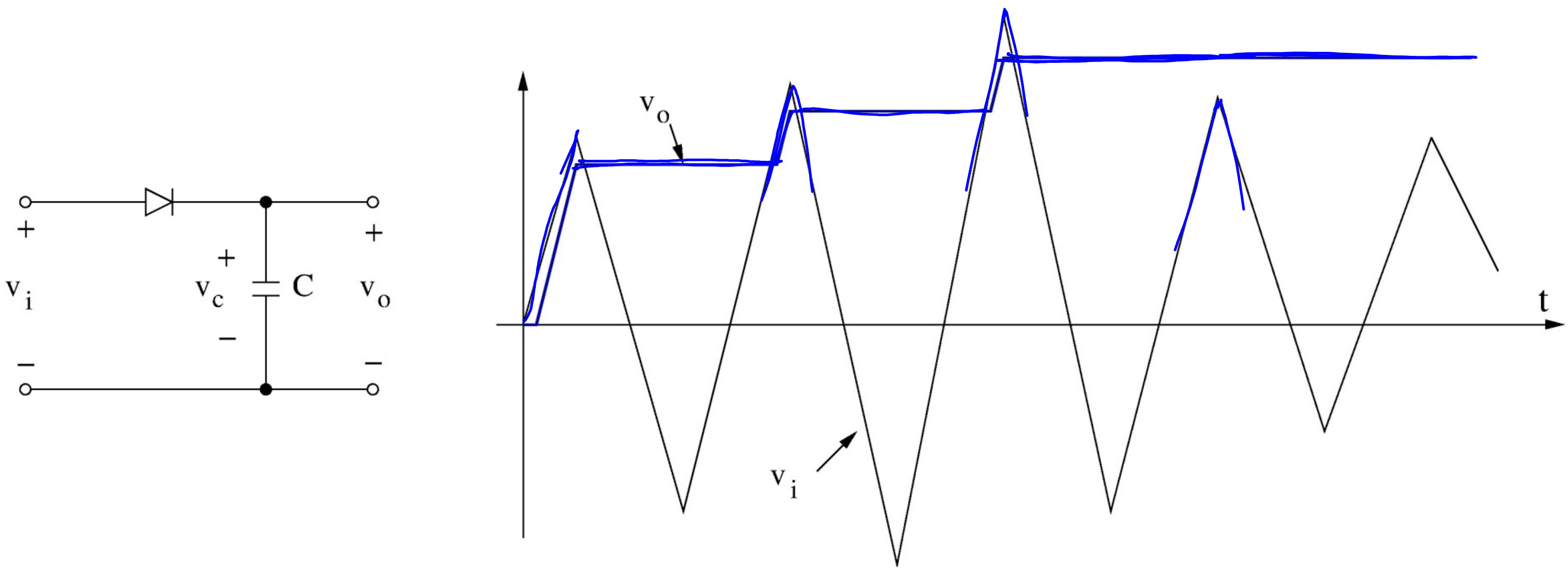


After v_i reached its peak value, the diode does not turn ON anymore.





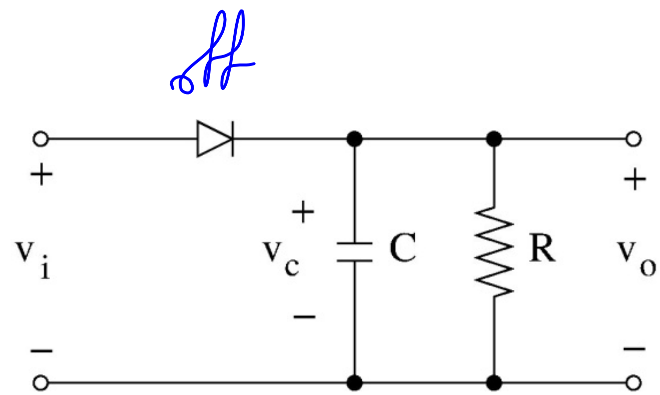
Response of the Ideal Peak Detector (v_i amplitude changes)

