ECE 65: Components & Circuits Lab

Lecture 2

Operational Amplifier (op-amp)

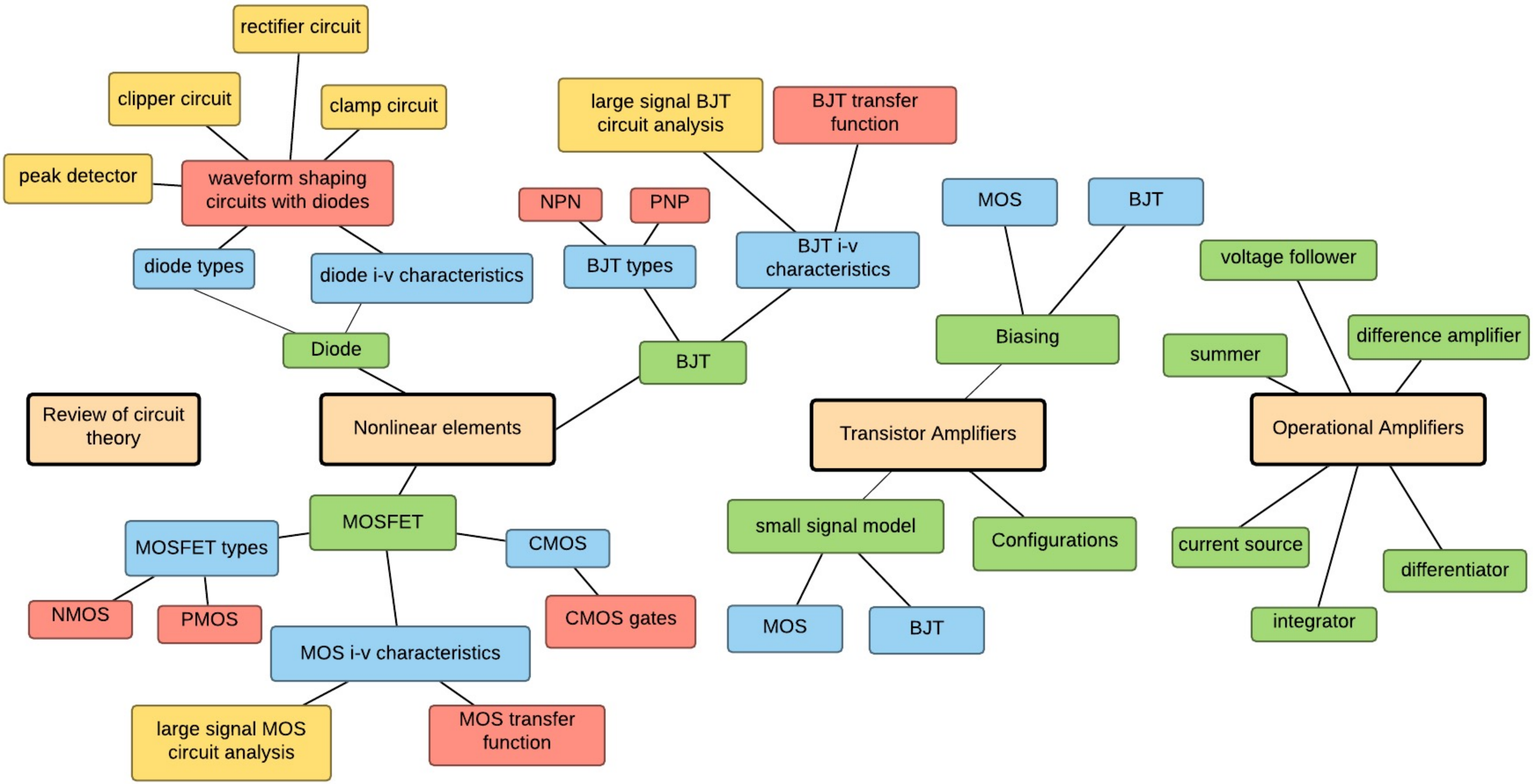
Reference notes: sections 7.1, 7.2

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

Saharnaz Baghdadchi

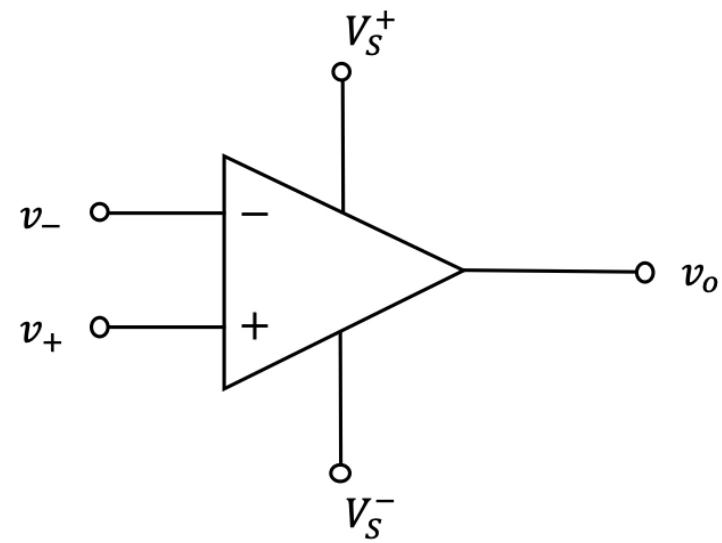
Course map

7. Operational amplifiers



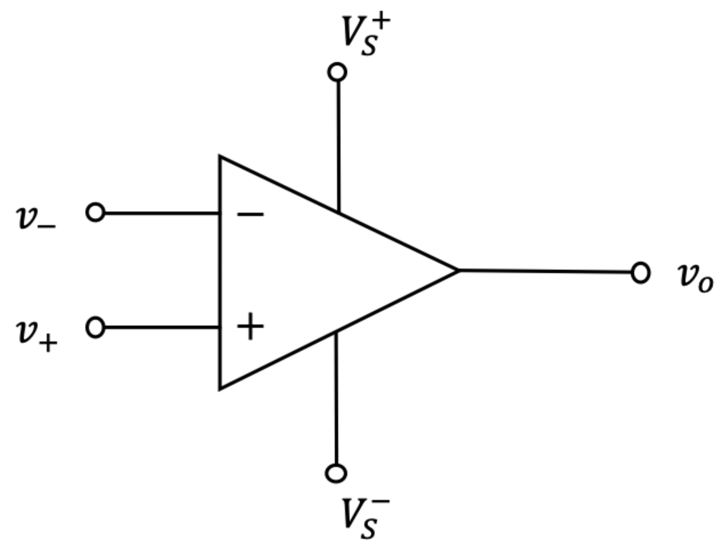
Operational Amplifiers

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



Operational Amplifiers

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



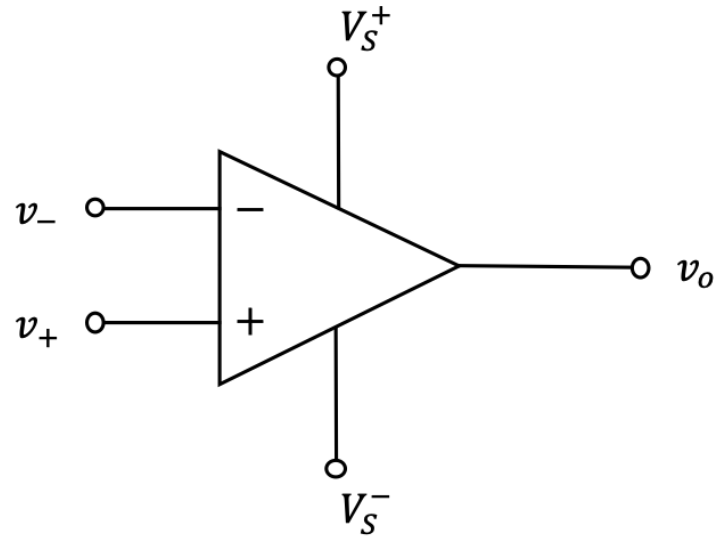
They are constructed such that they amplify the voltage difference between the two input signals.

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

open-loop voltage gain

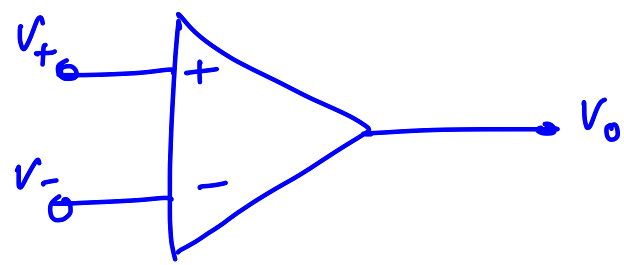
Operational Amplifiers

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



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

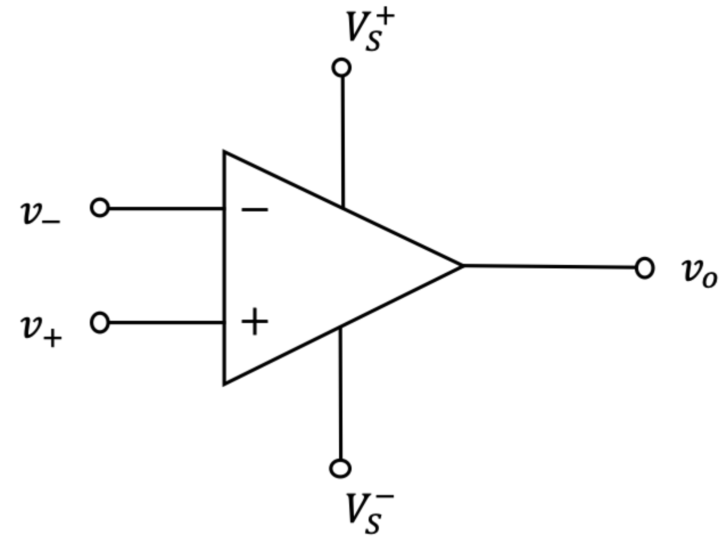
$$v_o = A(v_+ - v_-) = Av_d$$



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

Operational Amplifiers

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

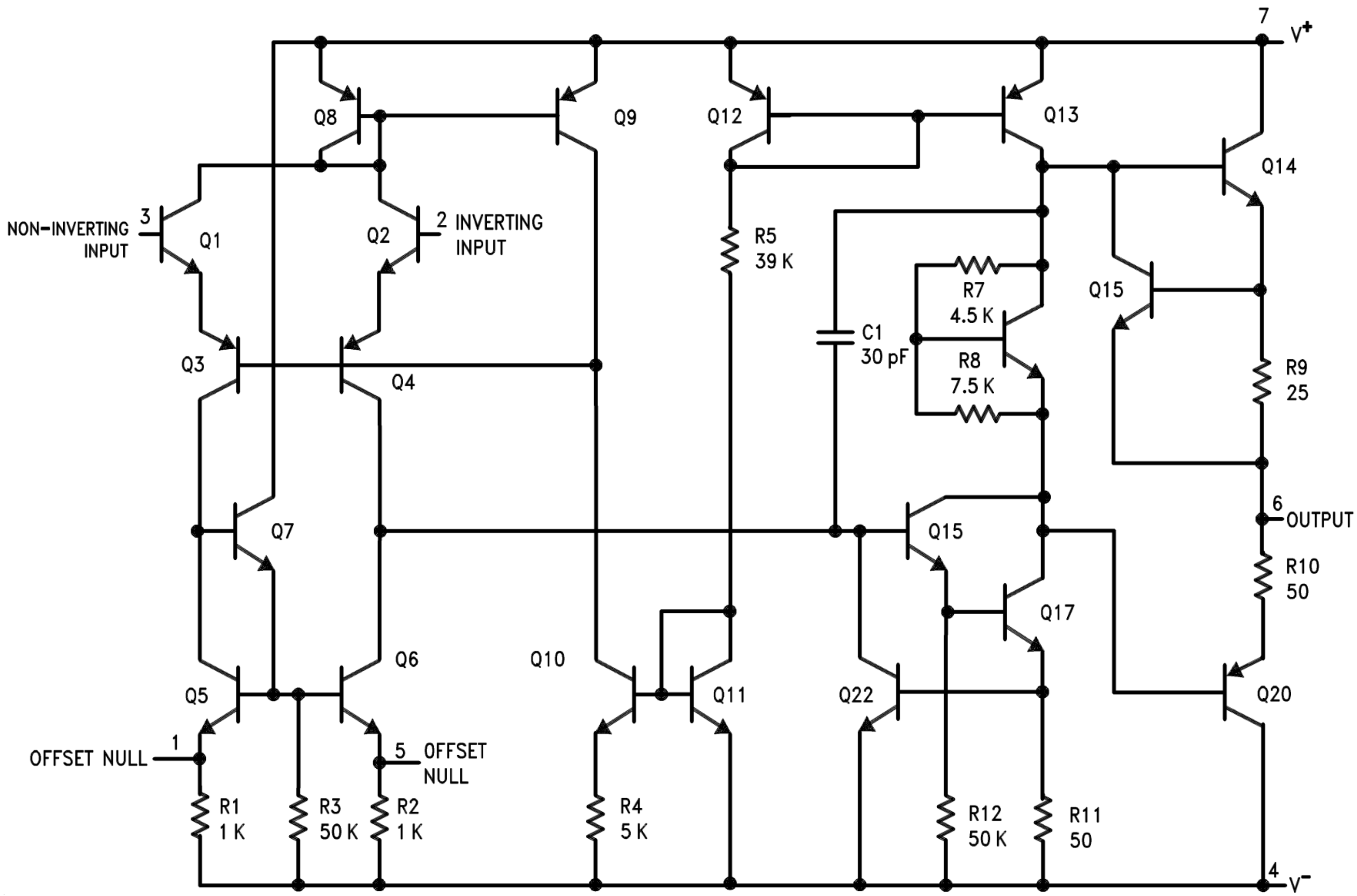


They are constructed such that they amplify the voltage difference between the two input signals.

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

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

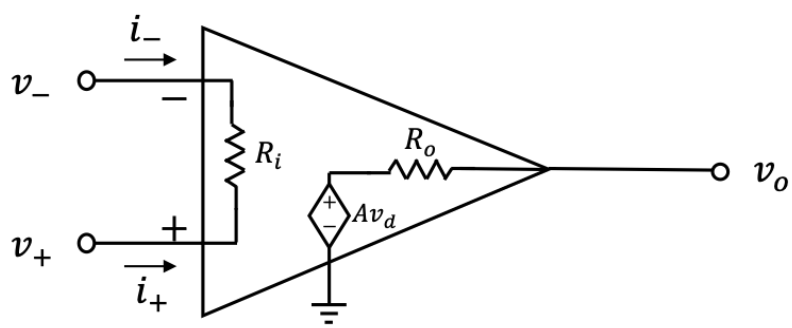
LM 741 op-amp



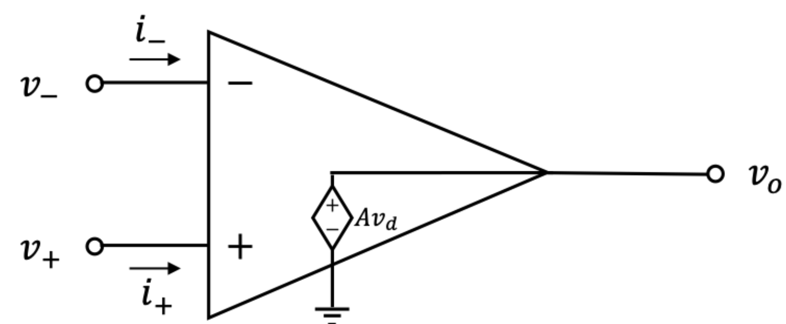
LM 741 op-amp (ti.com)

OpApp models

Linear model



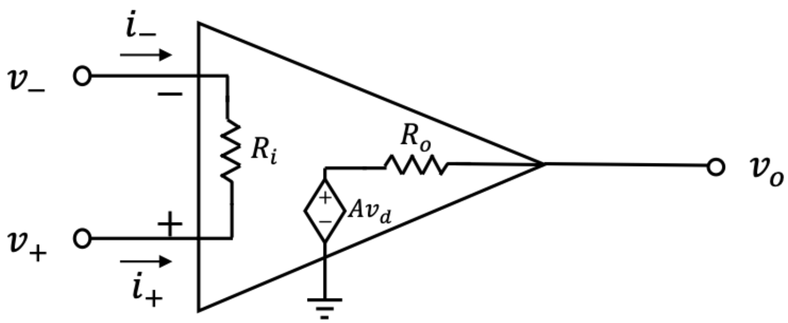
Ideal model



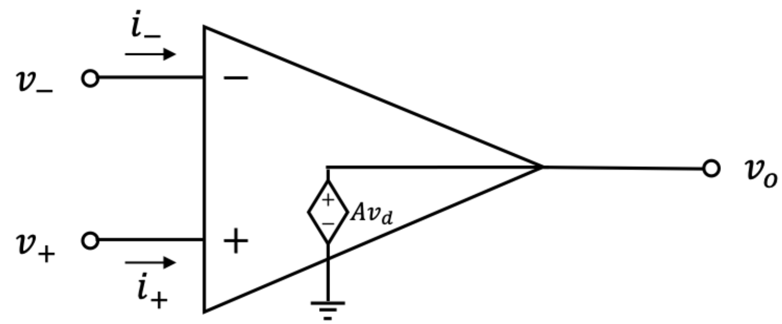
In op-amps, the input resistance, R_i , is very large, and the output resistance, R_o , is very small.

OpAmp models

Linear model



Ideal model

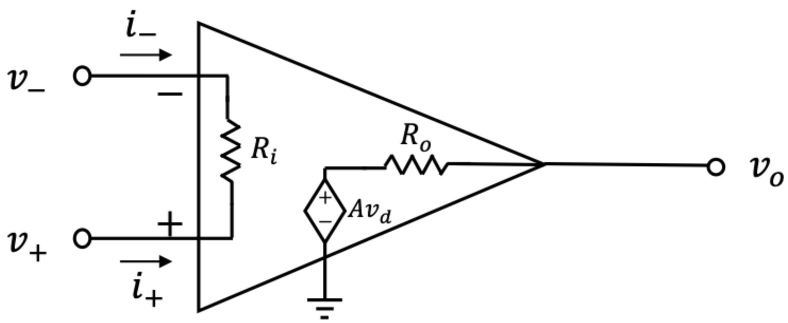


Because the input impedance of the op-amps is very large, the input current to the op-amp is very small.

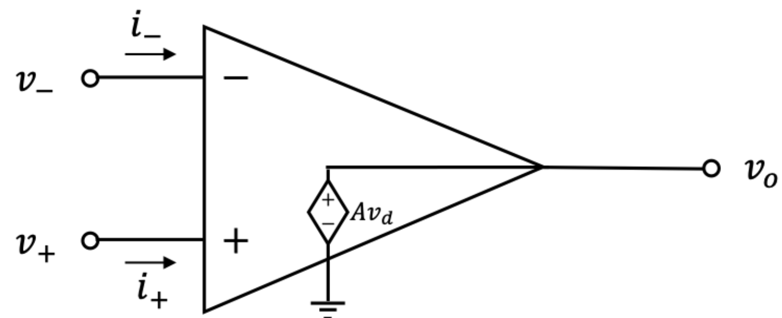
$$i_- \approx i_+ \approx 0$$

OpAmp models

Linear model



Ideal model

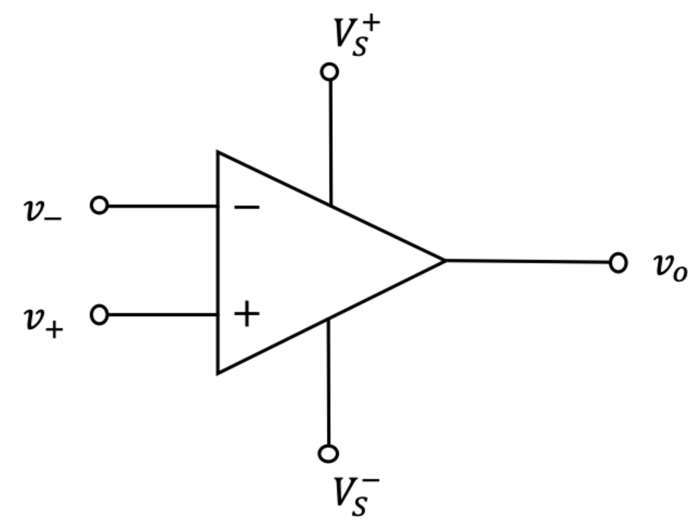


In the **ideal op-amp model**, $R_i = \infty$, $R_o = 0$, $i_- = i_+ = 0$

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.

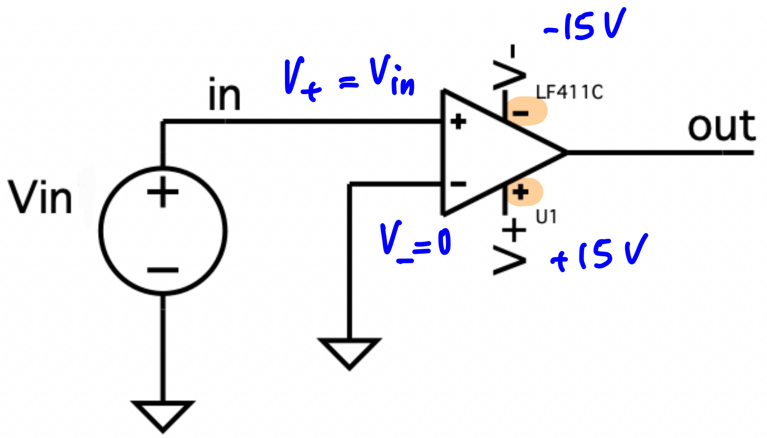
$$V_{S^-} < V_o < V_{S^+}$$

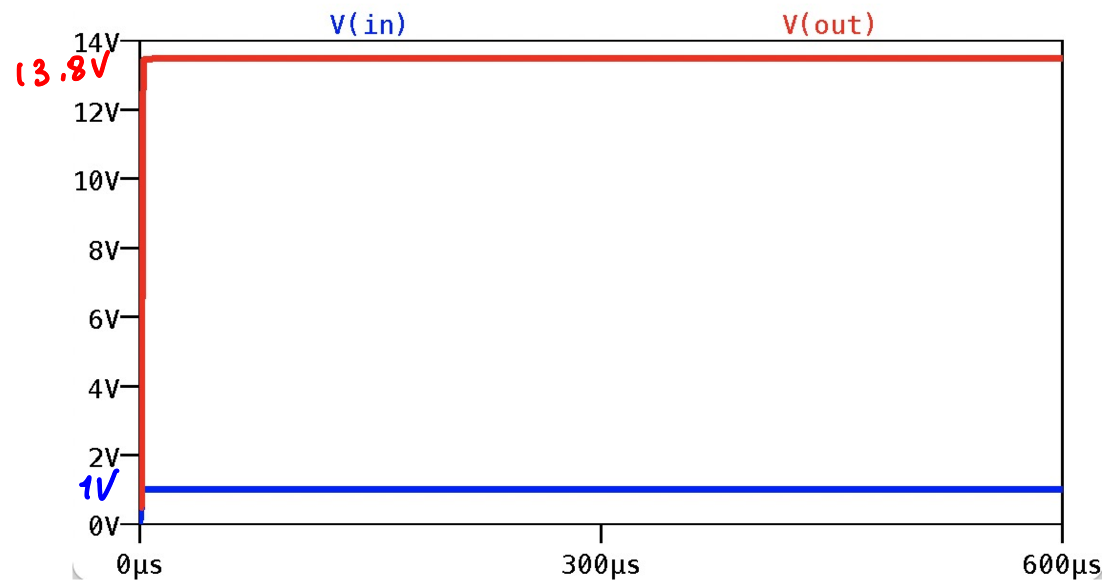


Open-loop operation of op-amps (no feedback)

$A = 10^5$

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





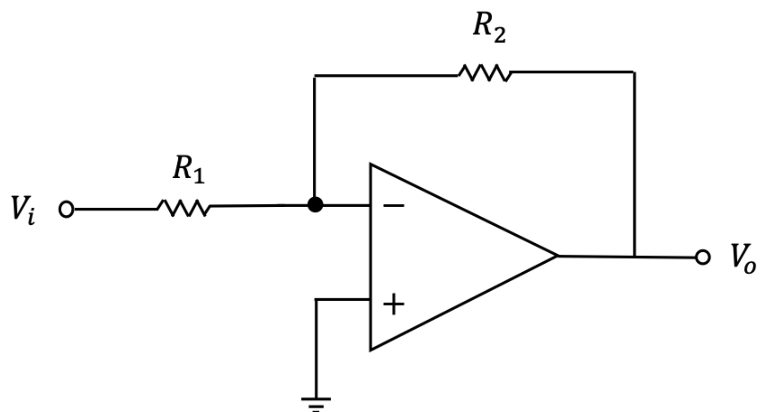
$V_{o\,max} = 13.8\,V$, here.