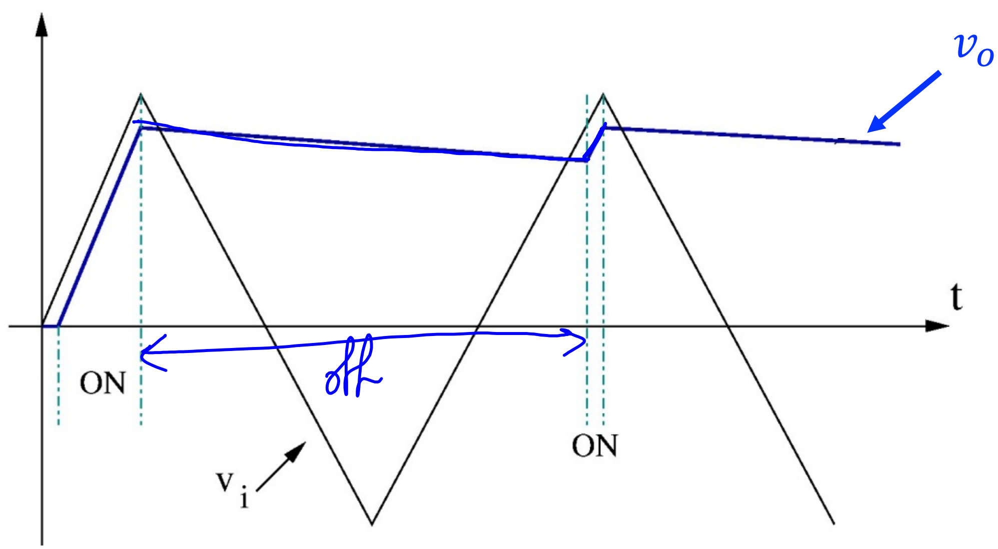


v_o is the "peak" value of input waveform ($V_p - V_{D0}$):

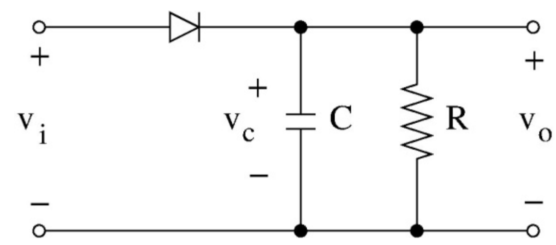
Note v_o did not "drop" after the peak was decreased in the 3rd cycle.