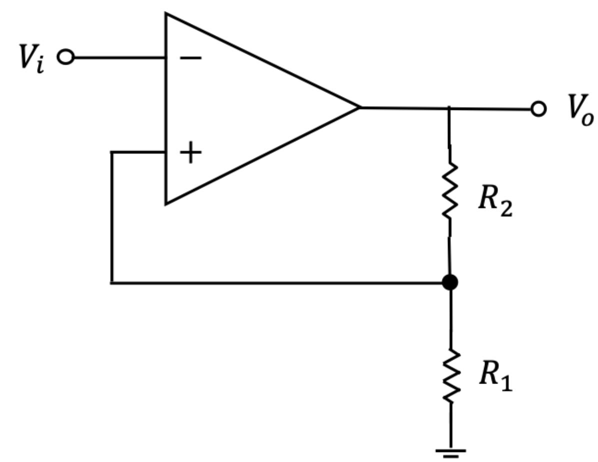
$V_o = 10^5 V_{in} \longrightarrow V_{in\,max} = \frac{V_{o\,max}}{10^5} = \frac{13.8\,V}{10^5} = 13.8\,V \times 10^{-5} = 138 \times 10^{-6}\,V = 138\,\mu V$

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

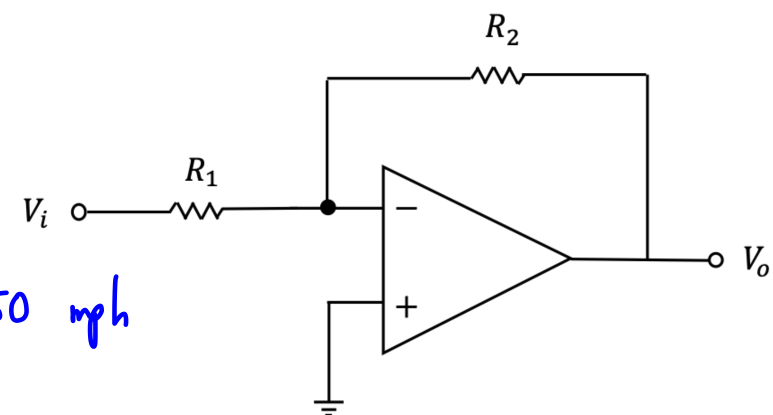
Feedback:
the concept, negative and positive feedback

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 ↗ 55 mph

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



if output ↙ 45 mph

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

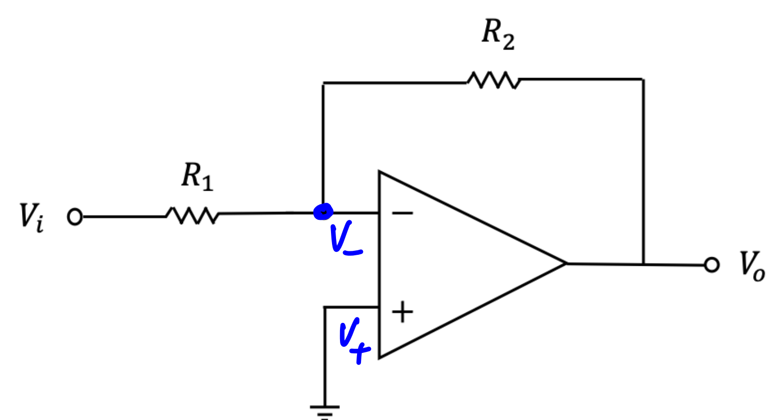
Feedback:
the concept, negative and positive feedback

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.

$V_o = A V_d$

$V_d = V_+ - V_-$

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

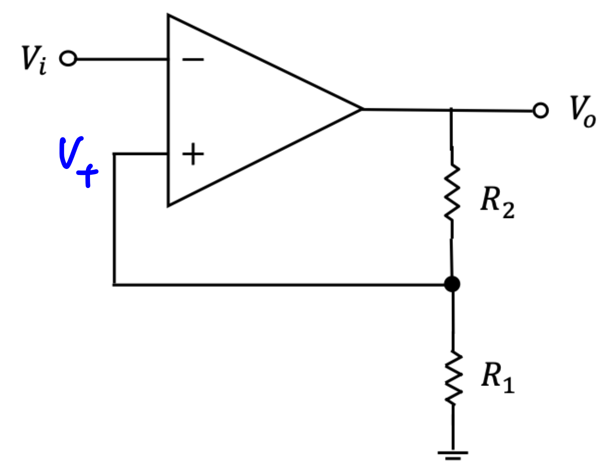


Feedback:
the concept, negative and positive feedback

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.

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

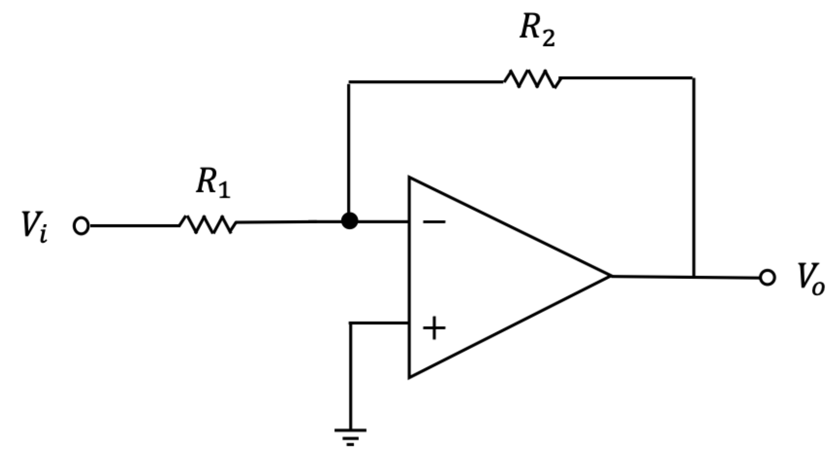
$$V_o = A(V_+ - V_-) = A(V_+ - V_i)$$



Solving op-amp circuits – example 1

Comprehensive solution

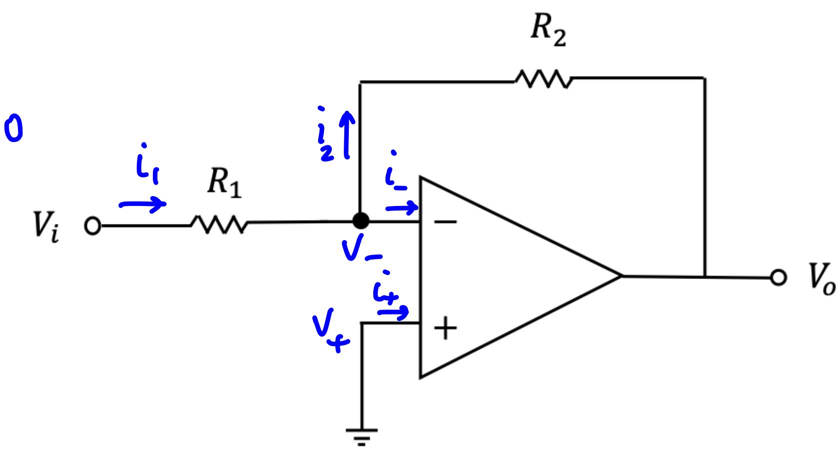
Find $\frac{v_o}{v_i}$ in the following op-amp circuit assuming an ideal op-amp.



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.



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:

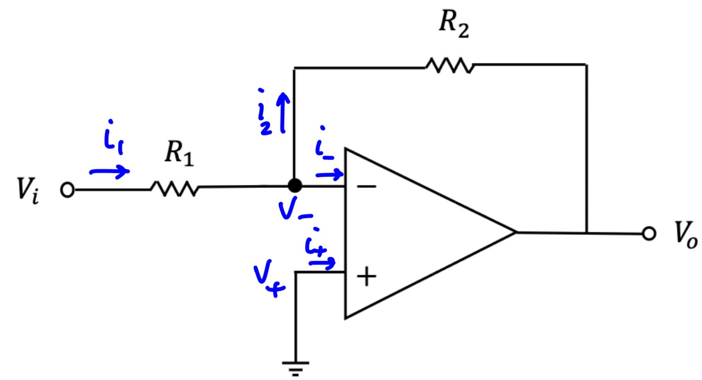
$i_1 = i_2 + i_-$, $i_- = 0 \longrightarrow i_1 = i_2$

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

Solving op-amp circuits – example 1

Comprehensive solution

$$i_1 = \frac{V_i - V_-}{R_1}, \quad i_2 = \frac{V_- - V_0}{R_2}$$



$$i_1 = i_2 \longrightarrow \frac{V_i - V_-}{R_1} = \frac{V_- - V_0}{R_2}$$

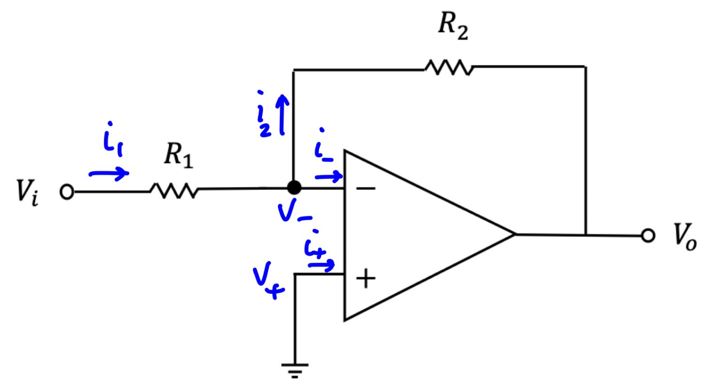
$$\left(\frac{-1}{R_1} - \frac{1}{R_2}\right) V_- = \frac{-1}{R_1} V_i - \frac{1}{R_2} V_0$$

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

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

Solving op-amp circuits – example 1

Comprehensive solution



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

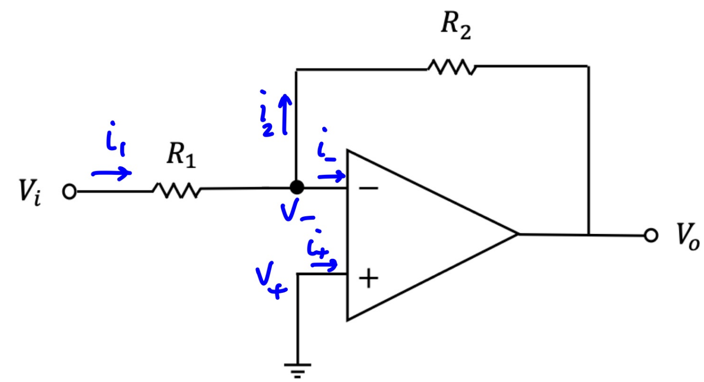
$$V_- = \frac{R_1 R_2}{R_1+R_2}\left(\frac{1}{R_1} V_i + \frac{1}{R_2} V_0\right)$$

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

Solving op-amp circuits – example 1

Comprehensive solution

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



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

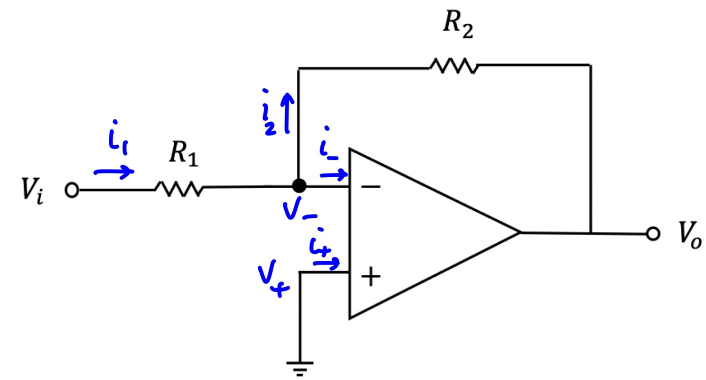
$$V_o = -A\left[\left(\frac{R_2}{R_1+R_2}\right) V_i + \left(\frac{R_1}{R_1+R_2}\right) V_o\right]$$

$$V_o + \left(\frac{AR_1}{R_1+R_2}\right) V_o = -\left(A\frac{R_2}{R_1+R_2}\right) V_i$$

$$\left[1 + \left(\frac{AR_1}{R_1+R_2}\right)\right] V_o = -\left(A\frac{R_2}{R_1+R_2}\right) V_i$$

Solving op-amp circuits – example 1

Comprehensive solution



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

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

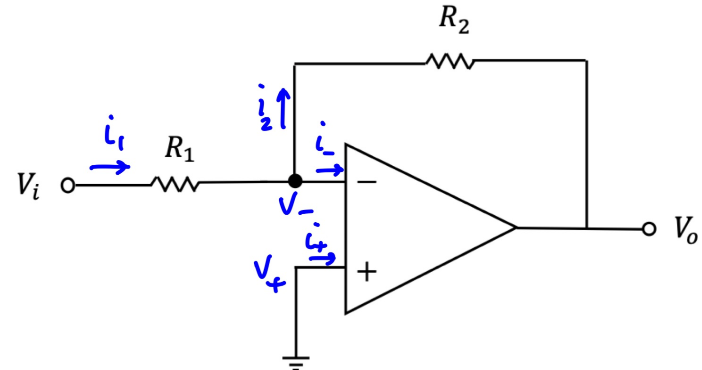
$$\rightarrow \frac{R_2}{R_1+R_2} = \frac{R_2}{R_1} \times \frac{R_1}{R_1+R_2} = \frac{R_2}{R_1} \times B$$

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

Solving op-amp circuits – example 1

Comprehensive solution

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



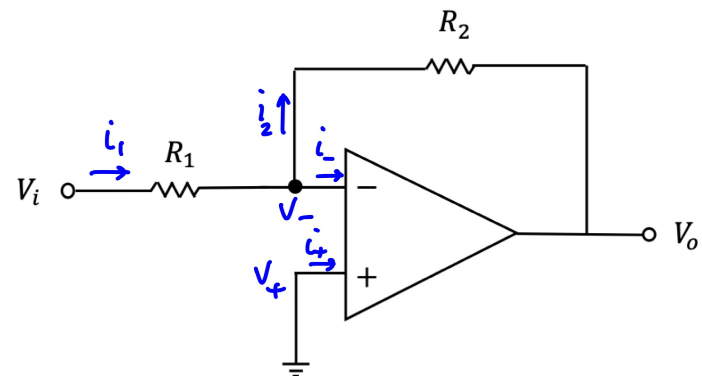
$$\frac{1}{AB} \times \left(1 + AB\right) V_o = \frac{1}{AB} \times -\frac{R_2}{R_1} AB \; V_i$$

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

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

Solving op-amp circuits – example 1

Comprehensive solution



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

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

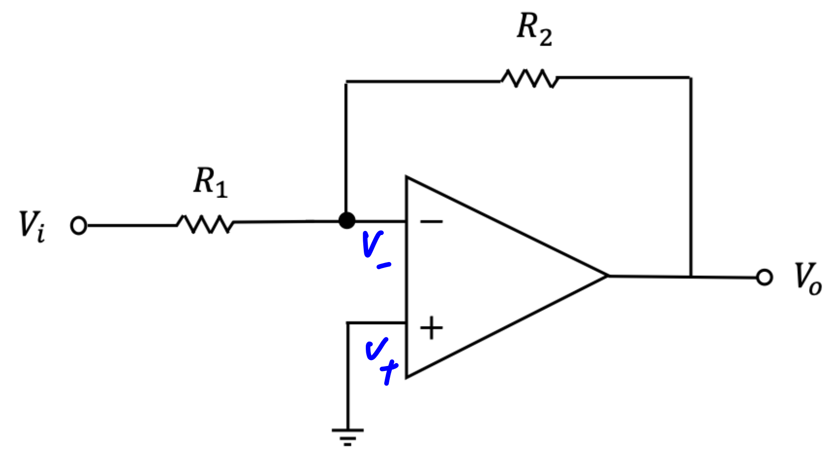
Example numbers : $R_1 = 1k\Omega$, $R_2 = 9\ k\Omega$, $A = 10^5$

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

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

virtual short principle in op-amp circuits with negative feedback

$v_o \approx$ a finite value



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

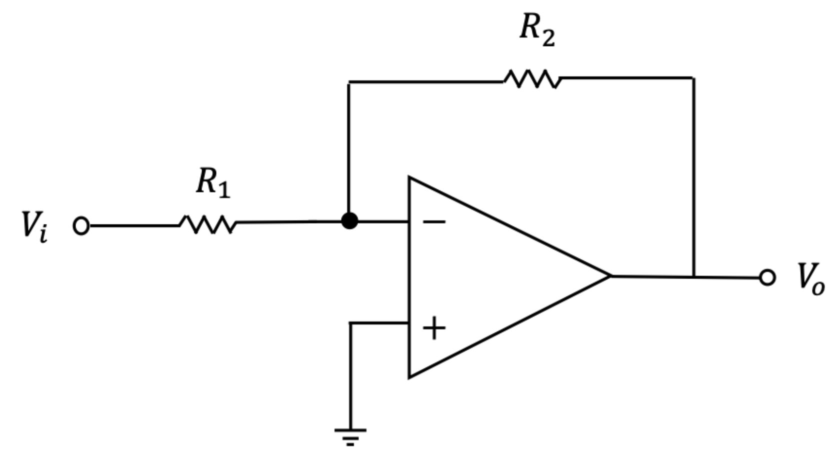
$$\Rightarrow v_+ \approx v_-$$

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

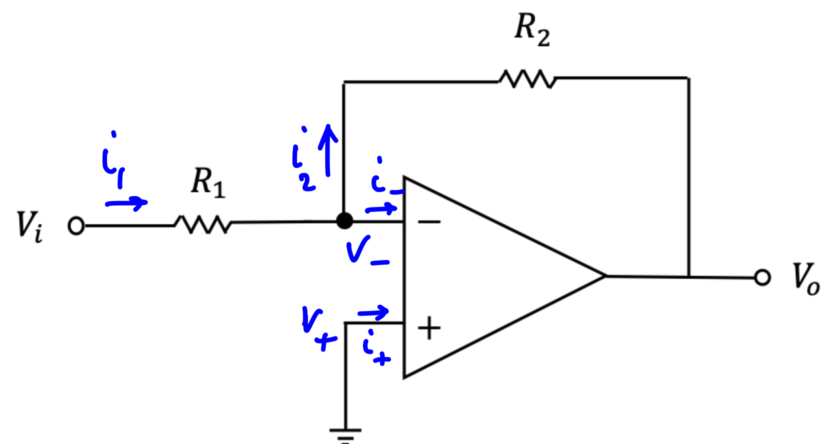
Find $\frac{v_o}{v_i}$ in the following op-amp circuit assuming an ideal op-amp.



Solving op-amp circuits – example 1

Approximate solution

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



$\left\{ \begin{array}{l} \text{ideal op-amp: } i_+ = i_- = 0 \\ \text{There is negative feedback: } V_+ \approx V_- \end{array} \right.$

$V_+ = 0 \longrightarrow V_- = 0$

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

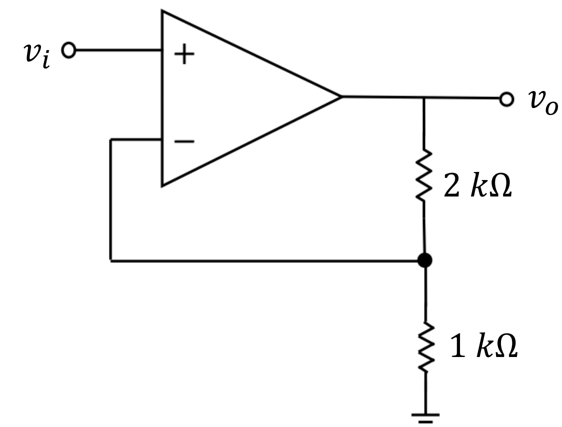
$i_1 = i_2 \Longrightarrow \frac{V_i - V_-}{R_1} = \frac{V_- - V_o}{R_2}$;

$V_- = 0 \longrightarrow \frac{V_i - 0}{R_1} = \frac{0 - V_o}{R_2} \Longrightarrow \frac{V_o}{V_i} = \frac{-R_2}{R_1}$

Lecture 2 reading quiz.

In the following amplifier circuit, the input signal is $v_i(t) = 1.5\sin(2\pi \times 10^3 t)\ V$

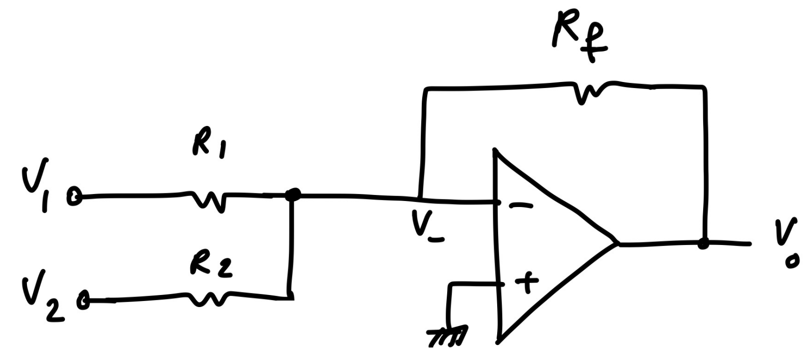
Which one of the options could be the output signal, $v_o(t)$?



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.



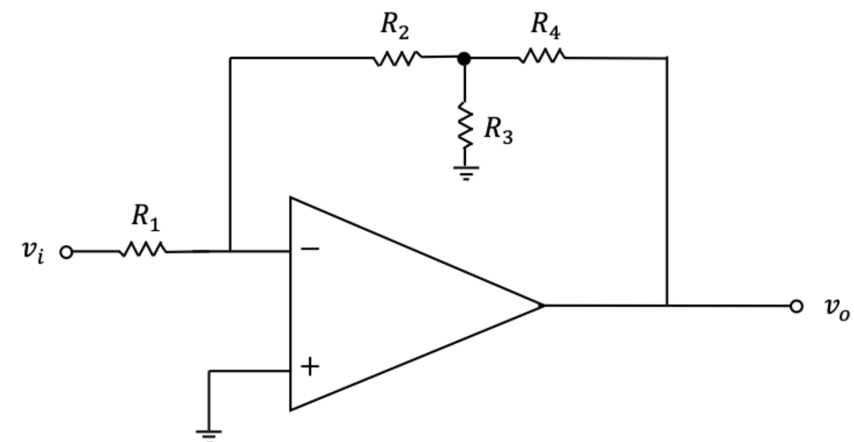
Discussion question 2. (non-inverting summer)

Using the structure of a non-inverting amplifier, design an op-amp circuit to achieve $v_o = 6v_1 + 4v_2$.

Assume an ideal op-amp.

Discussion question 3.