Practical Peak Detector Circuit

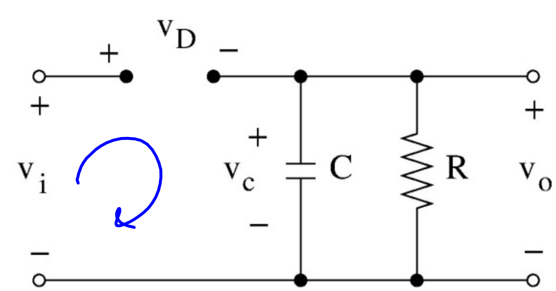




Practical Peak Detector Circuit



Diode OFF: $i_D = 0$ and $v_D < V_{D0}$

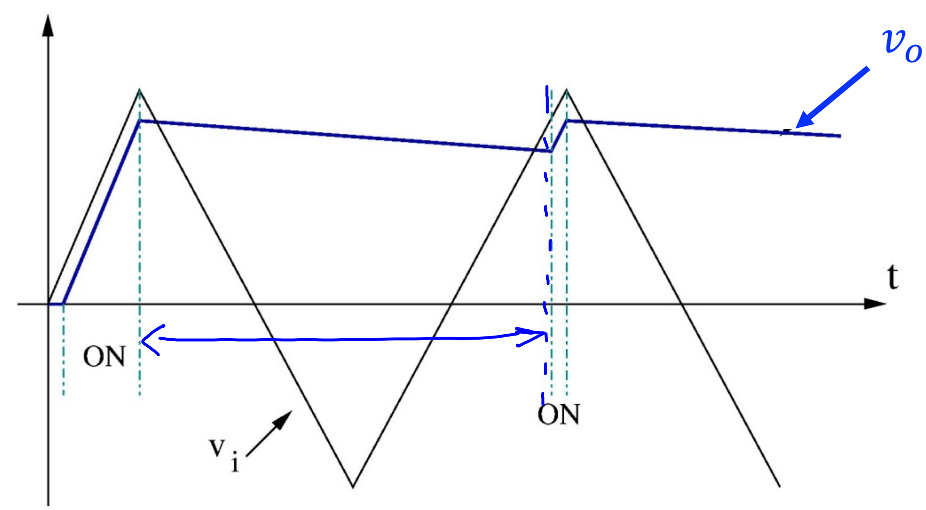


Capacitor discharges into the resistor with a time constant of $\tau = RC$

$$v_o = v_c(t) = v_{c_0}\, e^{-(t-t_0)/\tau}$$

$$v_D = v_i - v_c < V_{D0}$$

$$\rightarrow v_i < v_c(t) + V_{D0}$$

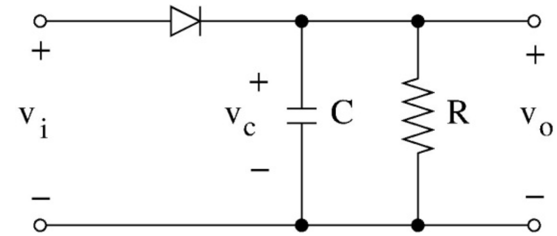


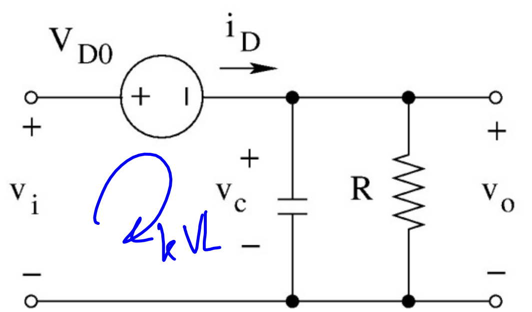
Practical Peak Detector Circuit

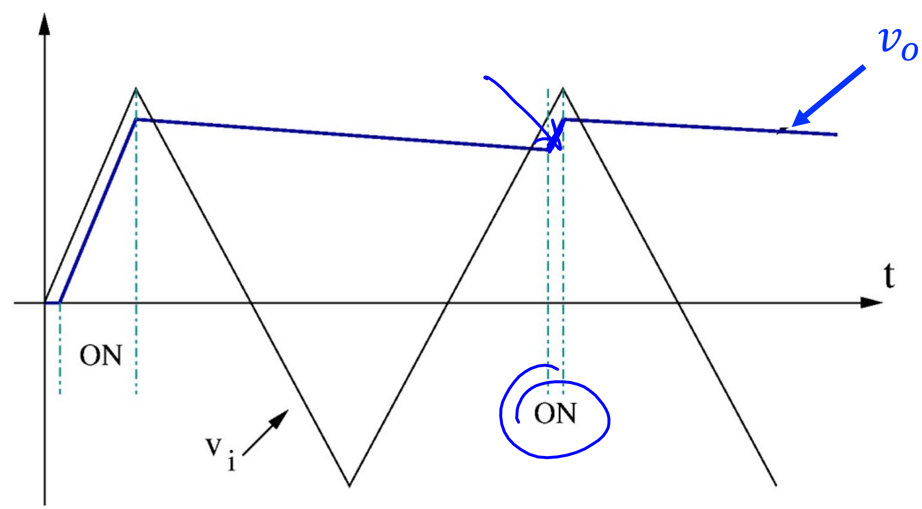
Diode ON: $v_D = V_{D0}$ and $i_D \geq 0$