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



ECE 65: Components & Circuits Lab

Lecture 3

Operational Amplifier limitations

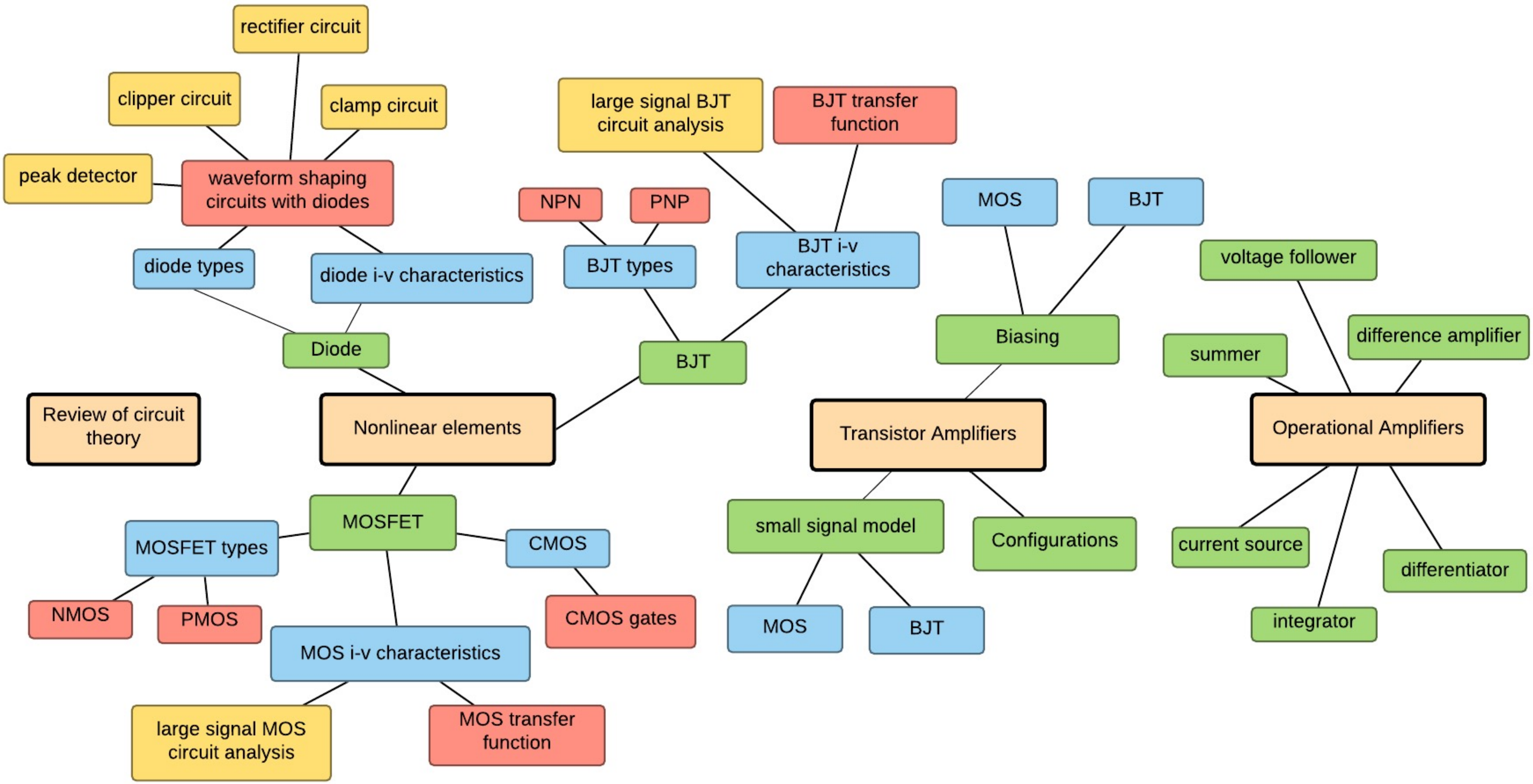
Reference notes: sections 7.5

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

Saharnaz Baghdadchi

Course map

7. Operational amplifiers

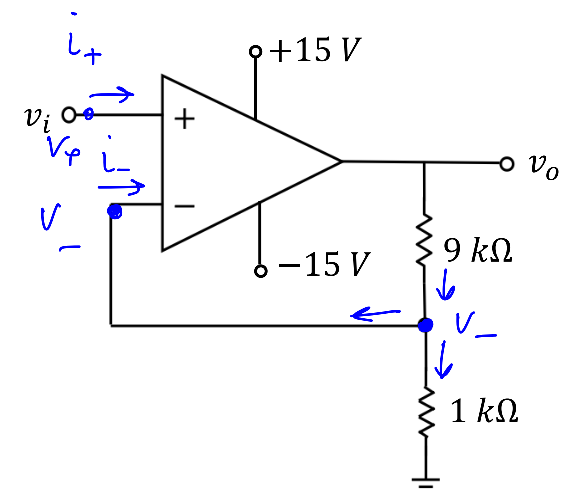


Voltage-supply limit or Saturation

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 : $v_+ = v_-$

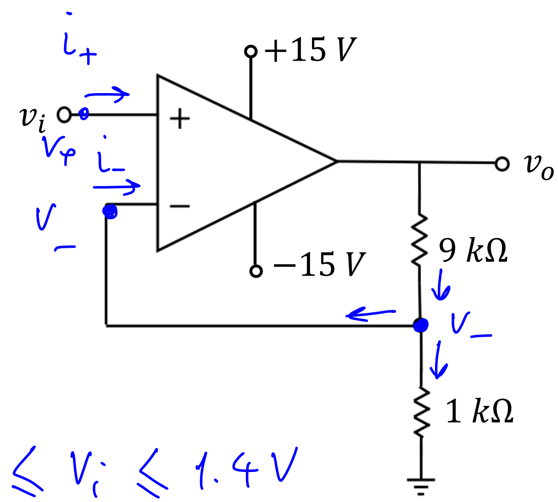
here, $v_+ = v_i$, $\frac{v_-}{1k\Omega} = \frac{v_o - v_-}{9k\Omega} \Longrightarrow v_o = 10\ v_- \Rightarrow \boxed{v_o = 10\ v_i}$

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.

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

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



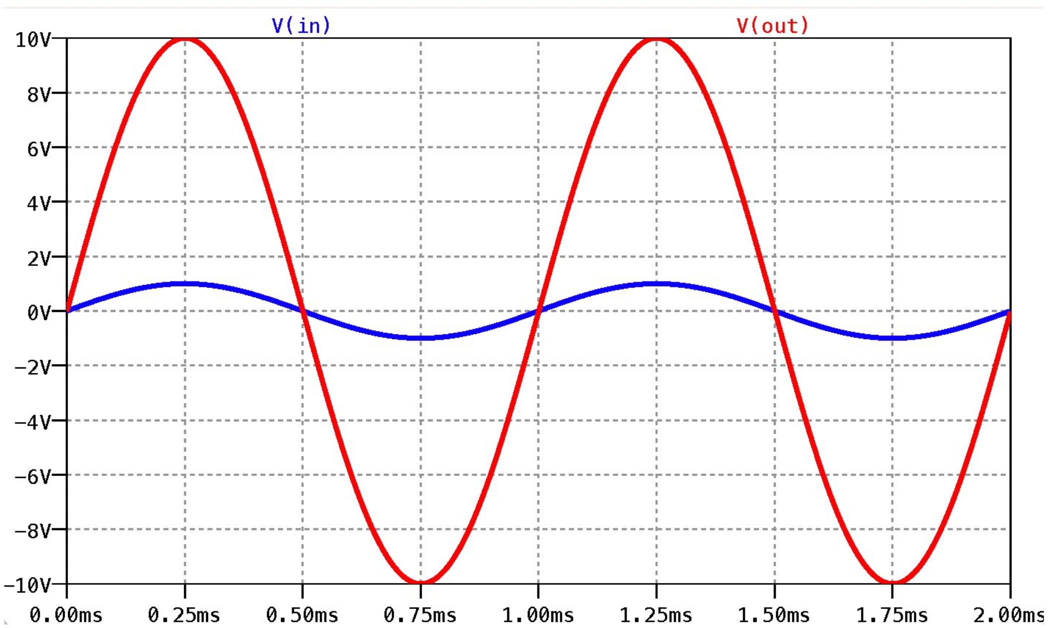
$V_{sat+} = 14\,V$

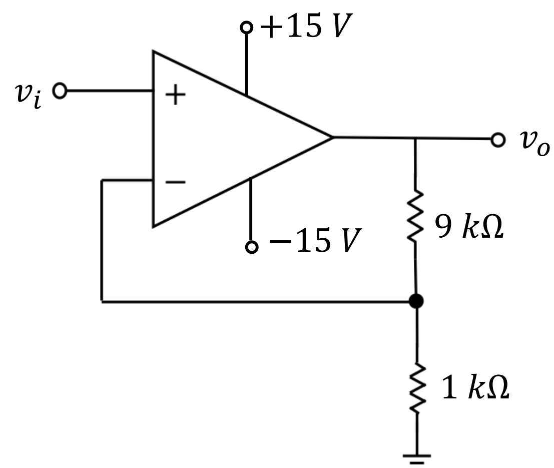
$V_{sat-} = -14\,V$

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

Voltage-supply limit or Saturation

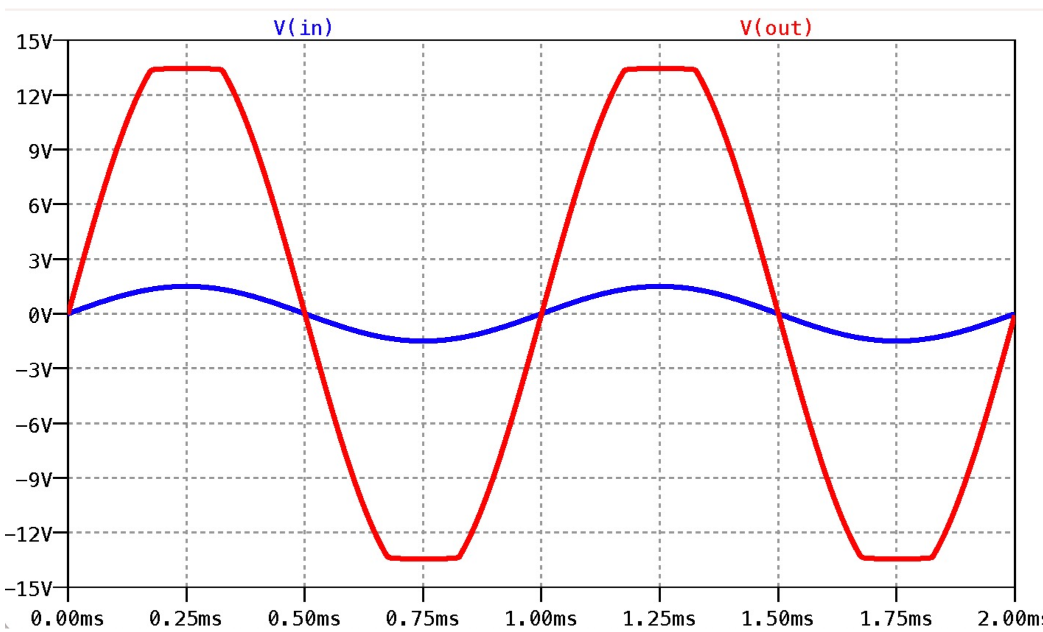
As we saw before, the maximum output voltage of op-amps is limited by the positive and negative voltage sources (V_{S^+} and V_{S^-}) used to power up the op-amp chip.

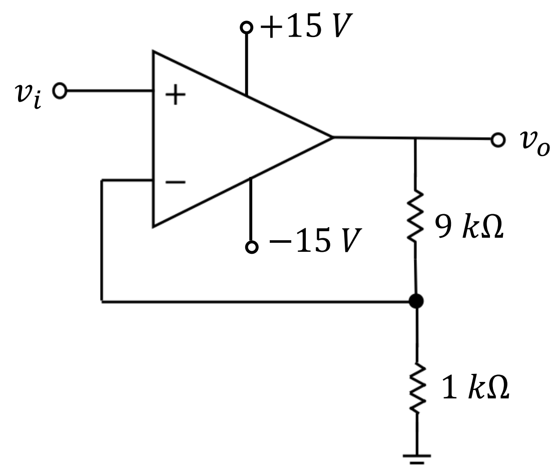




Voltage-supply limit or Saturation

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.

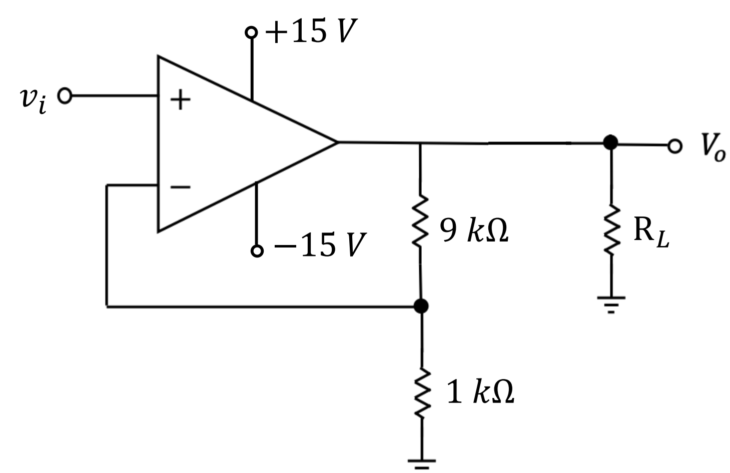




Maximum Output Current

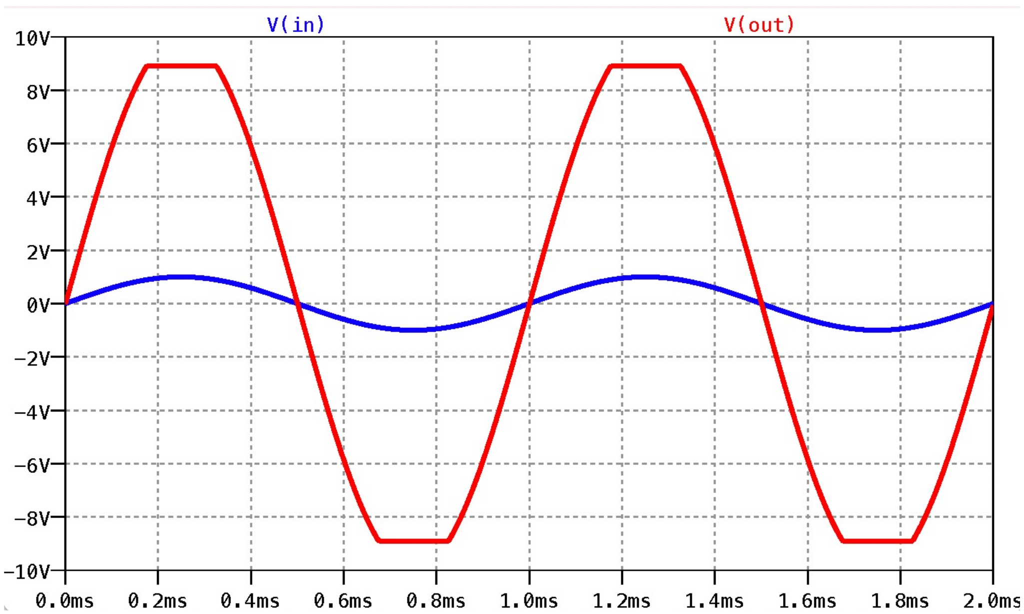
The output current of an op-amp is limited to a specified maximum value.

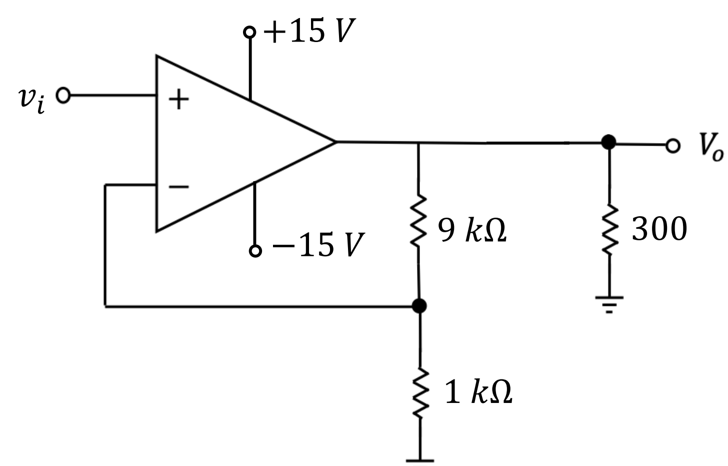
For example, in the 741 op-amp, the maximum output current is ±20mA.



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.

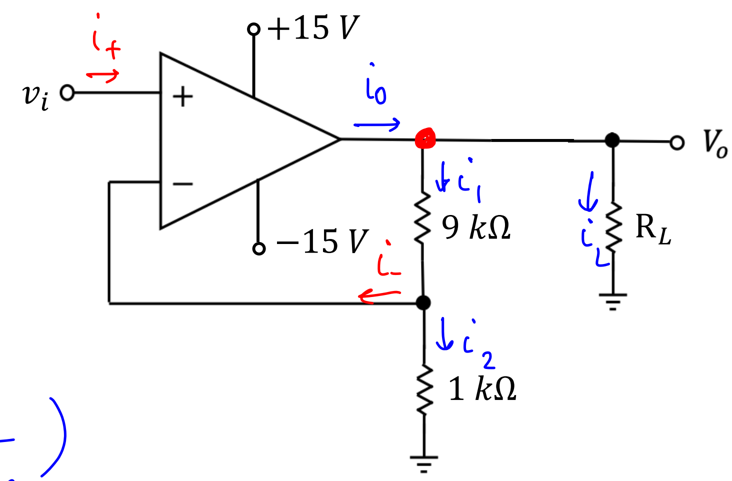




Maximum Output Current - Example

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: $i_o = i_1 + i_L$

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

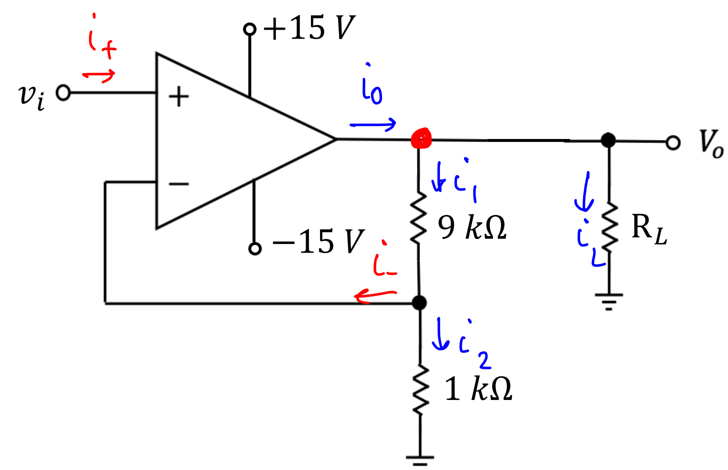
$$i_o = \frac{V_o}{10\,k\Omega} + \frac{V_o}{1k\Omega} = V_o\left(\frac{1}{10\,k\Omega} + \frac{1}{1k\Omega}\right)$$

$$= V_o \times 1.1$$

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.

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



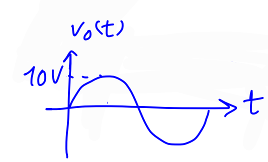
$i_o = V_o \times 1.1$

Assume linear amplification:

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

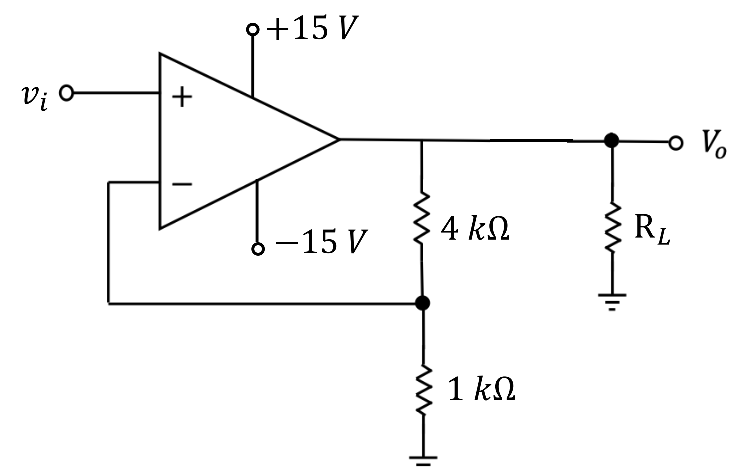
$\Rightarrow i_{o_{max}} = 10 \times 1.1 = 11\ mA < +20mA$

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



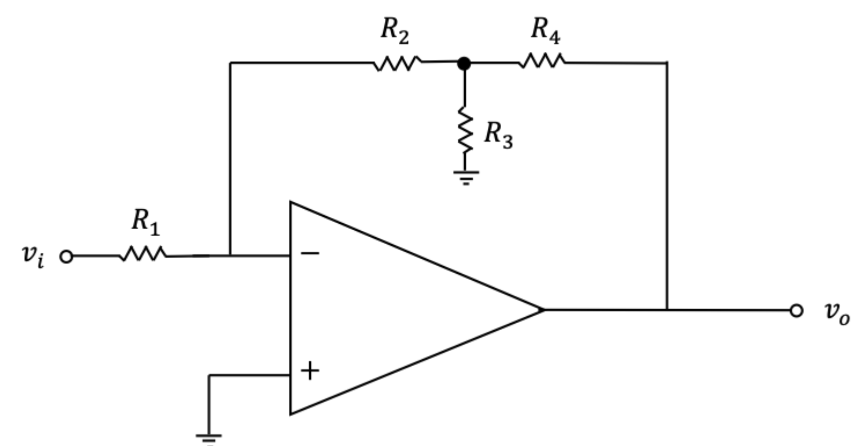
Lecture 3 reading quiz.

The following op-amp circuit is fed with a low-frequency sinusoidal signal with the peak amplitude of 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?



Discussion question 1.

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



Discussion question 2.

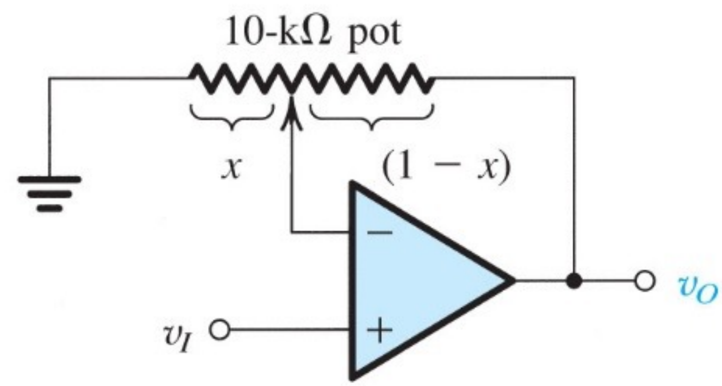
The following circuit uses a $10\ k\Omega$ potentiometer to obtain an adjustable gain amplifier.

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?

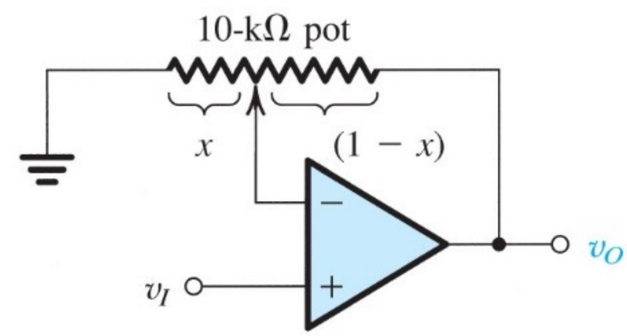
Assume an ideal op-amp.



Discussion question 2.

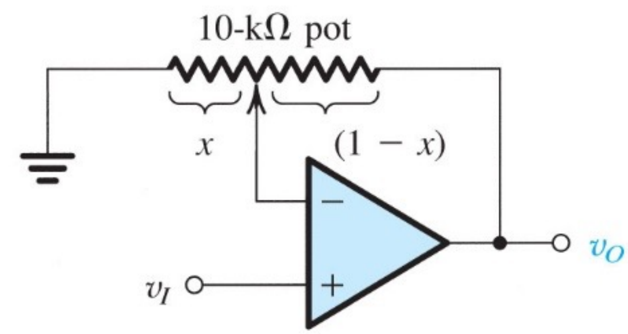
a) Derive an expression for the gain as a function of the potentiometer setting x.

Assume an ideal op-amp.



Discussion question 2.