$$v_o = v_C = v_i - V_{D0}$$

$$i_C = C\frac{dv_C}{dt} = C\frac{d(v_i - V_{D0})}{dt} = C\frac{dv_i}{dt}$$



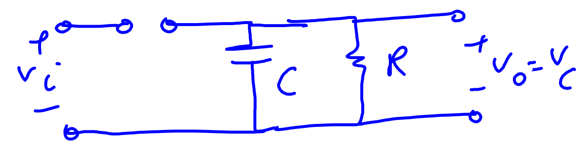




Response of the Practical Peak Detector

τ : time constant $= RC$

T : period of $v_i(t)$



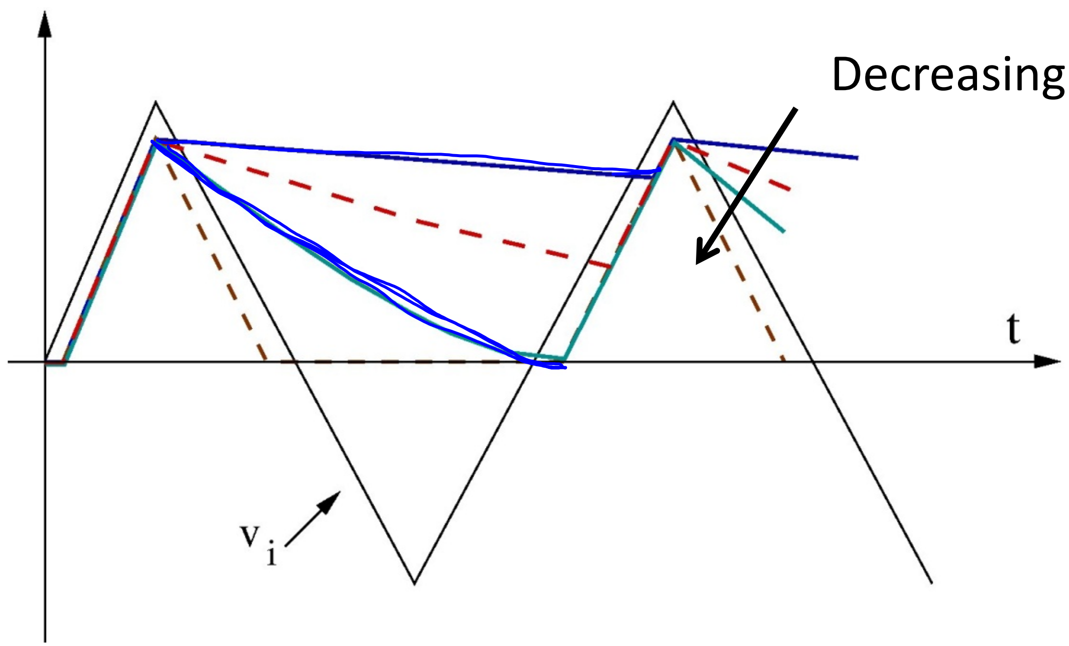
Shape of output signal depends on the ratio of τ/T

"ideal" peak detector: $\tau/\mathrm{T} \to \infty$

"Good" peak detector: $\tau/\mathrm{T} >> 1$

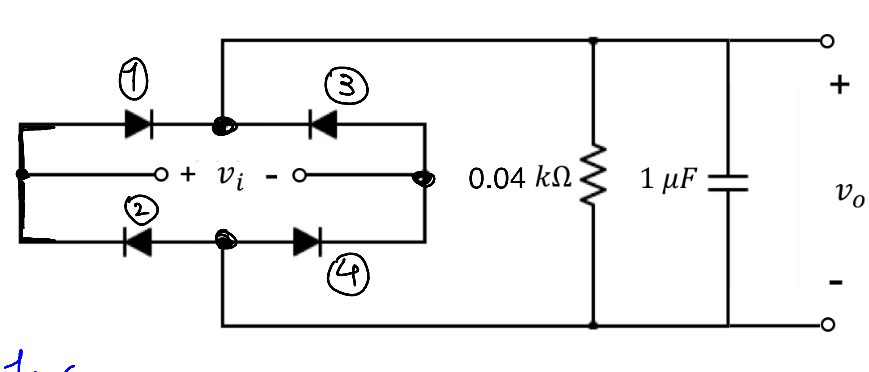
As τ/T decreases, the circuit departs from a peak detector.