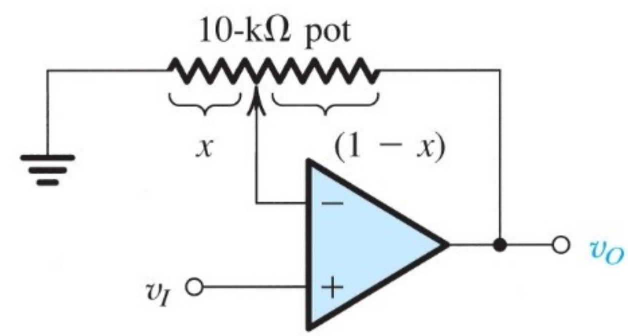
a) What is the range of the gain obtained? Assume an ideal op-amp.



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.



ECE 65: Components & Circuits Lab

Lecture 4

Diode introduction

and review of circuit theory

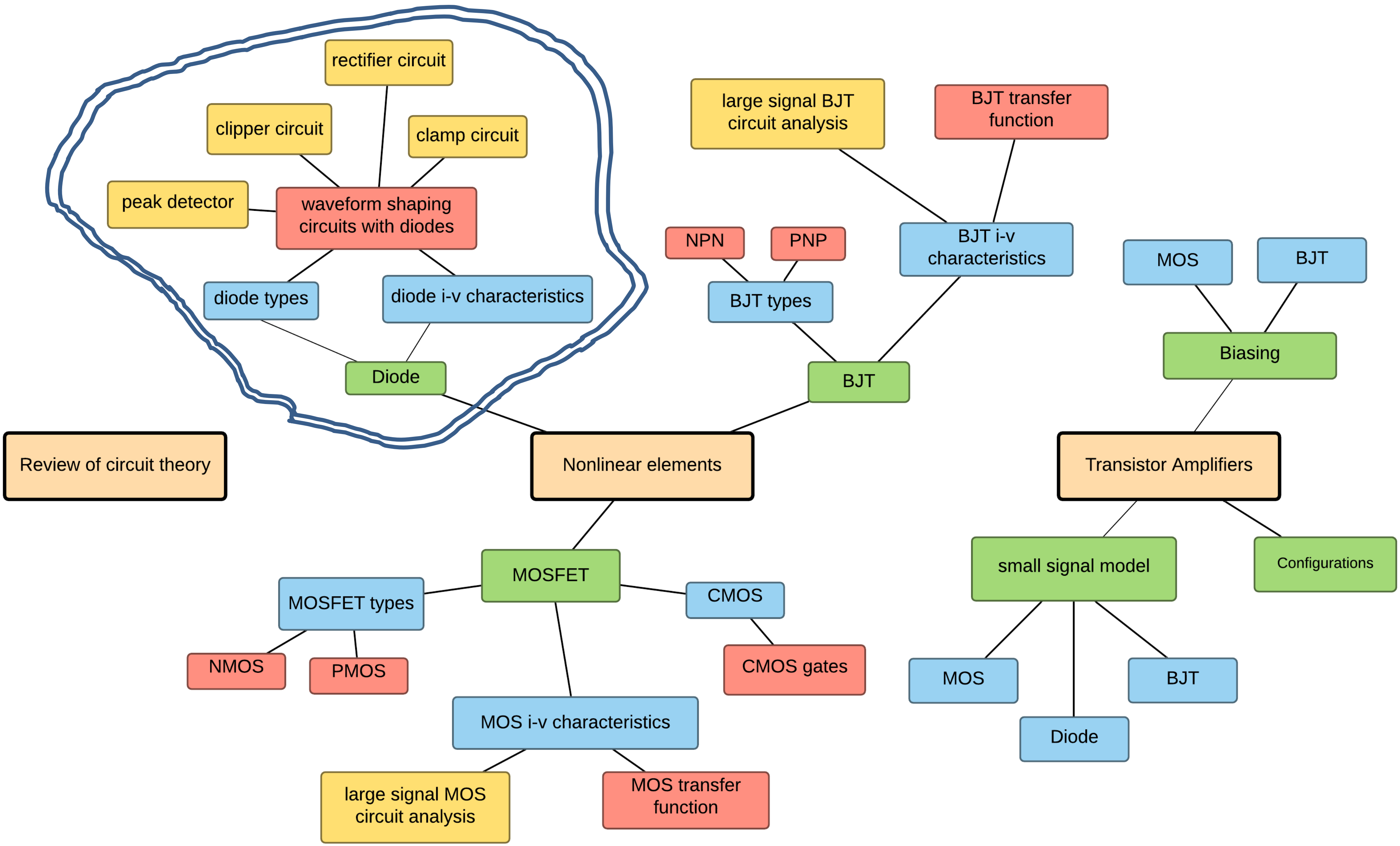
Reference notes: sections 2.1-2.8

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

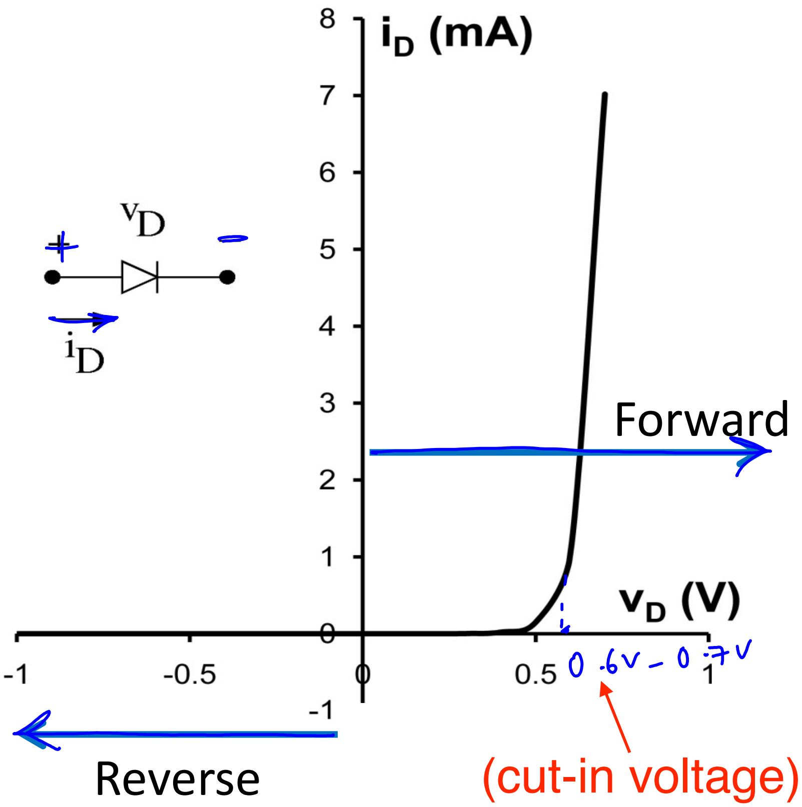
Saharnaz Baghdadchi

Course map

2. Diodes



The iv characteristics of a silicon junction diode



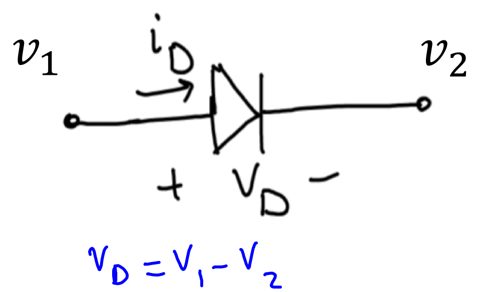
When the diode conducts,
$i_D \gg I_S$ and:

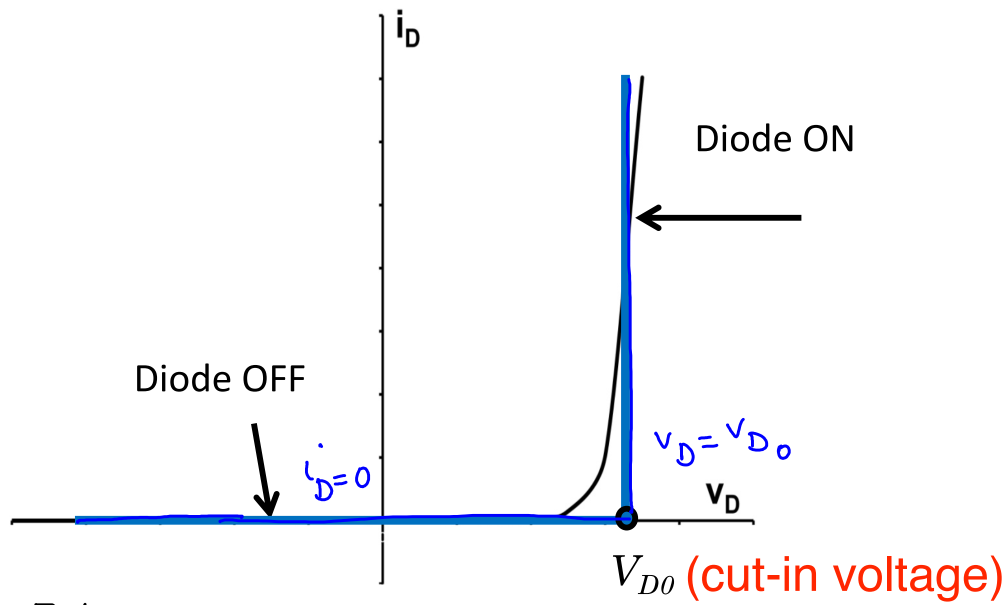
$$\boxed{i_D = I_S\, e^{v_D/V_T}}$$

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

V_T : Thermal voltage = 26mV at room temp.

Diode piecewise-linear model:





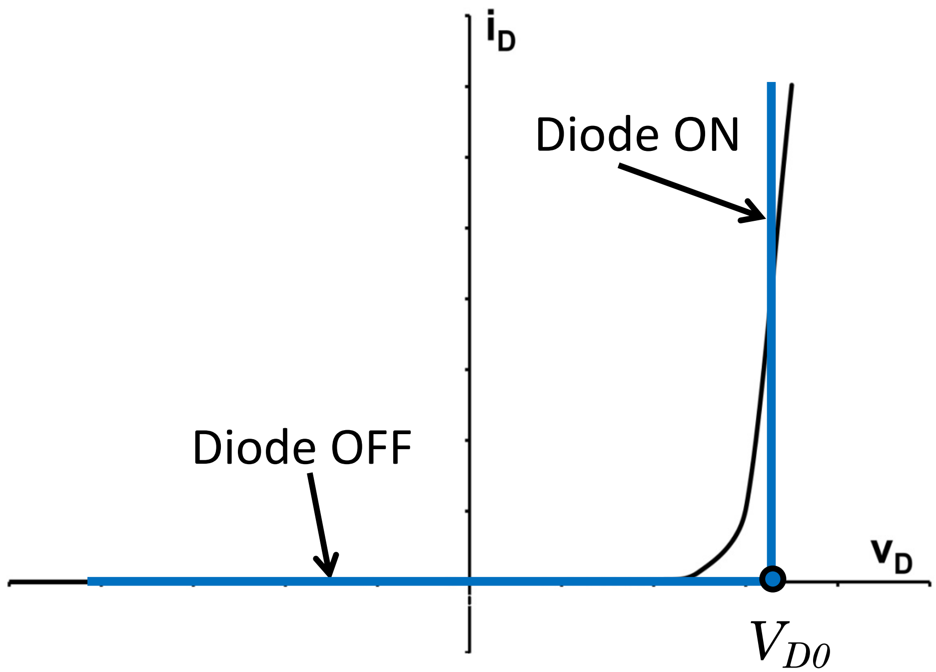
Assume Si Diode with $V_{D_0} = 0.7\,V$

Ⓐ When $\underline{V_1 - V_2 < 0}$ → diode is reverse-biased ⇒ $i_D = 0$

Ⓑ When $\underline{0 < V_1 - V_2 < 0.7}$ → diode is forward-biased, but it is not ON, yet ⇒ $\underline{i_D = 0}$

Ⓒ When $\underline{V_1 - V_2 = 0.7}$ → diode is forward biased and it's ON ⇒ $\underline{i_D > 0}$ & $\underline{V_D = V_{D_0} = 0.7}$

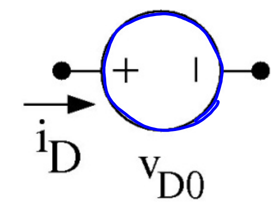
Diode piecewise-linear model:



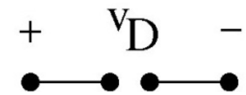
Constant Voltage drop Model:

Circuit Models:

ON:



OFF:

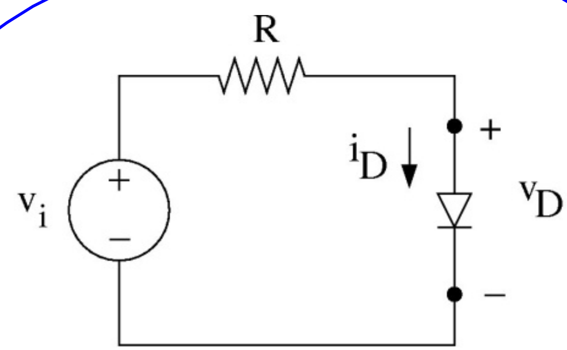


Diode ON: $v_D = V_{D0}$ and $i_D \geq 0$

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

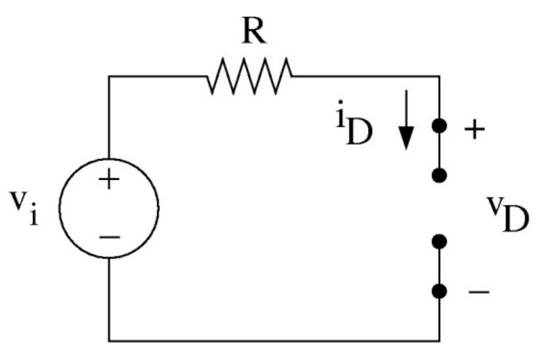
(cut-in voltage) $V_{D0} = 0.6 - 0.7\ V$ for Si

Diode circuit models:



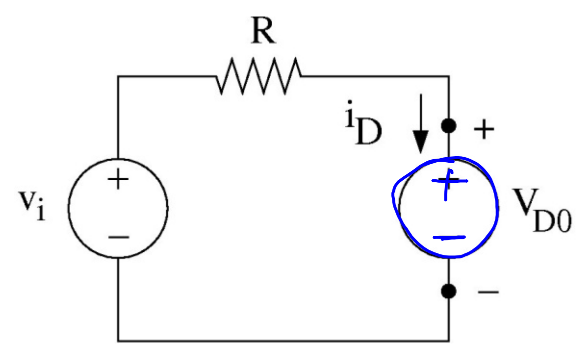
When Diode is OFF:

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



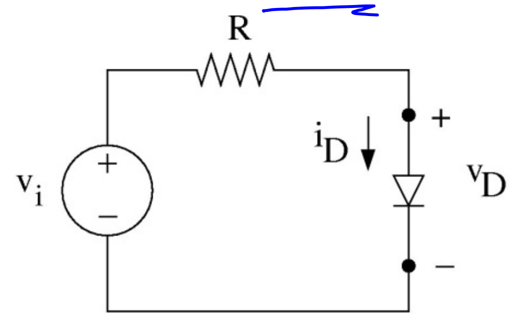
When Diode is ON:

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



Example 1:

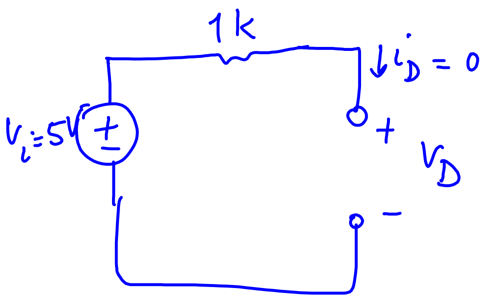
Find i_D and v_D for R = 1k, $V_i = 5$ V, and Si Diode ($V_{D0} = 0.7$ V).



Solution with diode circuit models:

Assume Diode is off

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

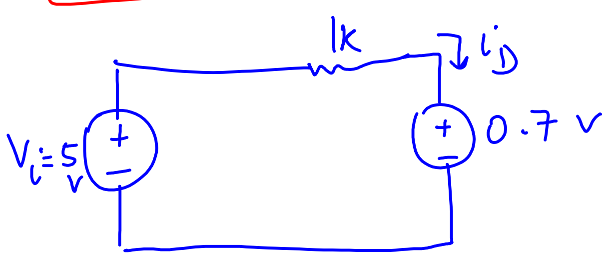


$V_i = 1k \times i_D + V_D$

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

Assume Diode is ON

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



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

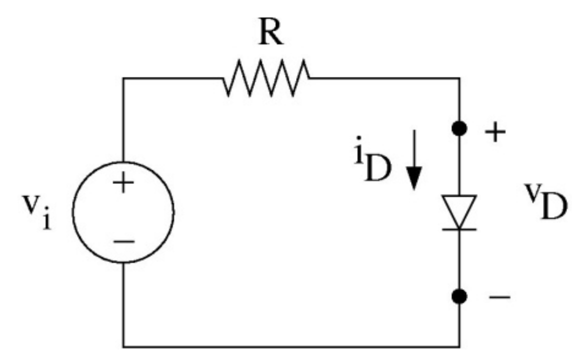
$\longrightarrow i_D = \dfrac{5 - 0.7}{1k} = \underline{4.3 \, mA > 0}$

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

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

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

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

---

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

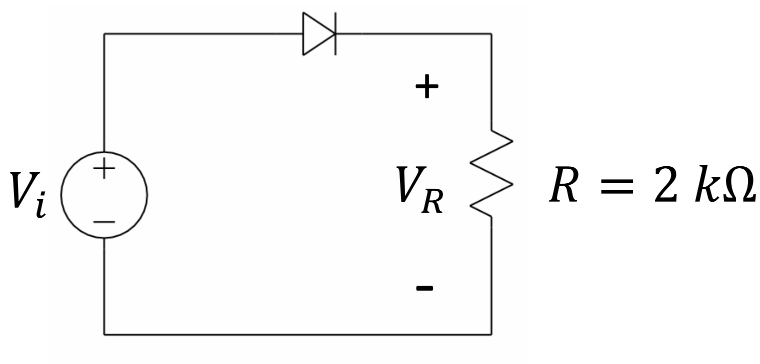
$V_i = R\, i_D + V_D \longrightarrow V_i = V_D$, $V_D < V_{D_0} \longrightarrow V_i < V_{D_0}$

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

Lecture 4 reading quiz

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

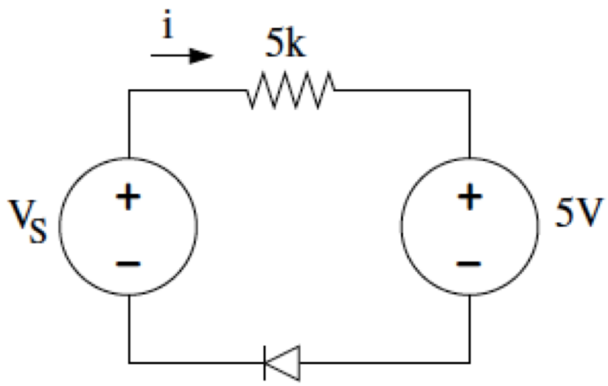
Assume $V_{D0} = 0.7\ V$



Clicker question 1.

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

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



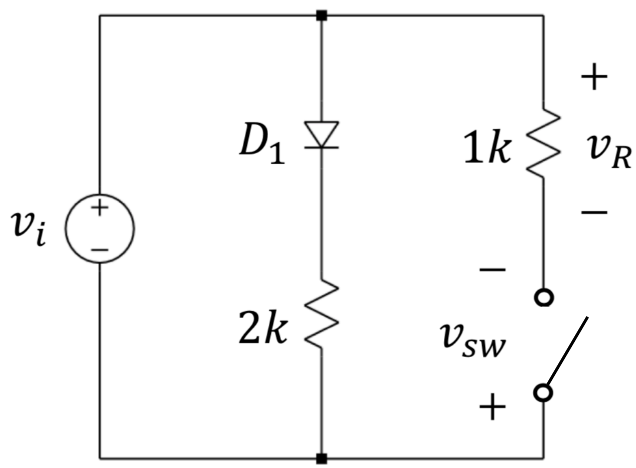
A. $v_s \geq 5\ V$

B. $v_s \geq 5.7\ V$

C. $v_s \geq 4.3\ V$

Clicker question 2.

In the below circuit, find v_{SW} and v_R when $v_i = 5\ V$.



A. $v_{SW} = 0\ V$ and $v_R = 0\ V$

B. $v_{SW} = 5\ V$ and $v_R = 0\ V$

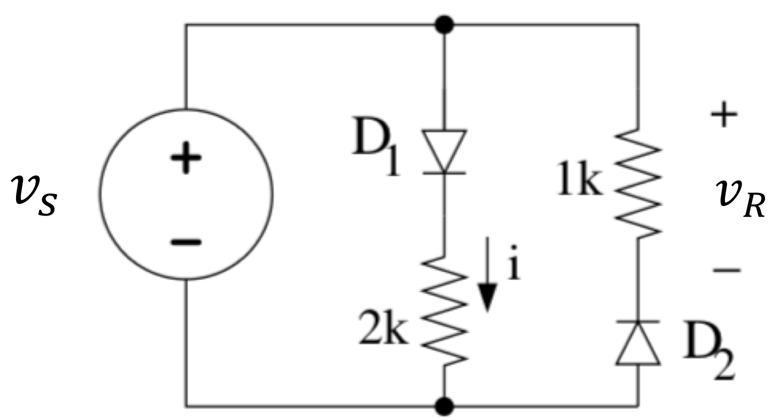
C. $v_{SW} = -5\ V$ and $v_R = 5\ V$

D. $v_{SW} = -5\ V$ and $v_R = 0V$

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

ECE 65: Components & Circuits Lab

Lecture 5

Zener Diode

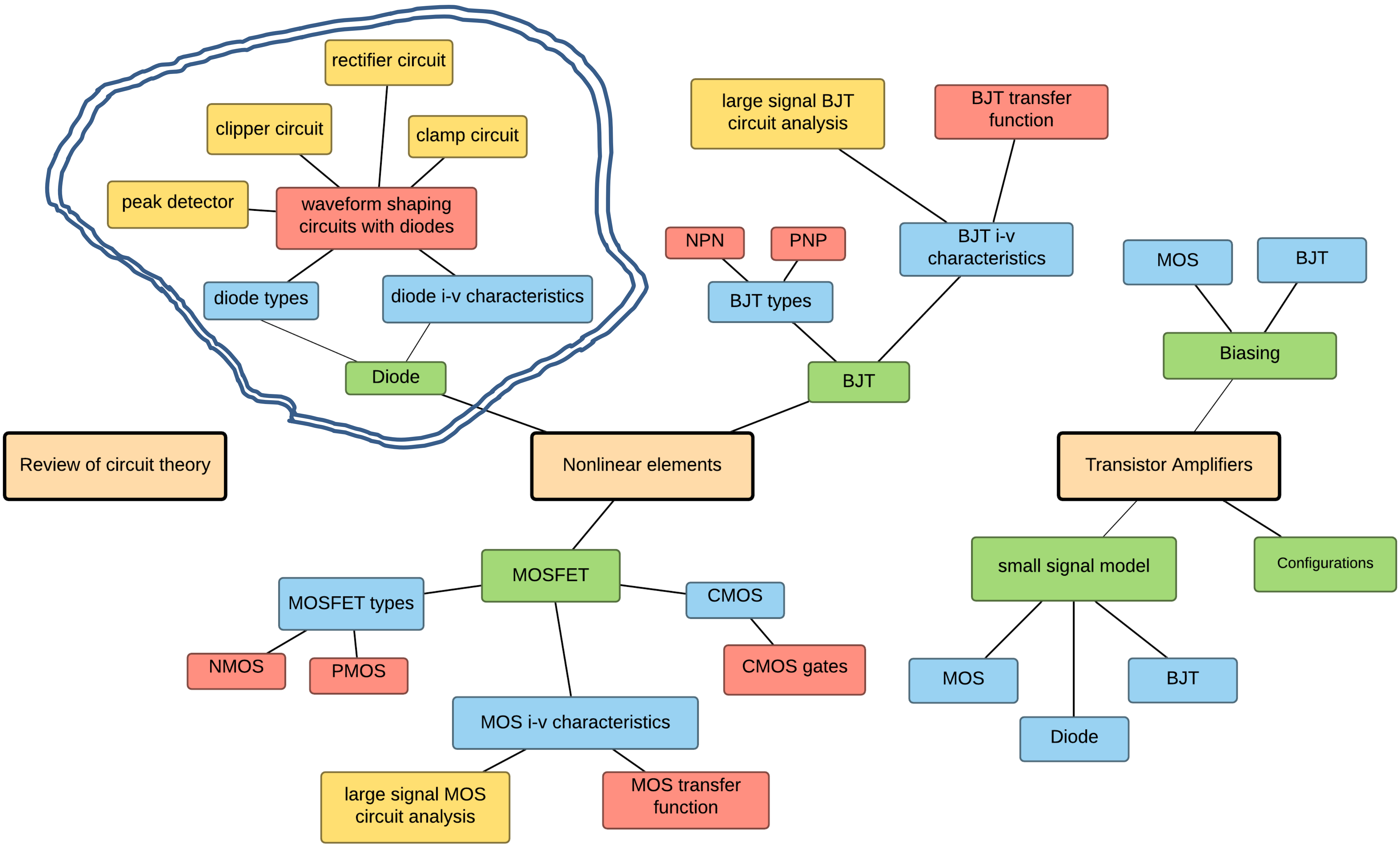
Reference notes: sections 2.1-2.8

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

Saharnaz Baghdadchi

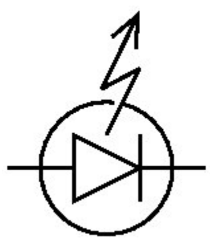
Course map

2. Diodes



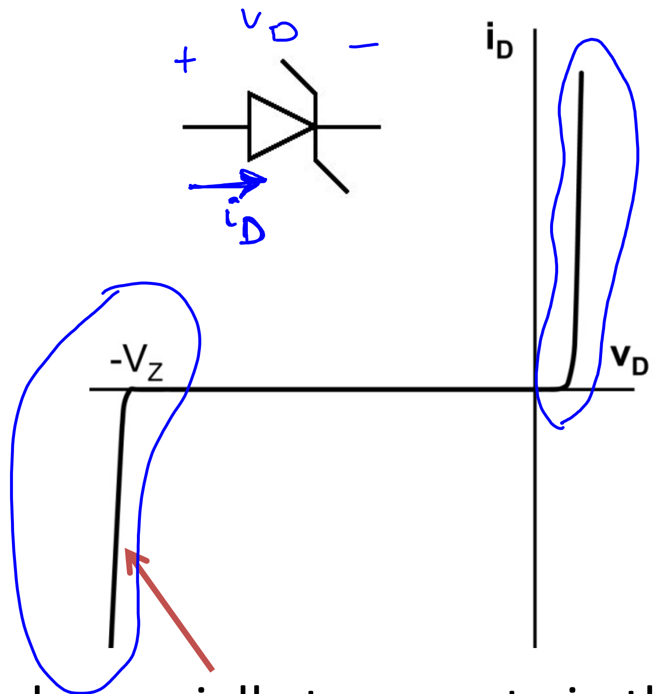
Other types of diodes

Light-emitting diode (LED)



$V_{D0} = 1.7 - 1.9$ V

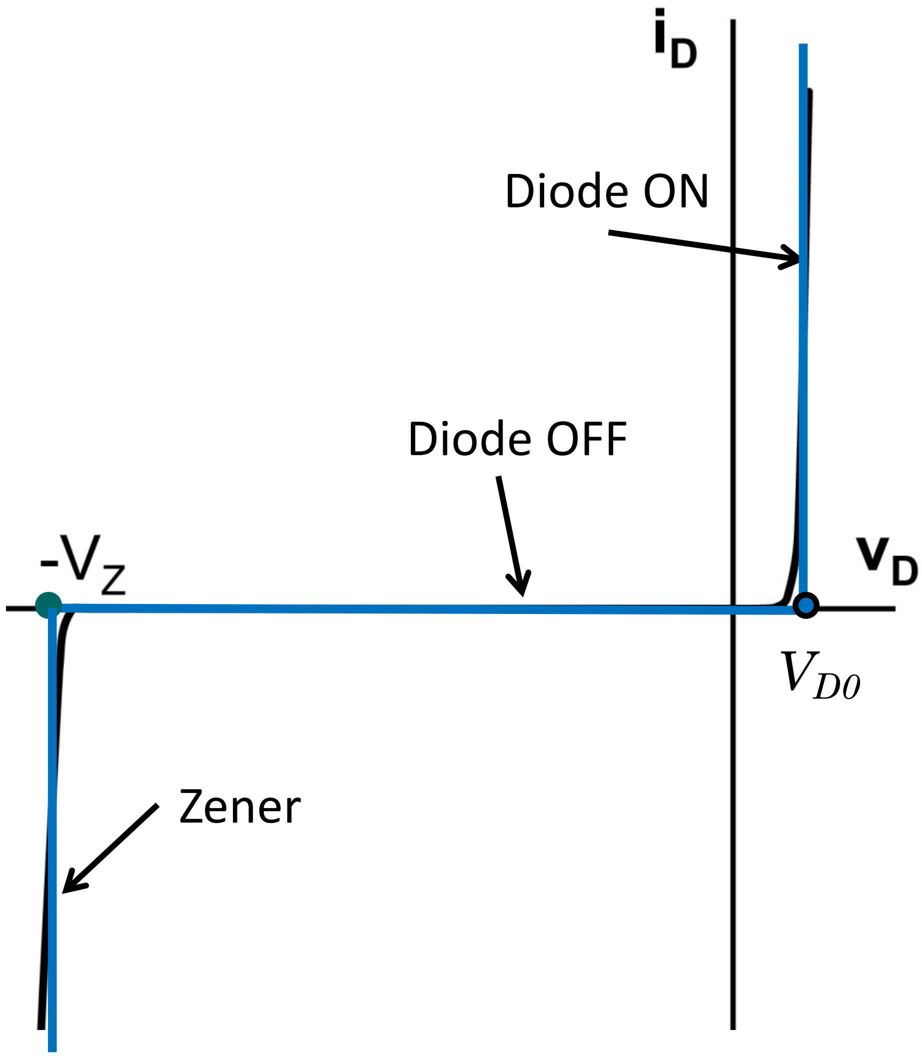
Zener Diode



Made specially to operate in the reverse breakdown region.

Useful as a “reference” voltage in many circuits.

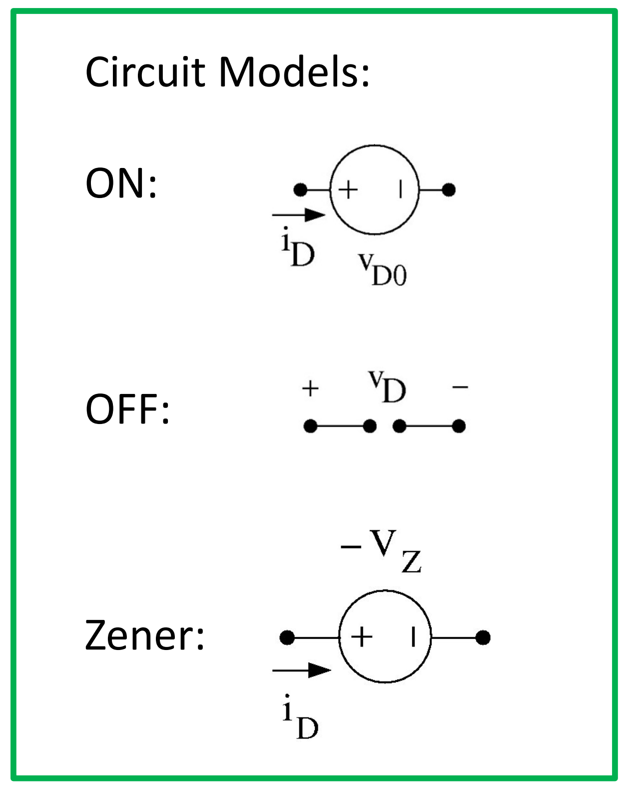
Zener Diode piecewise-linear model



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

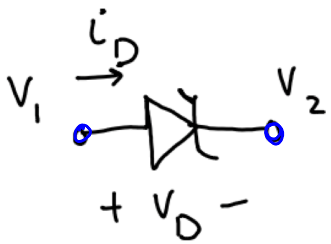
Diode OFF: $i_D = 0$ and $-V_Z < v_D < V_{D0}$

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



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. $\Rightarrow$ $i_D = 0$

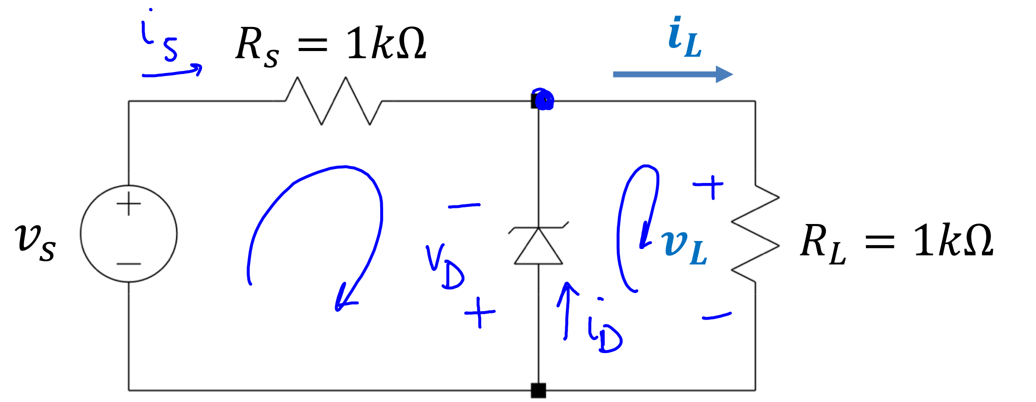
Ⓒ When $V_1 - V_2 = 0.7$, diode is forward-biased and it's ON $\Rightarrow$ $i_D \geq 0$ and $V_D = V_{D_0} = 0.7$ V.

Ⓓ 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:

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

$$\boxed{v_L = V_Z = 3\,V}$$

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

$$i_s = \frac{v_s + v_D}{R_s} = \frac{10V - 3V}{1k}$$

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

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

$$= -4mA < 0$$

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

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

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

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

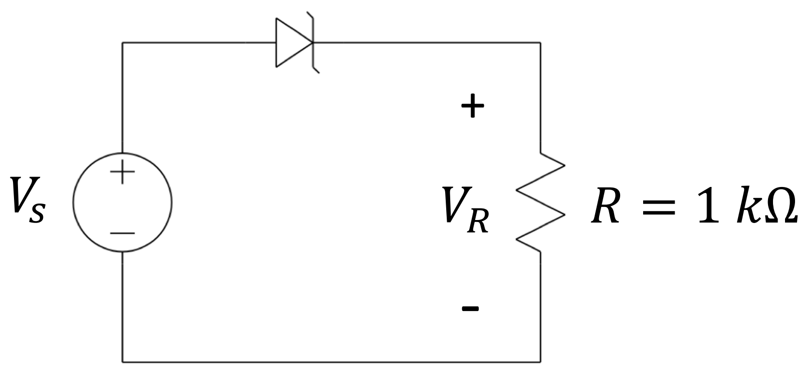
$$\boxed{\frac{V_s - V_Z}{R_s} \geq \frac{V_Z}{R_L}}$$

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

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

Lecture 5 reading quiz

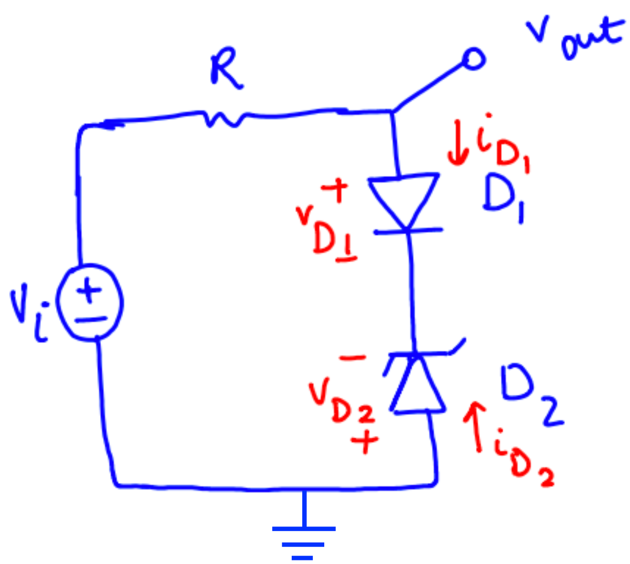
In the following circuit, find V_R for $V_s = +5\ V$ and $V_s = -5\ V$. Assume $V_Z = 3\ V$ and $V_{Do} = 0.7\ V$.



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}.

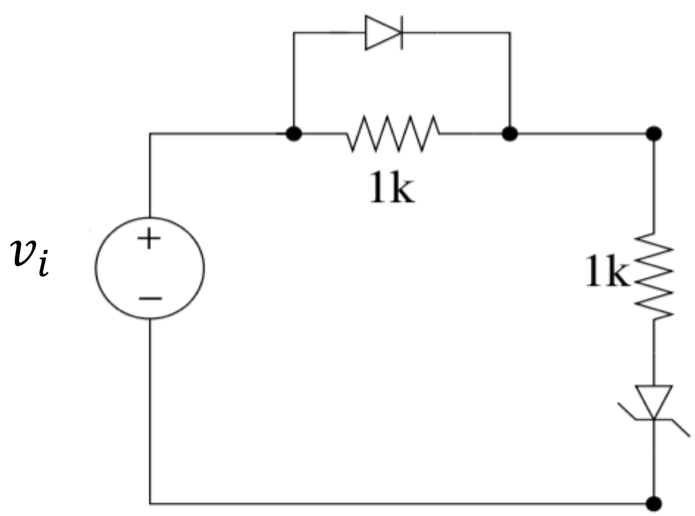
Are there any other possible states at which D_1 and D_2 can operate? Assume $V_{D0} = 0.7\ V$ and $V_Z = 5\ V$.



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

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. $v_i \geqslant 2.1$ V

B. $v_i \geqslant 1.4$ V

C. $v_i \geqslant 0.7$ V

D. Both diodes cannot be ON simultaneously.

ECE 65: Components & Circuits Lab

Lecture 6

Diode waveform shaping circuits

Rectifier circuits

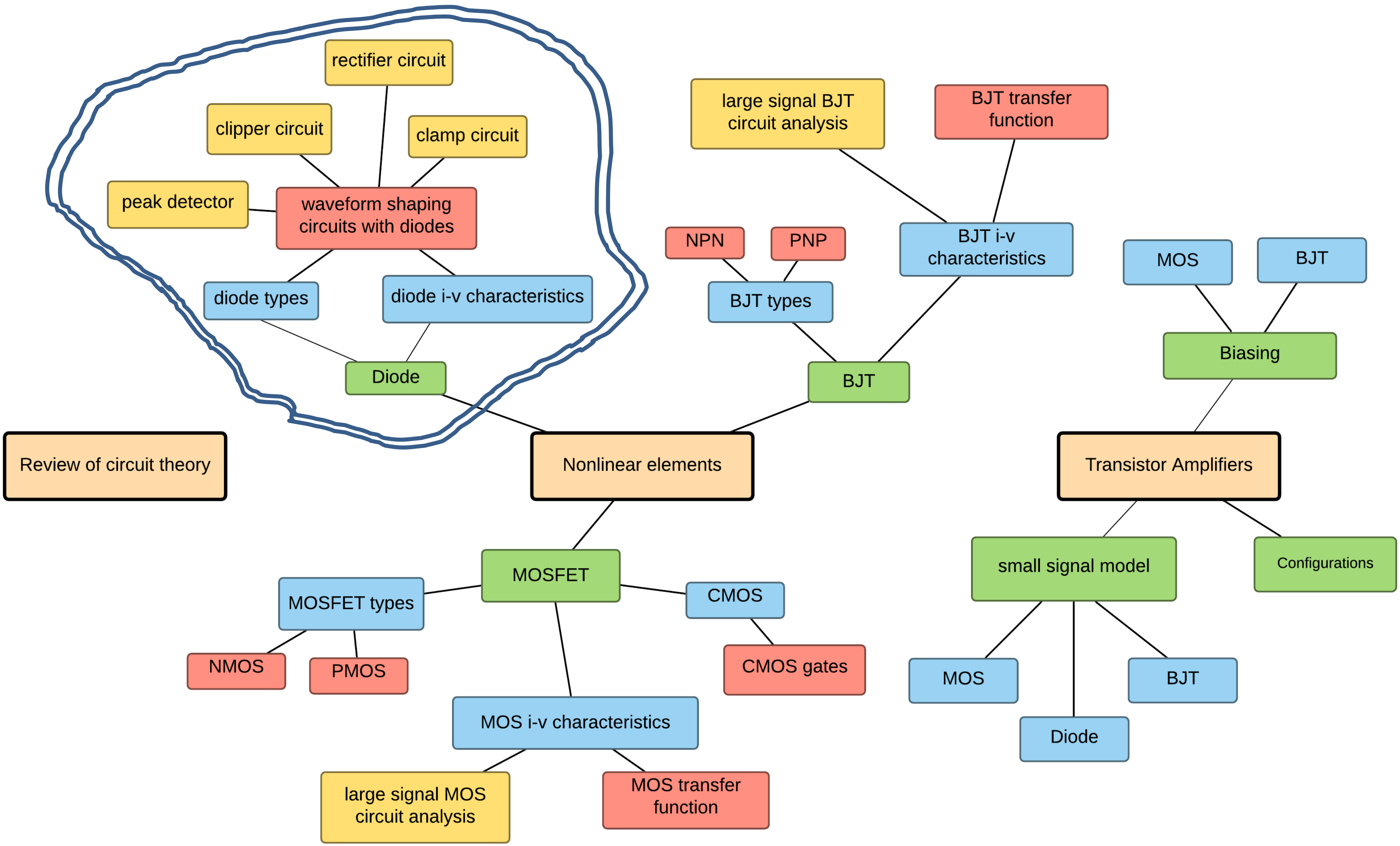
Reference notes: sections 2.9

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

Saharnaz Baghdadchi

Course map

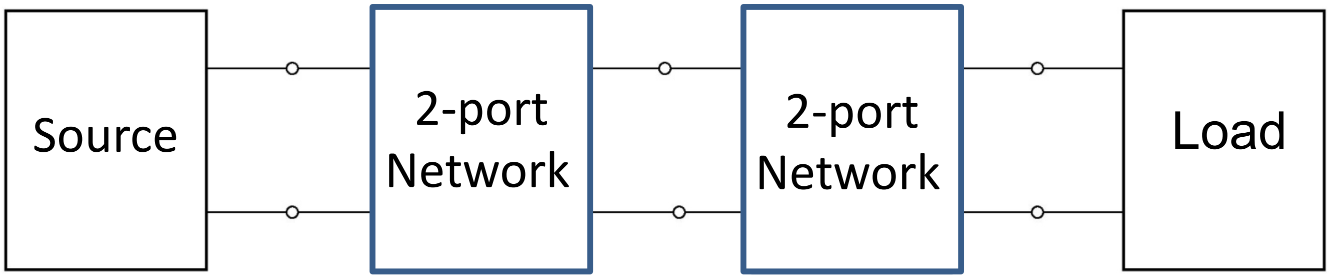
2. Diodes

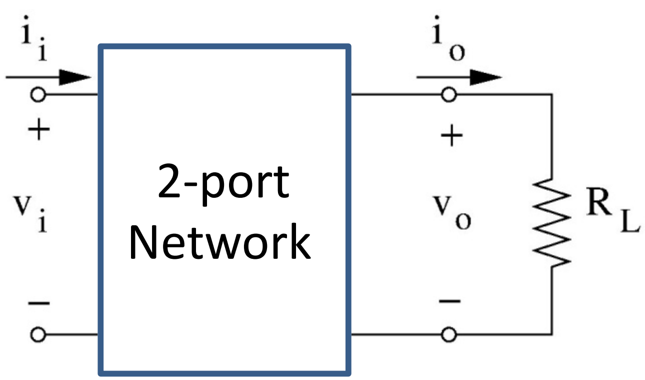


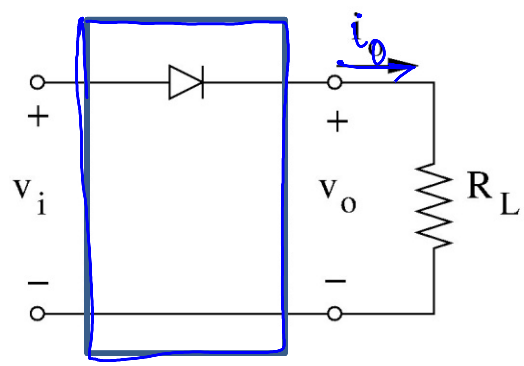
Diodes Waveform shaping Circuits

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

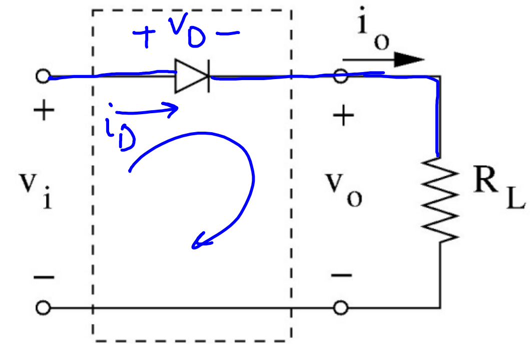
"Open-loop" Transfer function is v_o vs v_i when $R_L \to \infty$ or $i_o = 0$.