For $\tau/\mathrm{T} << 1$, capacitor discharges very fast and circuit resembles a rectifier circuit



Lecture 8 reading quiz.

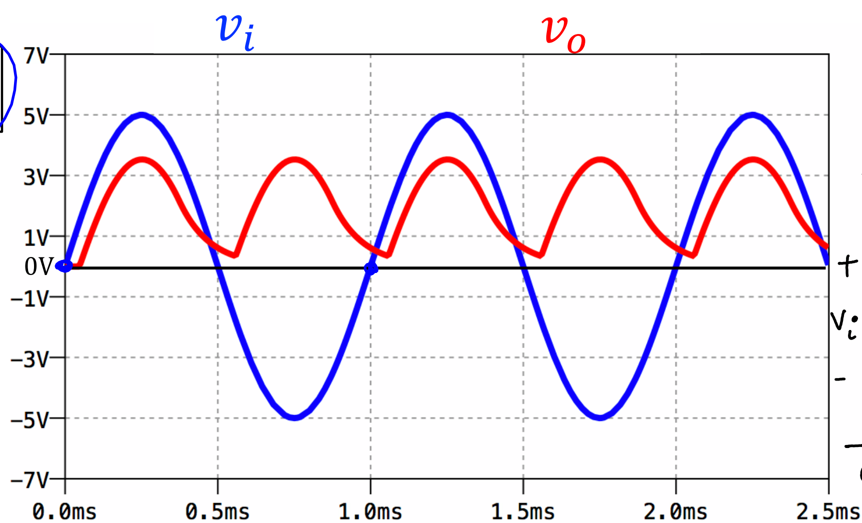
In the following diode circuit, which one of the options could be the input and output voltages for this circuit? $V_{D0} = 0.7\ V$.

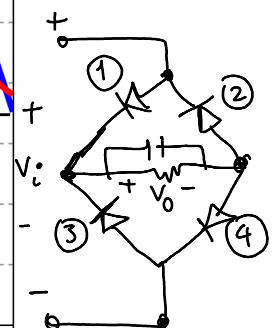


$T = 1ms$

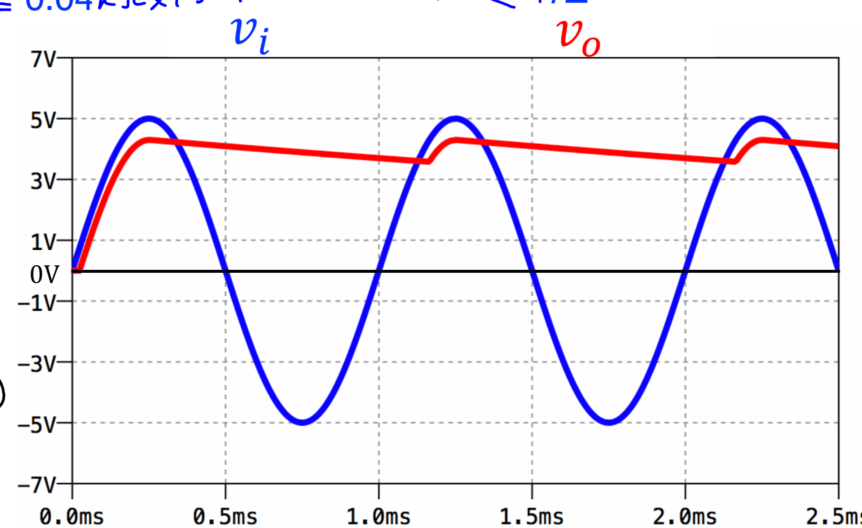
$\tau = RC = 0.04k\Omega \times 1\mu F = 0.04ms < T/2$

A.