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

$V_o = R_L i_D = 0$

$V_i = V_D + V_o \Rightarrow V_i = V_D < V_{D_0} \longrightarrow V_i < V_{D_0}$

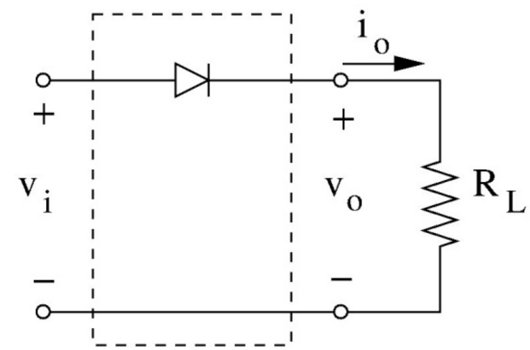
Diode ON: $v_D = V_{D0}$ & $i_D \geq 0$

$V_o = V_i - V_{D_0}$

$i_D = \dfrac{V_i - V_D}{R} = \dfrac{V_i - V_{D_0}}{R} \geq 0 \longrightarrow V_i \geq V_{D_0}$

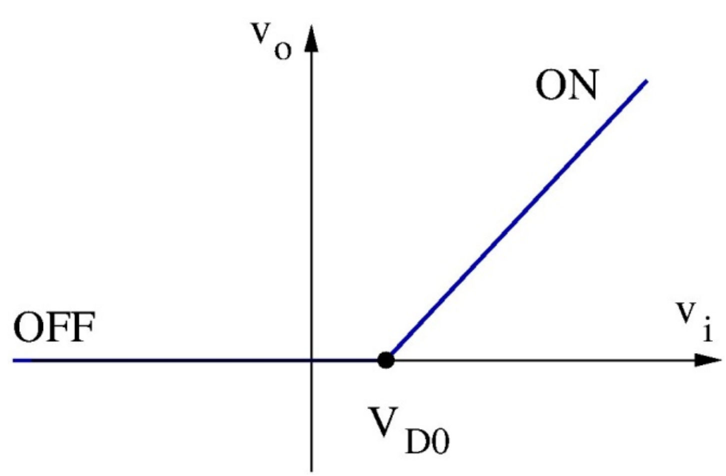
Rectifier Circuit

Transfer Function is non-linear:

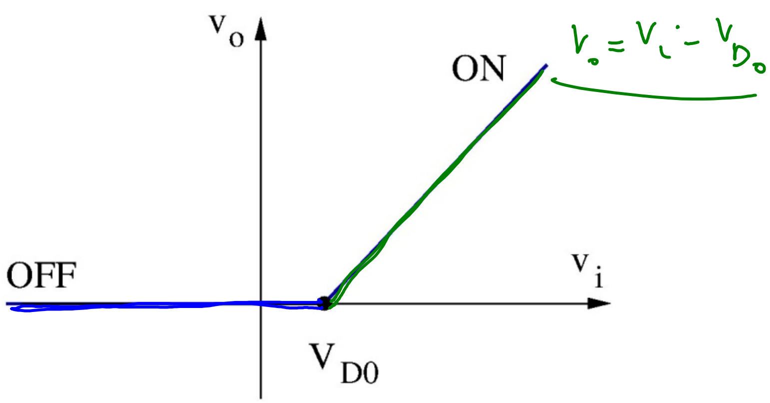


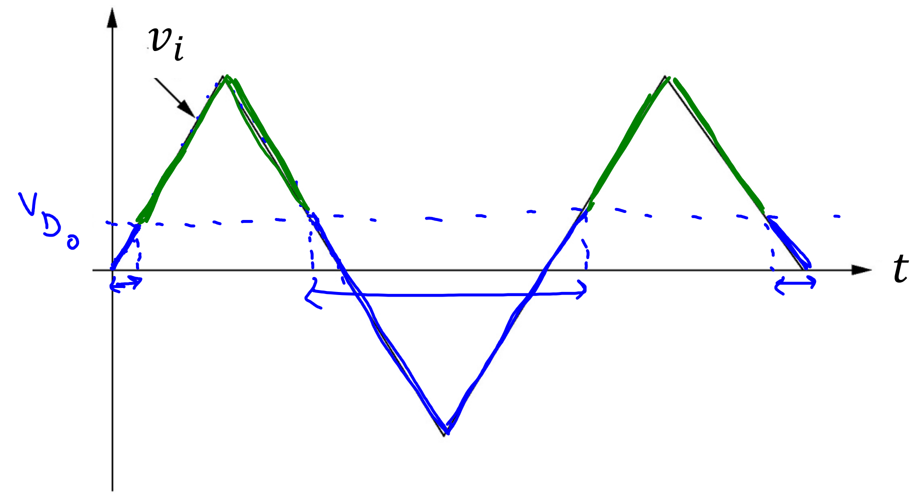
For $v_i \geq V_{D0}$, $v_o = v_i - V_{D0}$ (Diode is ON)

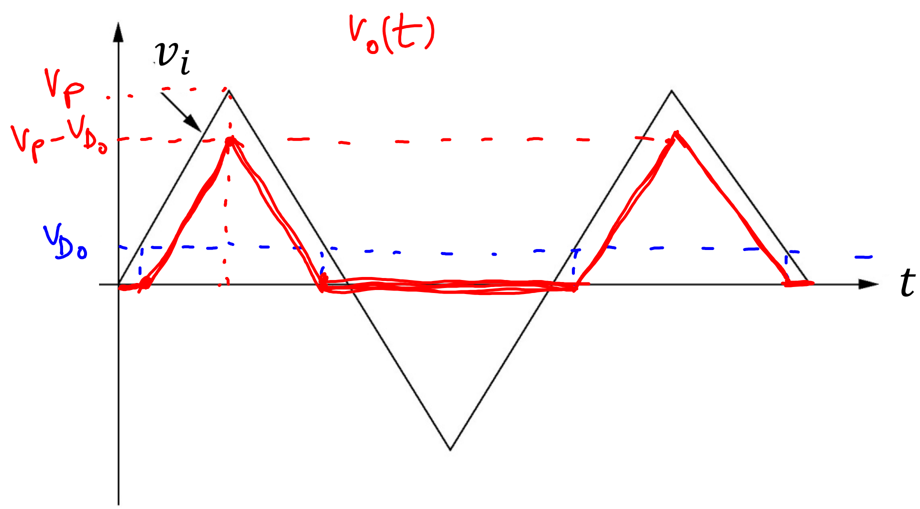
For $v_i < V_{D0}$, $v_o = 0$ (Diode is OFF)

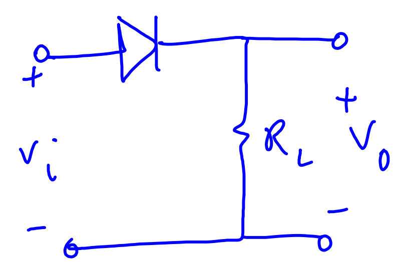


Rectifier Circuit:
example input - output waveforms



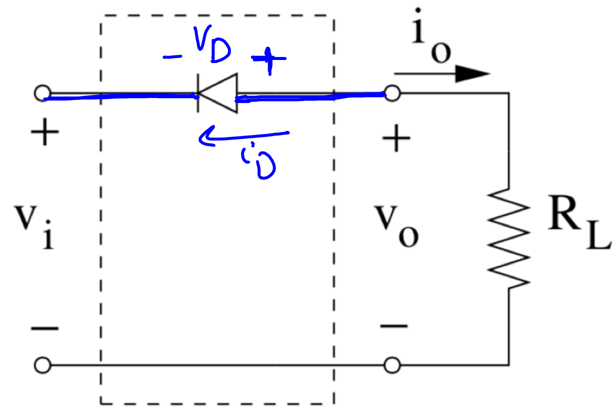






Rectifier Circuit for the negative part of v_i

Transfer Function is non-linear:



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

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

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

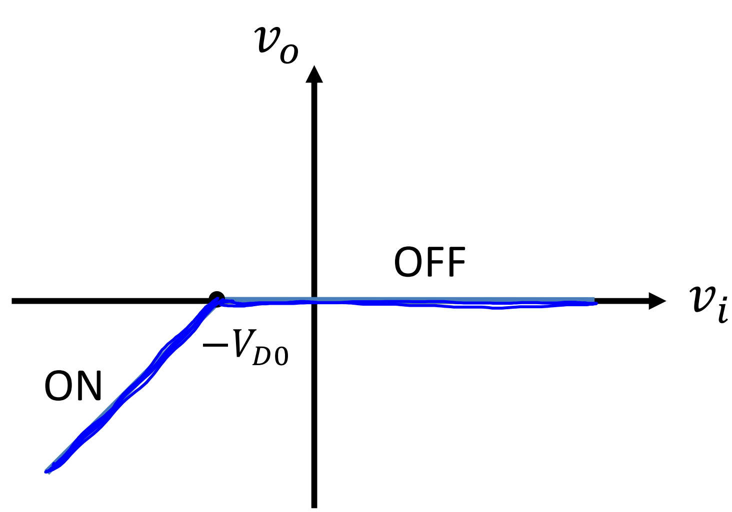
KVL :

$v_i = -V_D - R_L i_D$

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

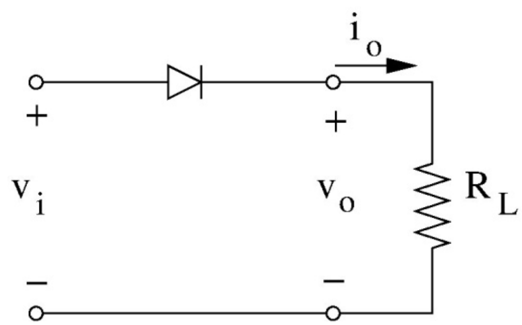
$i_D = \dfrac{-V_{D_0} - V_i}{R_L} \geqslant 0$

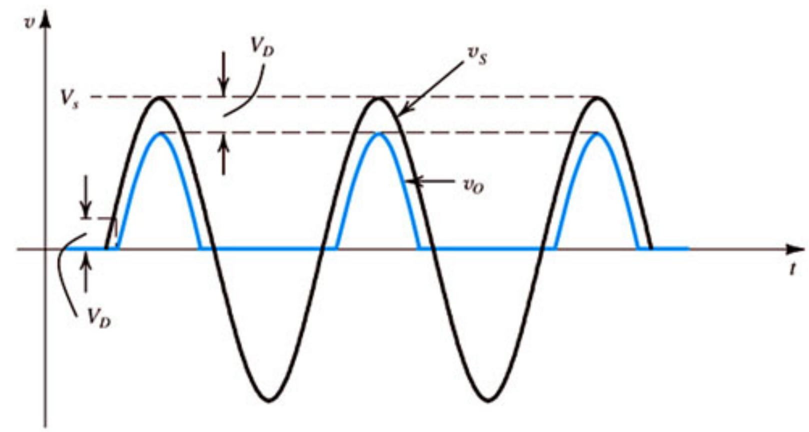
$\rightarrow V_i \leqslant -V_{D_0}$



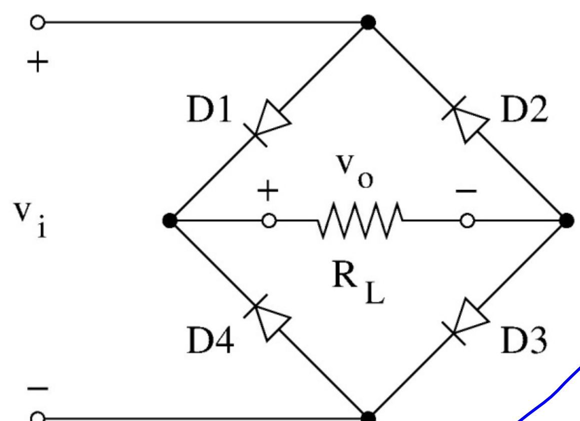
Application of Rectifier Circuit:
AC to DC convertor for power supply

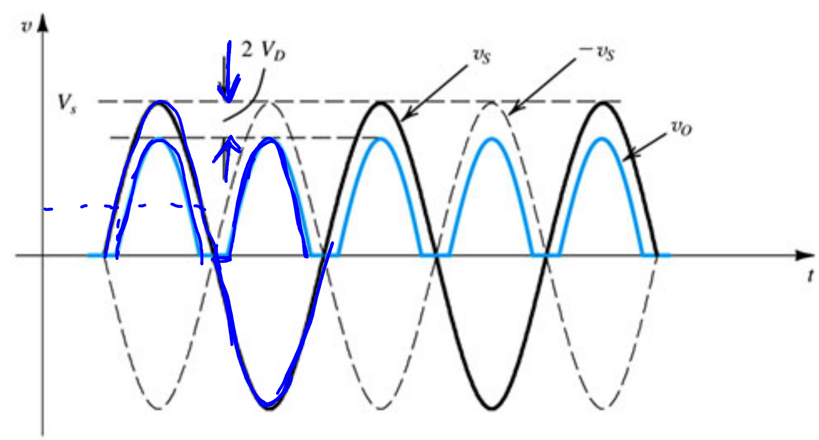
Half-wave rectifier



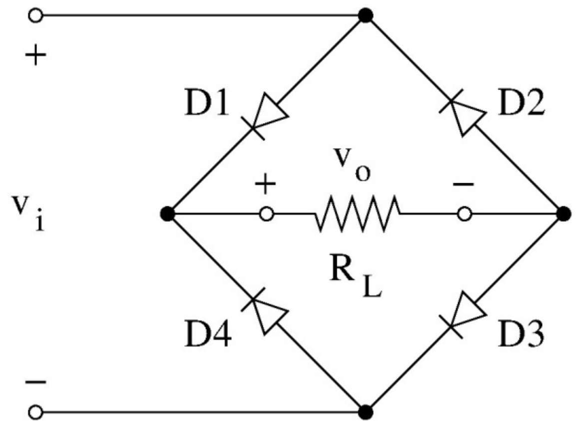


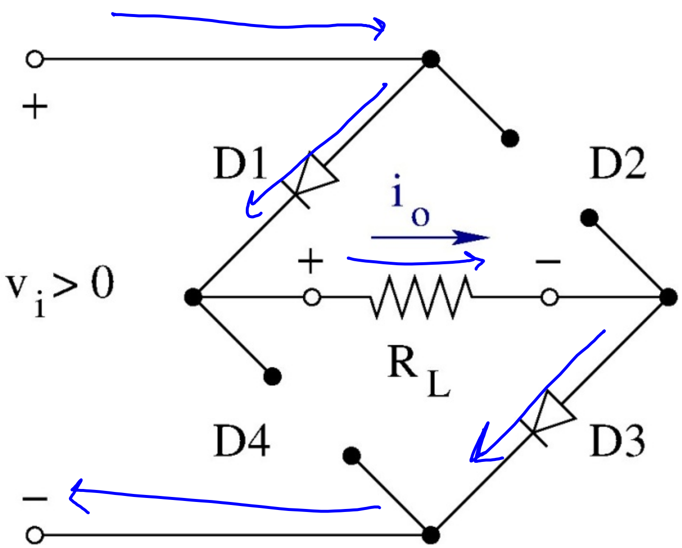
Full-wave rectifier

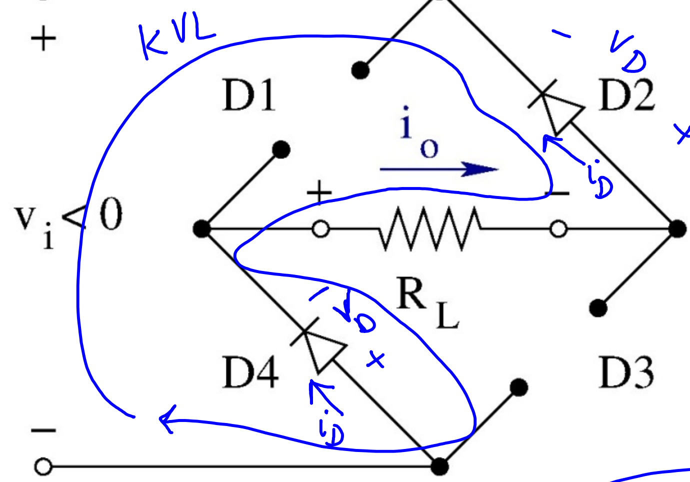




Each pair of diodes conduct only for half of the cycle





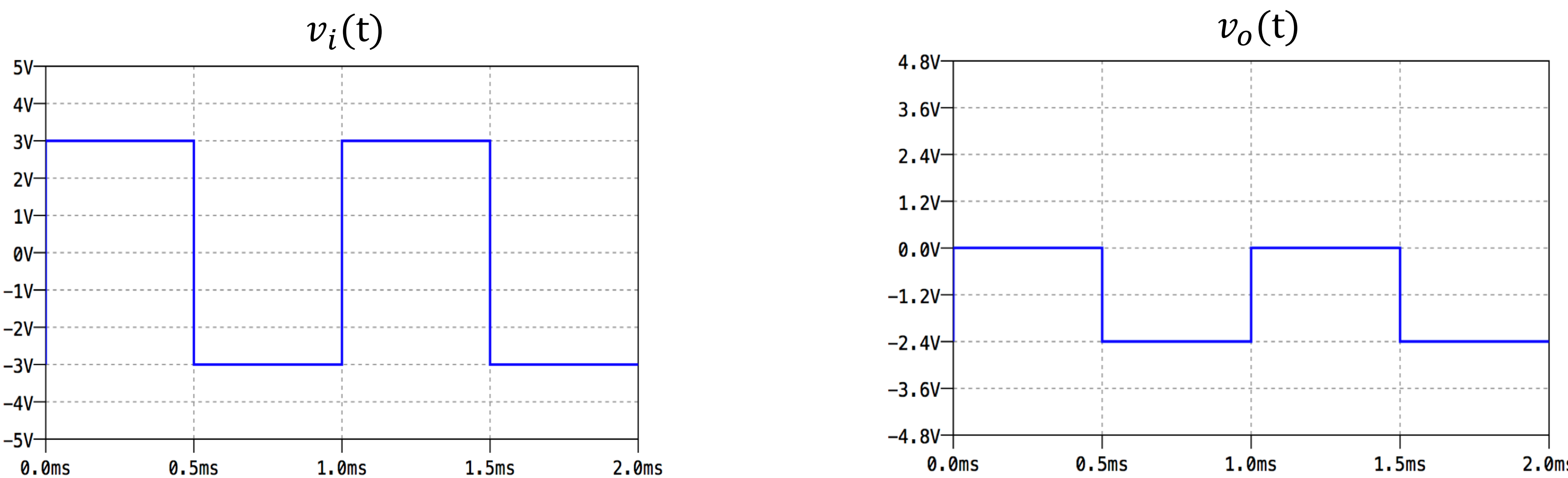


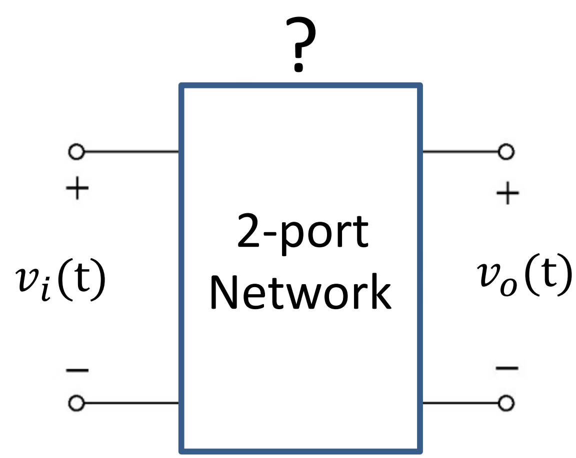
$-v_i - V_{D_0} - v_o - V_{D_0} = 0 \rightarrow v_o = -v_i - 2V_{D_0}$

$v_i \leq -2V_{D_0}$

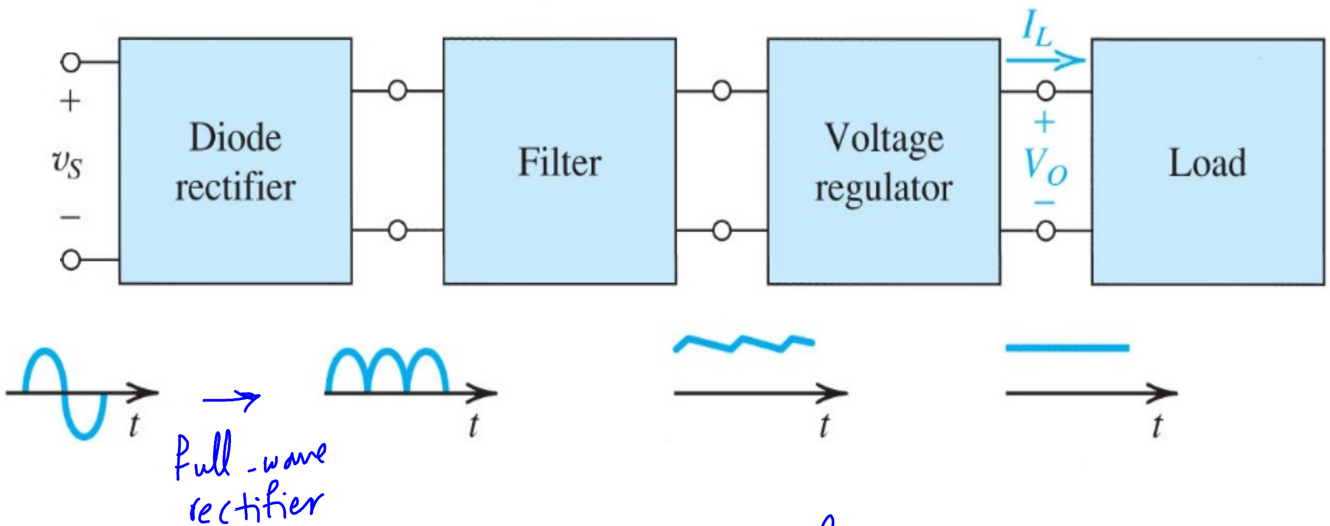
Lecture 6 reading quiz

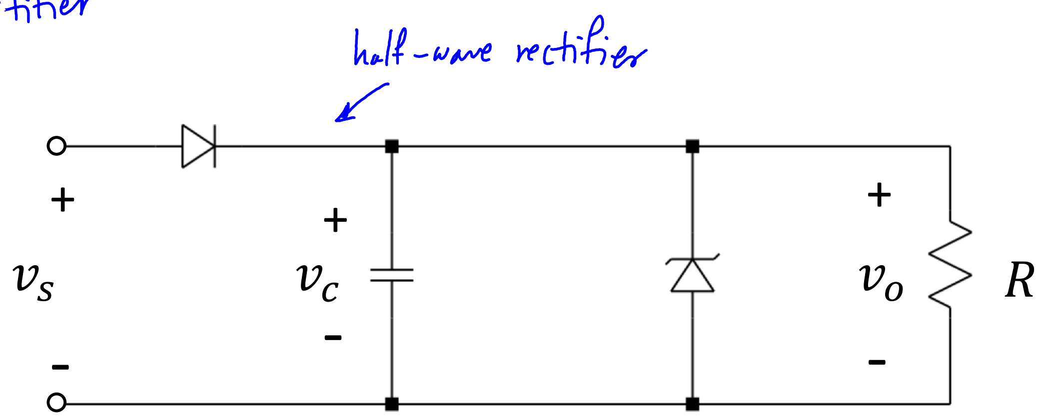
Which one of the circuits in the provided options could produce the shown output waveform for the given input signal?





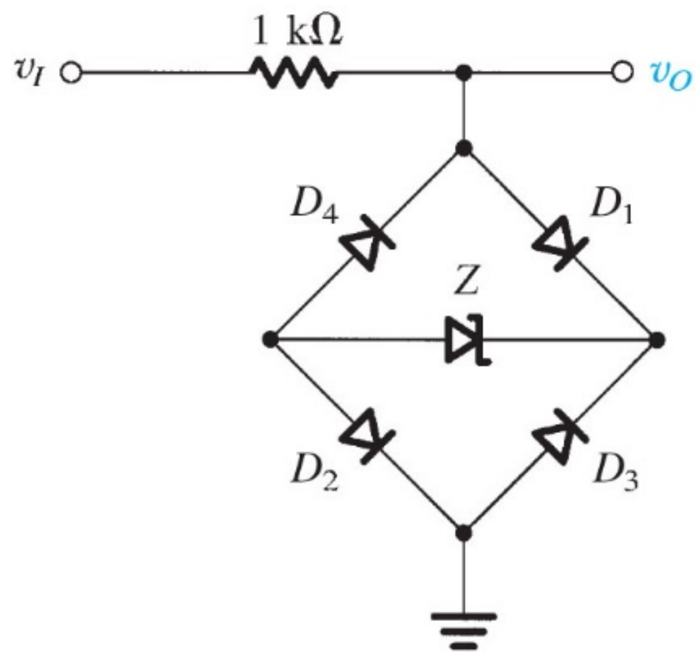
Block Diagram of a DC Power Supply





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 $V_{D0}= 0.7\ V$, $V_Z= 4\ V$.

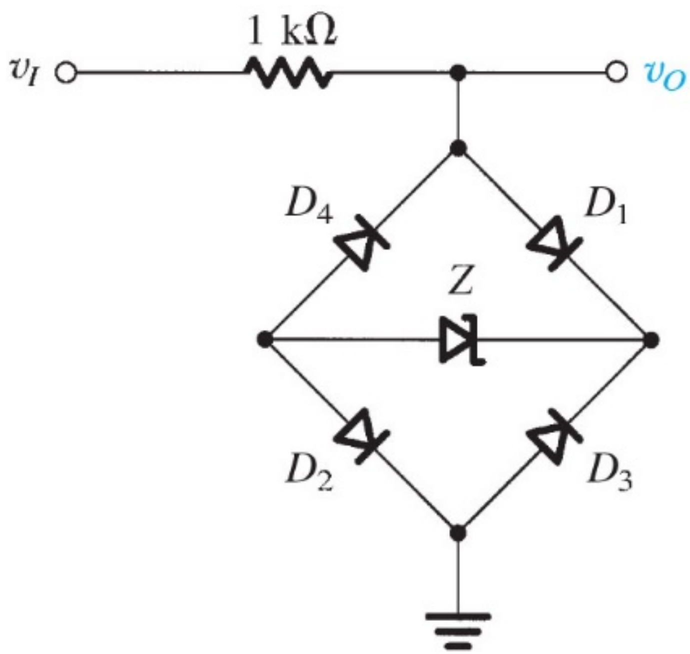


Extra activity:
Draw the output voltage waveform if $v_i = 2\sin(\omega t)$.