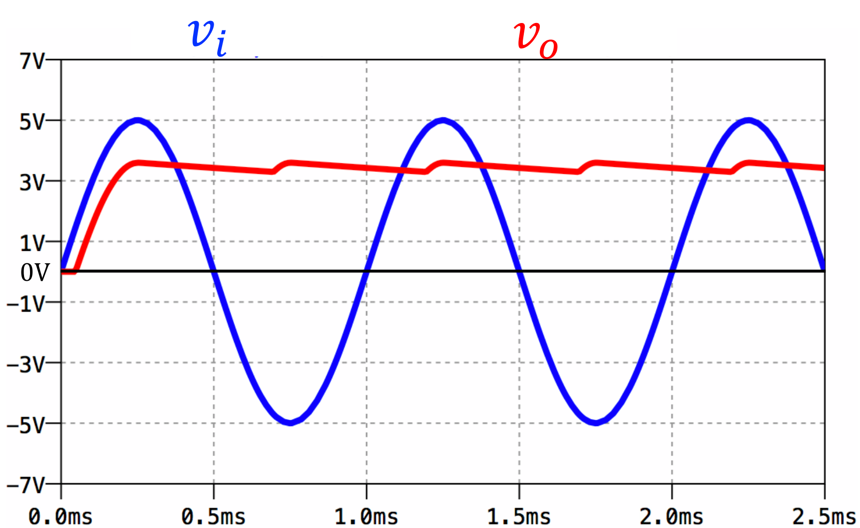




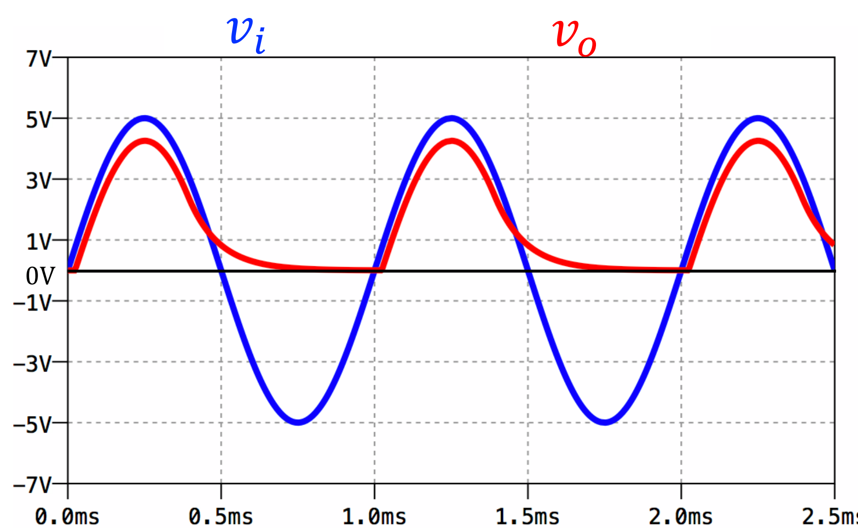
C.



B.



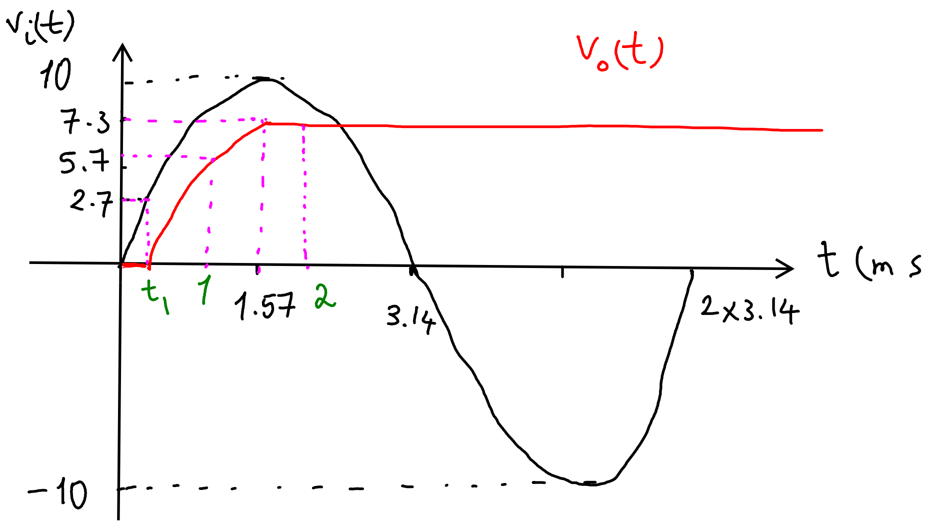
D.