Hints:

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 $V_{D0}= 0.7\ V$, $V_Z= 4\ V$.



- Label all the diode currents and voltages.
- Think about how current can flow in the circuit. Trace the direction of the current flow, starting from the positive terminal of the vi and ending at the negative terminal of vi and the other way around.
- Which diodes will conduct when vi is positive enough, and which diodes will conduct when vi is negative enough?
- Use your answer to the above question to create the list of diode cases for this problem.
- For each case, using KVL (and KCL, if needed) and the diode current or voltage inequality, find the range of vi.
- For each case, using KVL (and KCL, if needed), find vo as a function of vi. Note that vo might be constant and independent of vi for some ranges of vi. It will translate to a line with a slope of zero in the graph of vo vs. vi (the transfer characteristic graph)

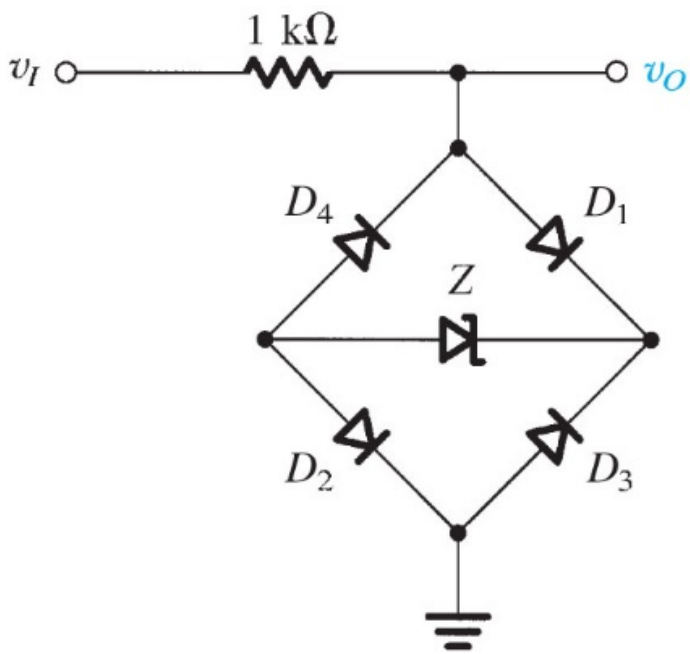
Extra activity:

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

Hints:

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 $V_{D0} = 0.7\ V$, $V_Z = 4\ V$.



Extra activity:

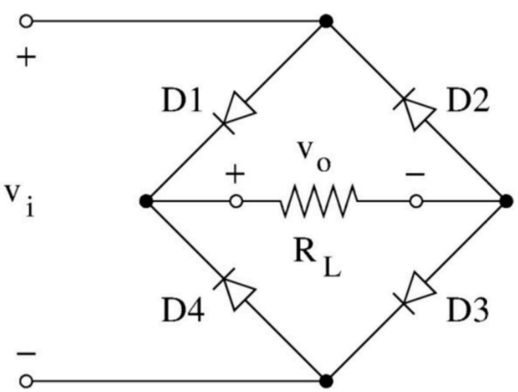
- What are the maximum and minimum amplitudes of the given vi?
- Looking at the transfer characteristic graph, what are the corresponding amplitudes for vo?

Extra activity:

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

Discussion question 2.

Plot the transfer function of the following full-wave rectifier. Find v_o for different ranges of v_i and plot a graph that shows the relationship between v_i and v_o.



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

ECE 65: Components & Circuits Lab

Lecture 7

Diode waveform shaping circuits

Clipper circuits

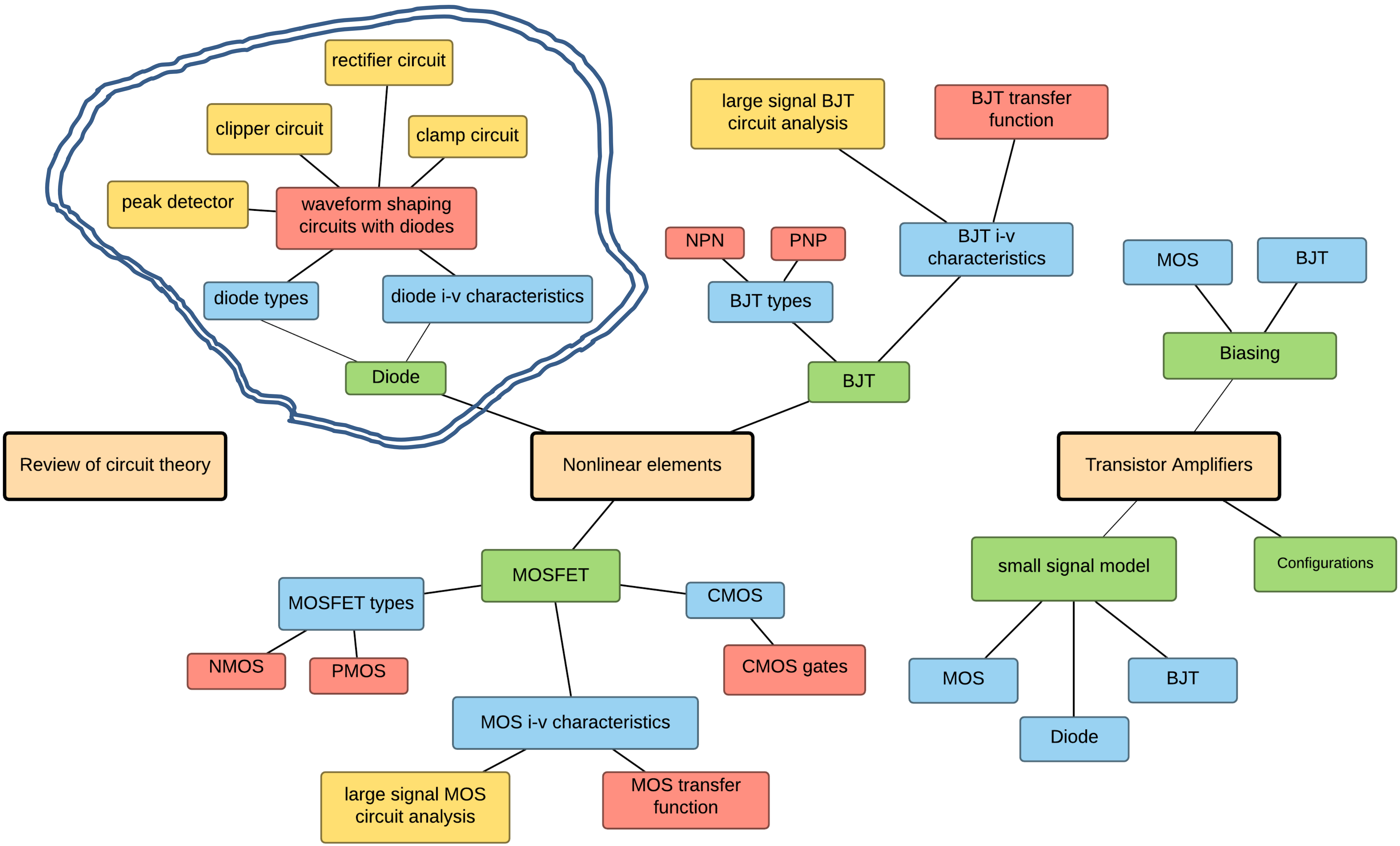
Reference notes: sections 2.9

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

Saharnaz Baghdadchi

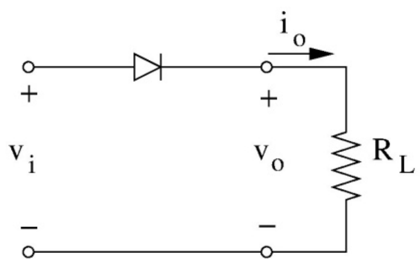
Course map

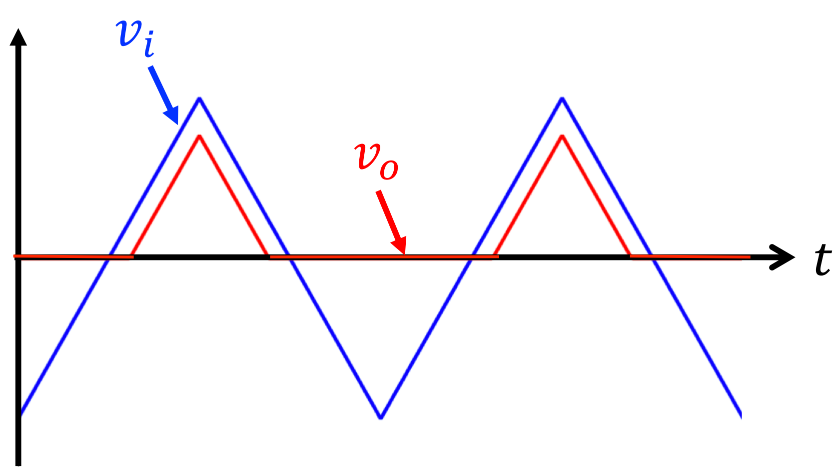
2. Diodes



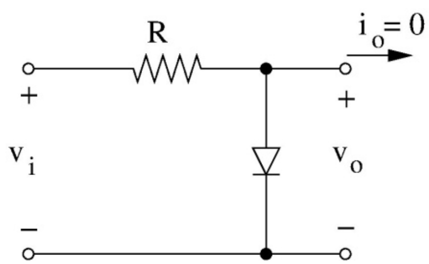
Rectifier & clipper circuits

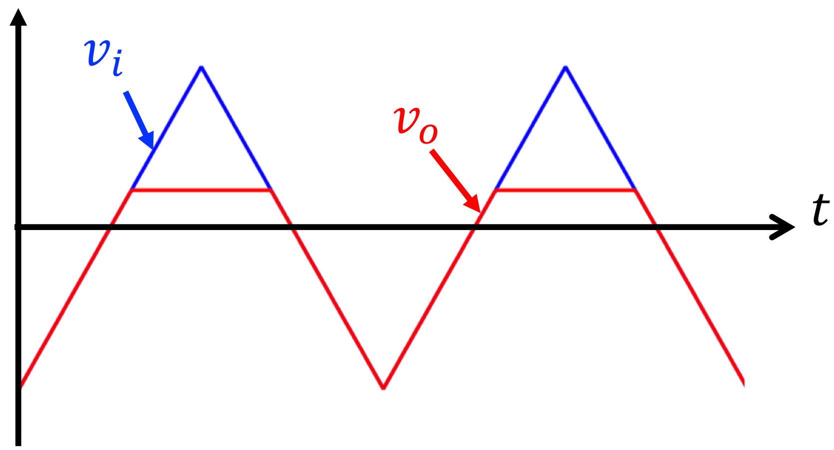
Half-wave Rectifier



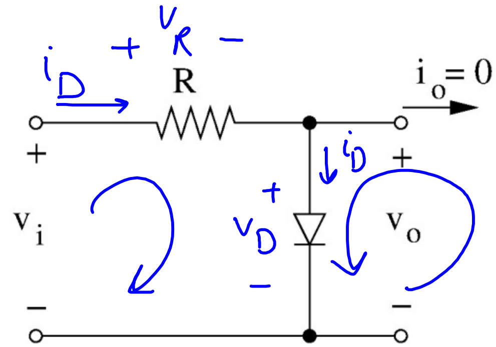


Clipper





Clipper or Limiter Circuit



$-v_o + v_D = 0$

$v_o = v_D$

KVL: $v_i = v_R + v_D$ ✓

KVL: $v_o = v_D$ ✓

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

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

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

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

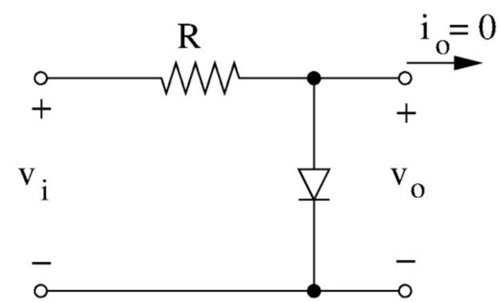
Diode ON: $v_D = V_{D0}$ & $\boxed{i_D \geq 0}$

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

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

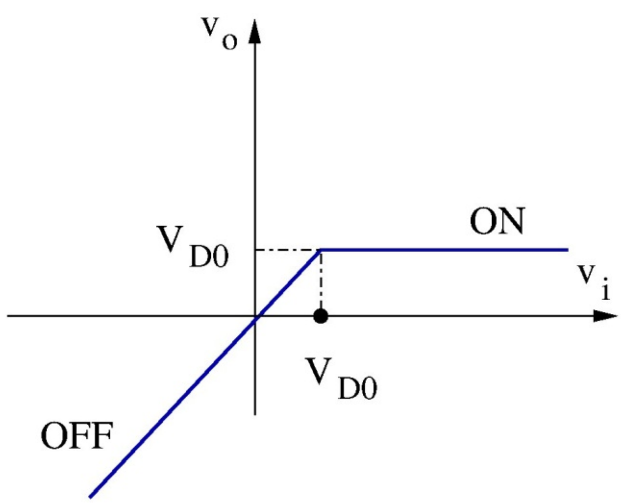
Clipper Circuit
open loop transfer function

Transfer Function is non-linear:

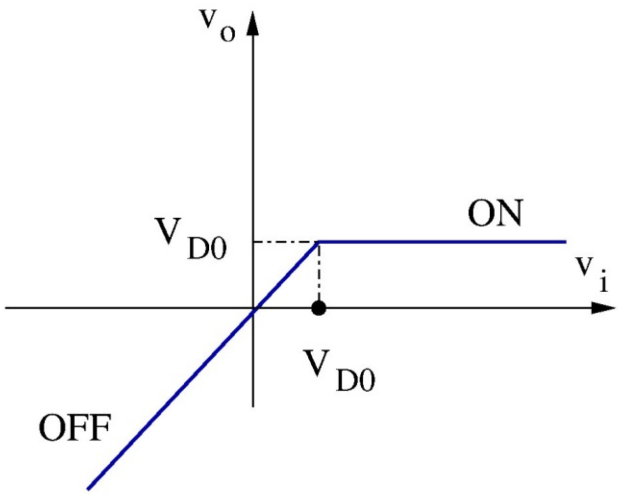


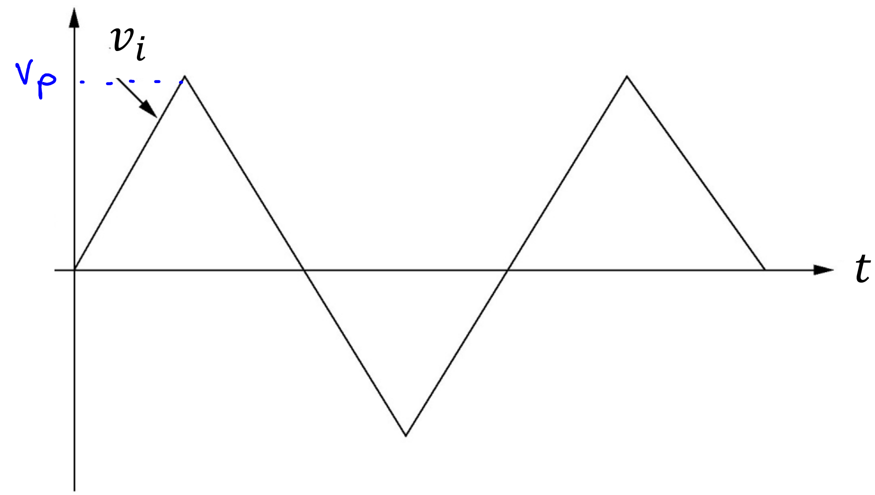
For $v_i \geq V_{D0}$, $v_o = V_{D0}$ (Diode is ON)

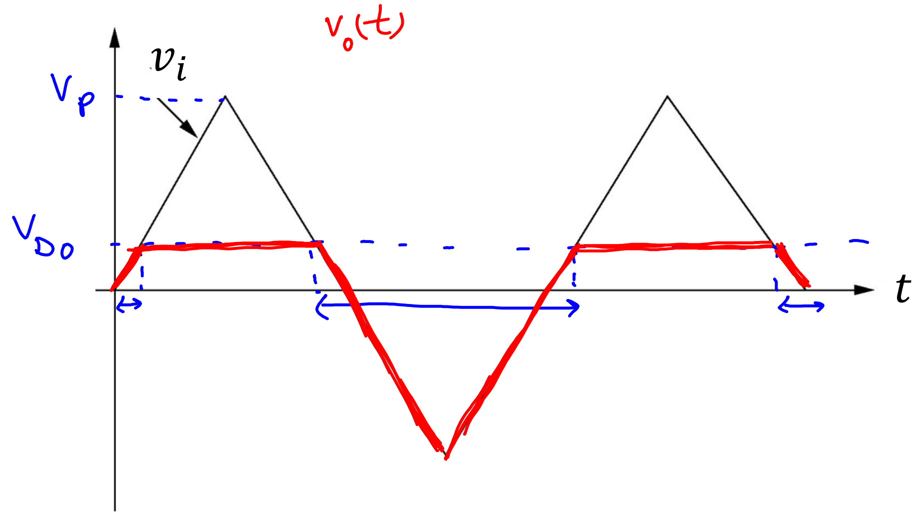
For $v_i < V_{D0}$, $v_o = v_i$ (Diode is OFF)



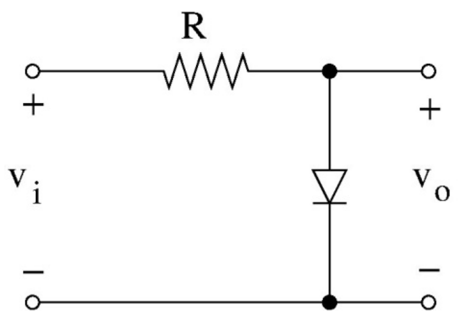
Clipper Circuit: example input-output waveforms

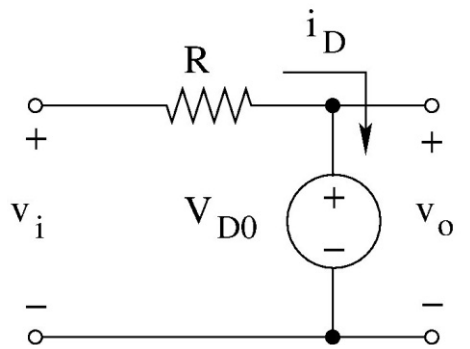


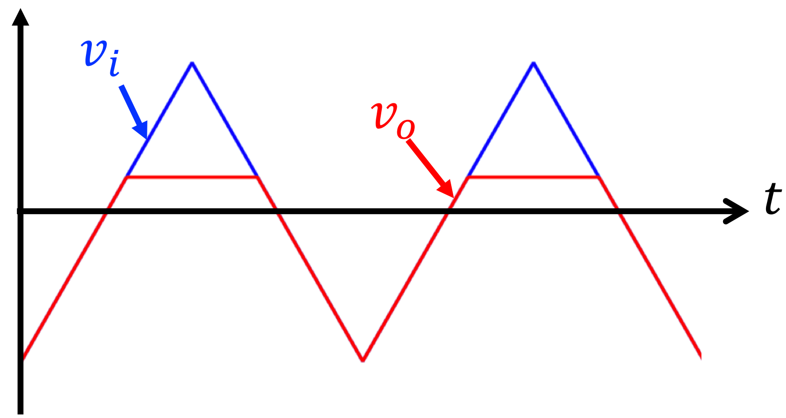


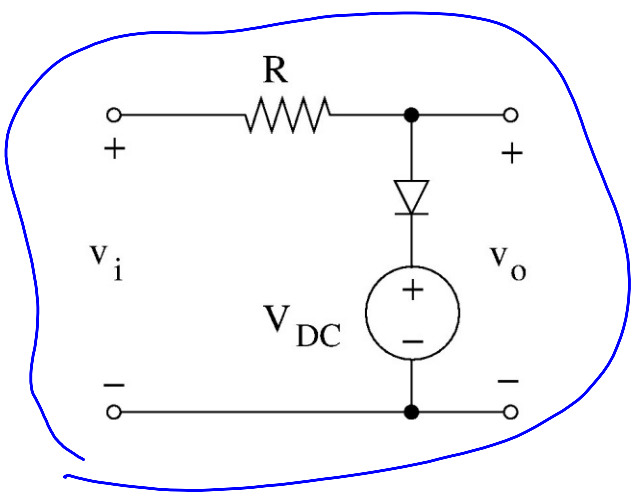


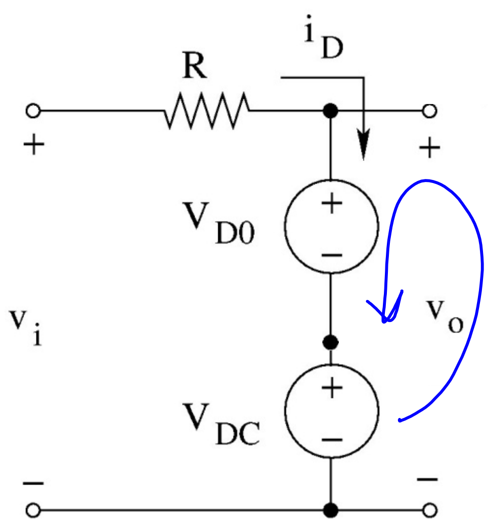
Adjusting the limiting voltage in the clipper circuit