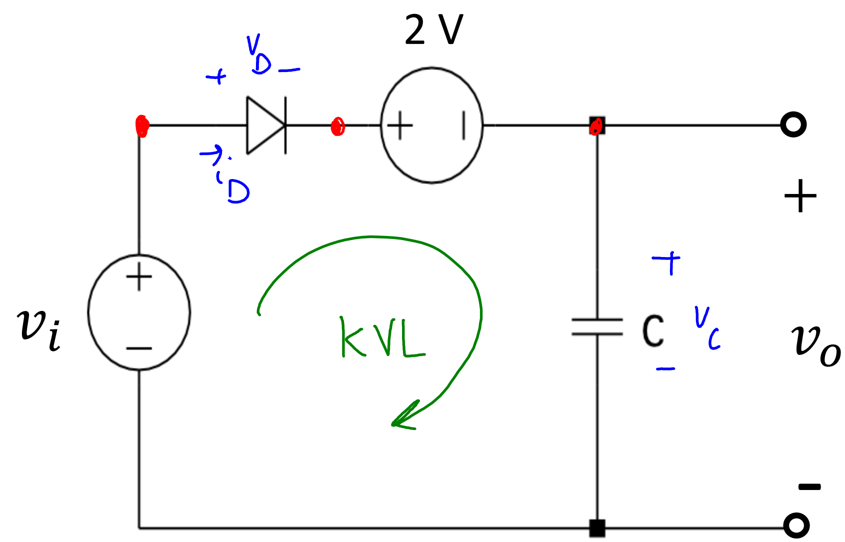


$$T = \frac{2\pi}{\omega} = \frac{2\pi\ (\text{rad})}{1000\ (\text{rad/s})} = 2\pi\ (\text{ms}) = 2 \times 3.14\ \text{ms}$$

Discussion question 1.

In the circuit below, $v_i(t) = 10\sin(\omega t)$ where ω=1000 rad/s, $v_c(0) = 0$. $V_{D0} = 0.7\ V$. What is the value of $v_o(t)$ at t = 1ms and t=2 ms? Draw one cycle of the input and output waveforms.





For $0 < t < t_1 \longrightarrow$ diode is off $\longrightarrow V_o = V_c = 0$

For $t_1 < t < 1.57\,\text{ms} \longrightarrow$ diode is ON and capacitor is charging $\Rightarrow V_D = V_{D0}$ and

KVL: $-V_i + V_D + 2V + V_o = 0$, here: $-V_i + 0.7V + 2V + V_o = 0 \longrightarrow \boxed{V_o = V_i - 2.7\,V}$

$t = 1ms$ is before the peak of V_i, ($t_{peak} = 1.57\,ms$).

$V_i(t = 1ms) = 10 \sin(1000\,(rad/s) \times 1ms) = 8.4V$

$8.4V > V_i(t = t_1) = 2.7V \Longrightarrow$ diode is ON at $t = 1ms$ and the capacitor is charging.

$V_o(t = 1ms) = V_i(t = 1ms) - 2.7V = 8.4V - 2.7V = 5.7V$

$t = 2ms$ is after the peak of $V_i \Longrightarrow$ the diode is off and the voltage across the capacitor is constant even when V_i changes.

KVL still holds, and $V_D < V_{D_0}$.

After $t = 1.57\,ms$, $V_o = V_c = 10V - 2.7V = 7.3V$