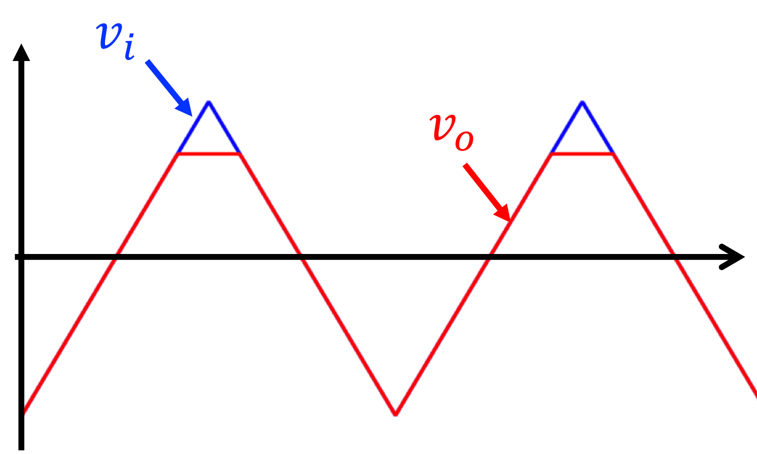




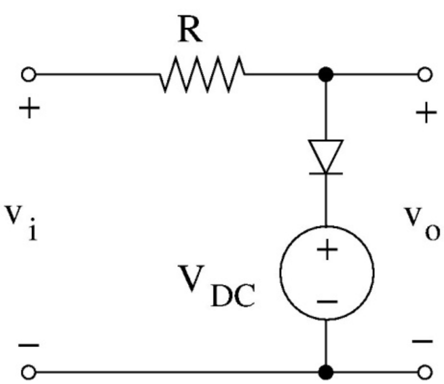




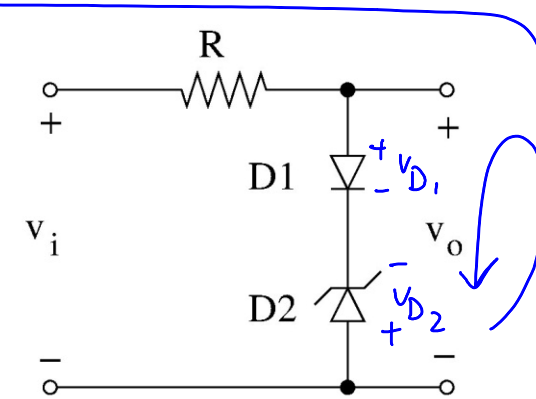
$V_o = V_{D0} + V_{DC}$



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



v_o **limited to ≤** $V_{D0} + V_Z$



D₁ is ON

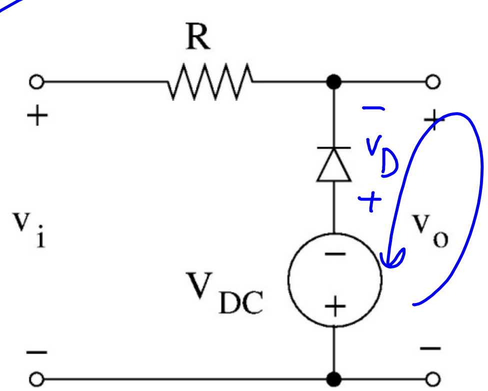
D₂ is Zener

$v_{D_1} = V_{D_0}$

$v_{D_2} = -V_Z$

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

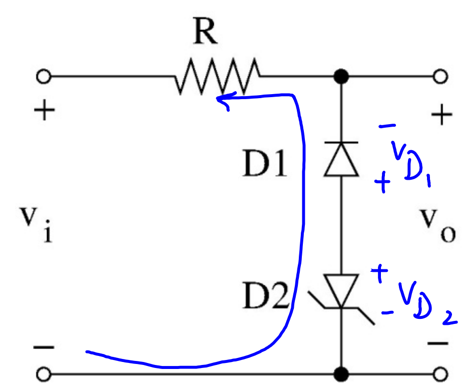
$V_o = V_{D_0} + V_Z$



$V_o = -v_D - V_{DC}$

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

v_o **limited ≥ –** $V_{D0} - V_Z$



$v_{D_1} = V_{D_0}$

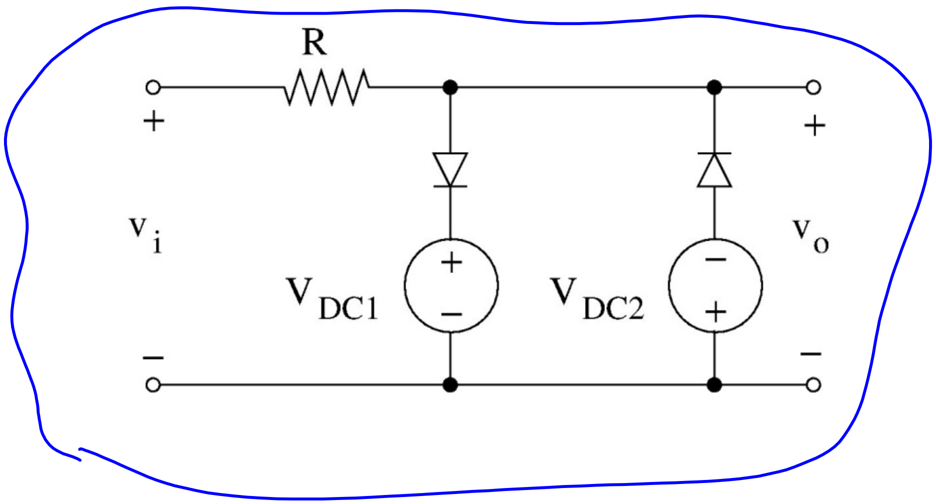
$v_{D_2} = -V_Z$

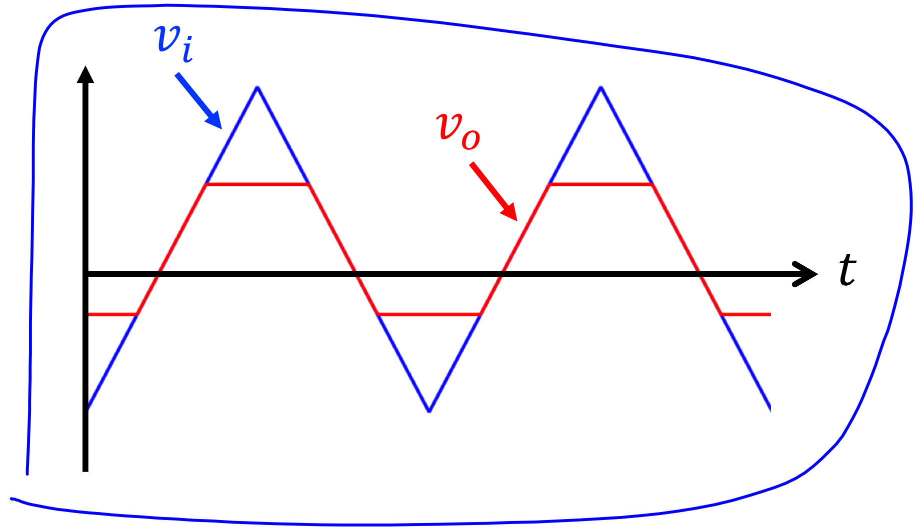
$v_o = -V_{D_0} - V_Z$

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

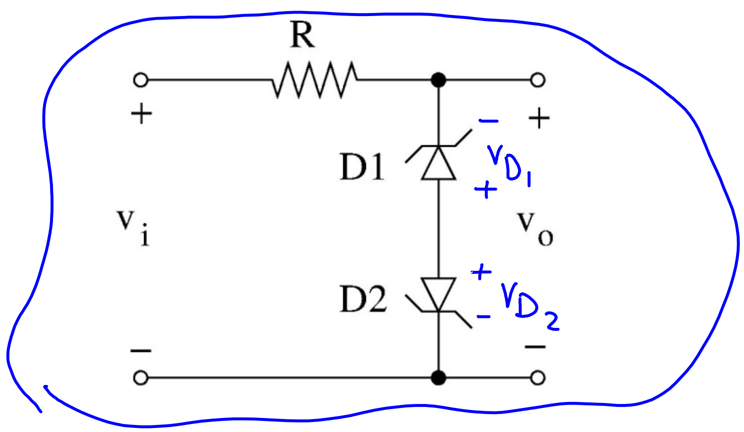
Clipping both the top & bottom portions of the signal simultaneously

v_o **limited to ≤** $V_{D0} + V_{DC1}$ **and ≥** $- V_{D0} - V_{DC2}$



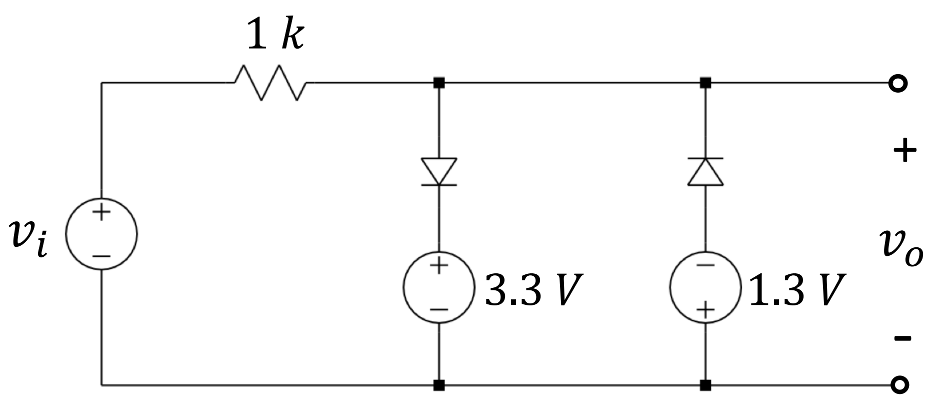


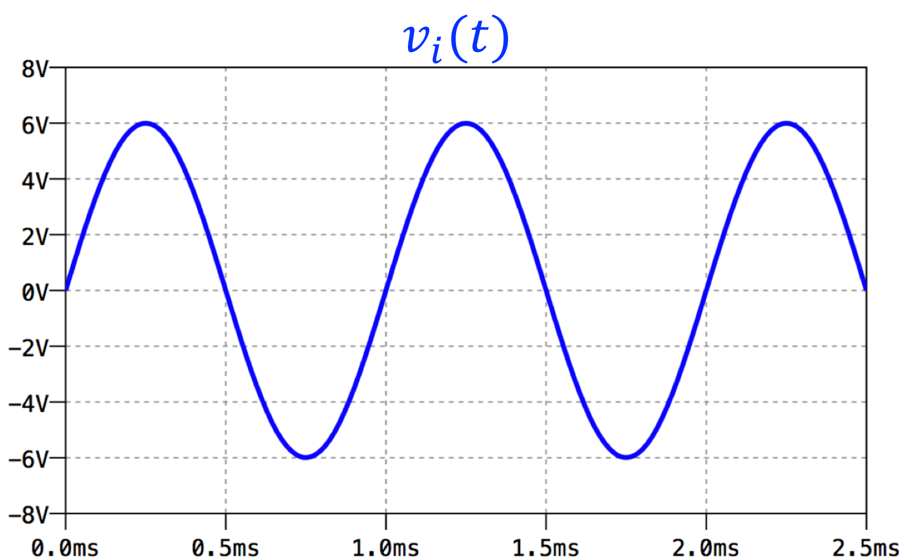
v_o **limited to ≤** $V_{D0} + V_{Z1}$ **and ≥** $- V_{D0} - V_{Z2}$



Lecture 7 reading quiz

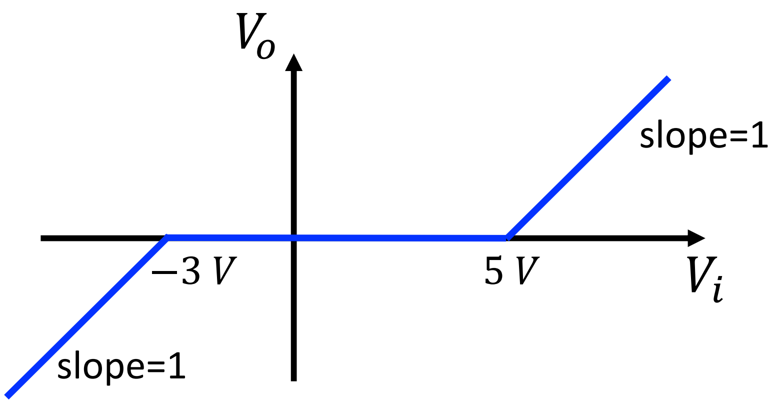
Calculate and draw the output of the following two-port network for the given input signal.



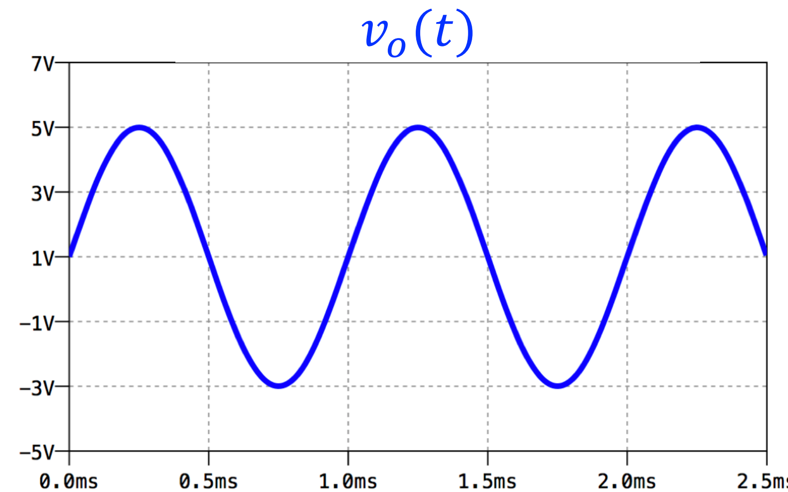


Clicker question 1

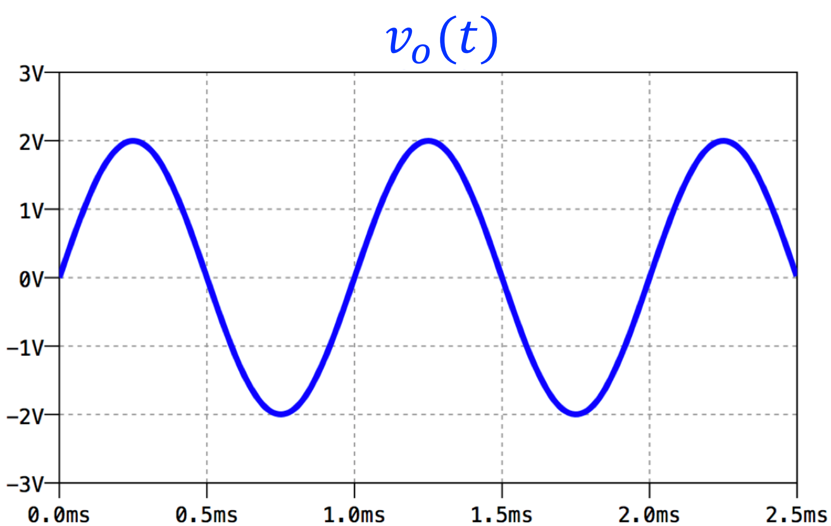
Which one of the waveforms could be the output of a two-port network with the below transfer function for the input $v_i(t) = 2\sin(\omega t)$?



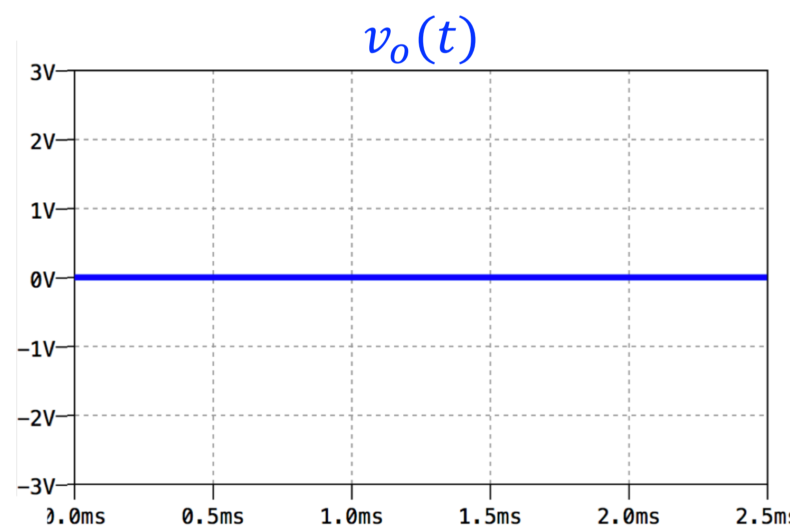
A.



B.



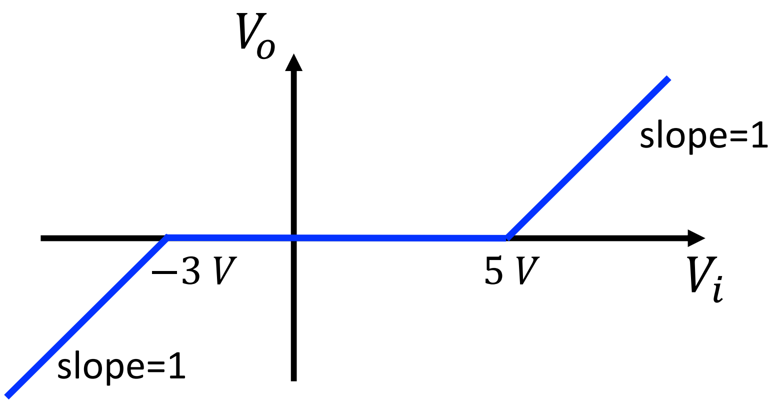
C.



Hints:

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

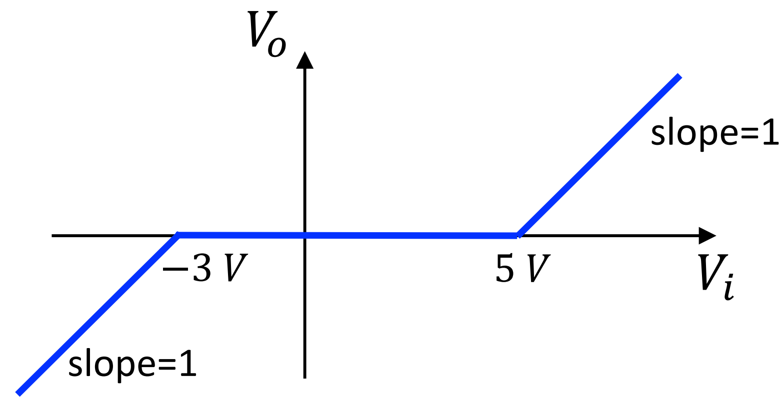


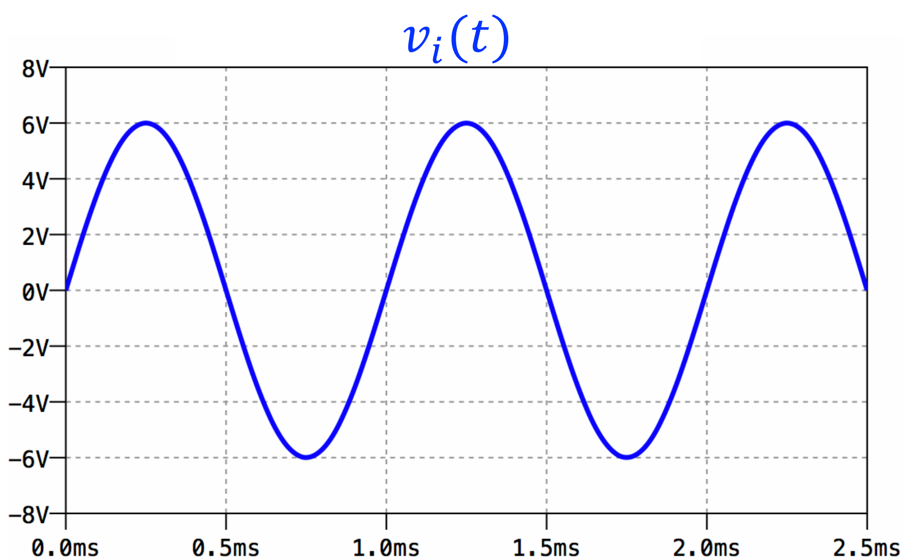
- Looking at the transfer characteristic graph, for what range of Vi values, will the output be equal to zero?

- What is the range of Vi values for the given input signal?

Discussion question 1.

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





Hints:

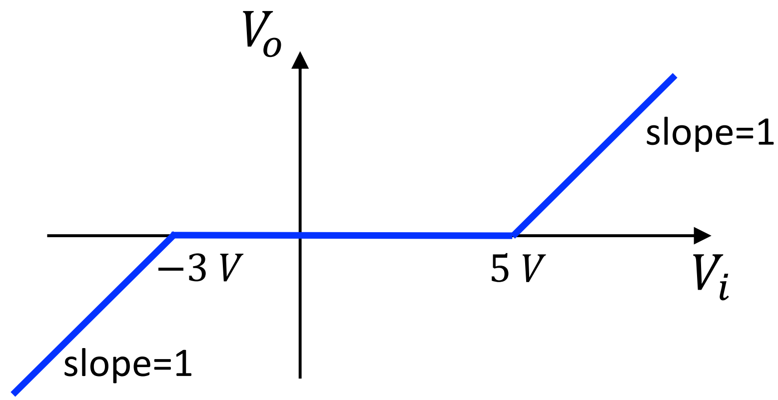
Discussion question 1.

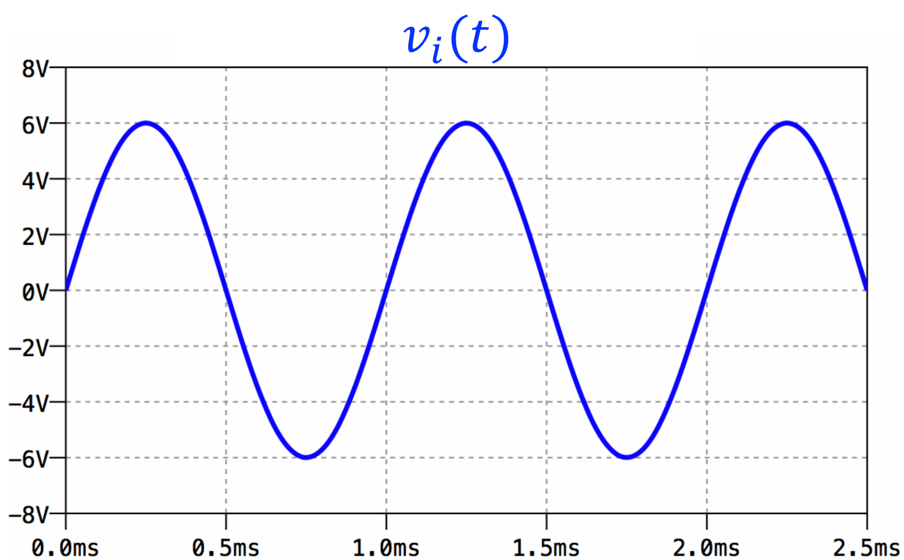
Draw the output of a two-port network with the shown transfer function to the below input signal.

- Write the equation of a line that relates Vo to Vi when Vi is greater than 5V?

- Write the equation of a line that relates Vo to Vi when Vi is less than -3V?

- On the graph of vi(t), find and label when vi is less than -3, greater than 5, and in between. Follow the Vi vs. Vo equations that you found and draw vo(t).

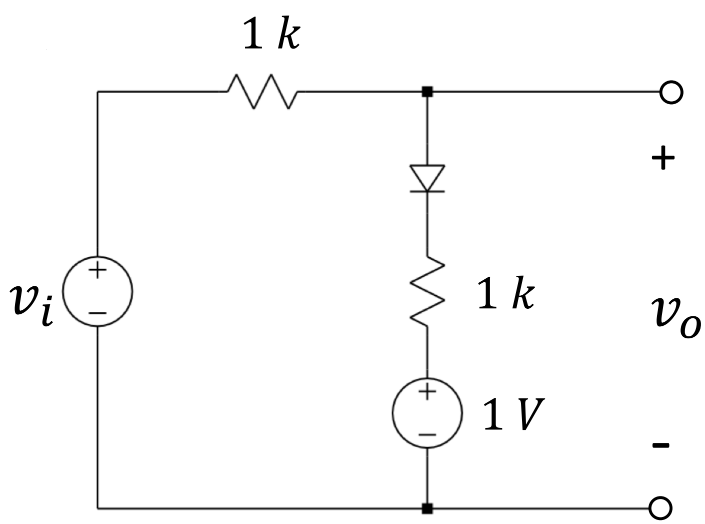




Discussion question 2

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

$(V_{D0} = 0.7V)$

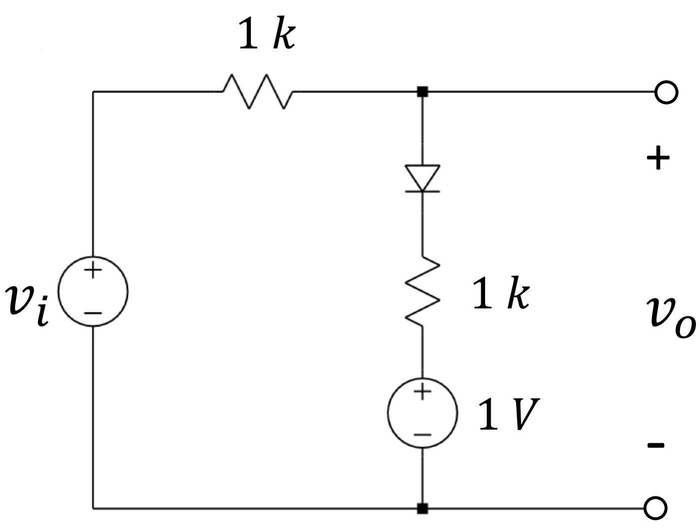


Hints:

Discussion question 2

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

$(V_{D0} = 0.7V)$



- Label the diode voltage and current.

- List the cases of operation of the diode. You have two cases in this circuit.

- You need to find the range of vi values for each case and the relationship between vi and vo for each case.

- Use KVL to complete the above task.

- Using the ranges of vi and the relationship between Vi and Vo for each range, draw the transfer function or transfer characteristic graph, which is a graph showing the relationship between Vo and Vi.

ECE 65: Components & Circuits Lab

Lecture 8

Diode waveform shaping circuits

Peak detector circuits

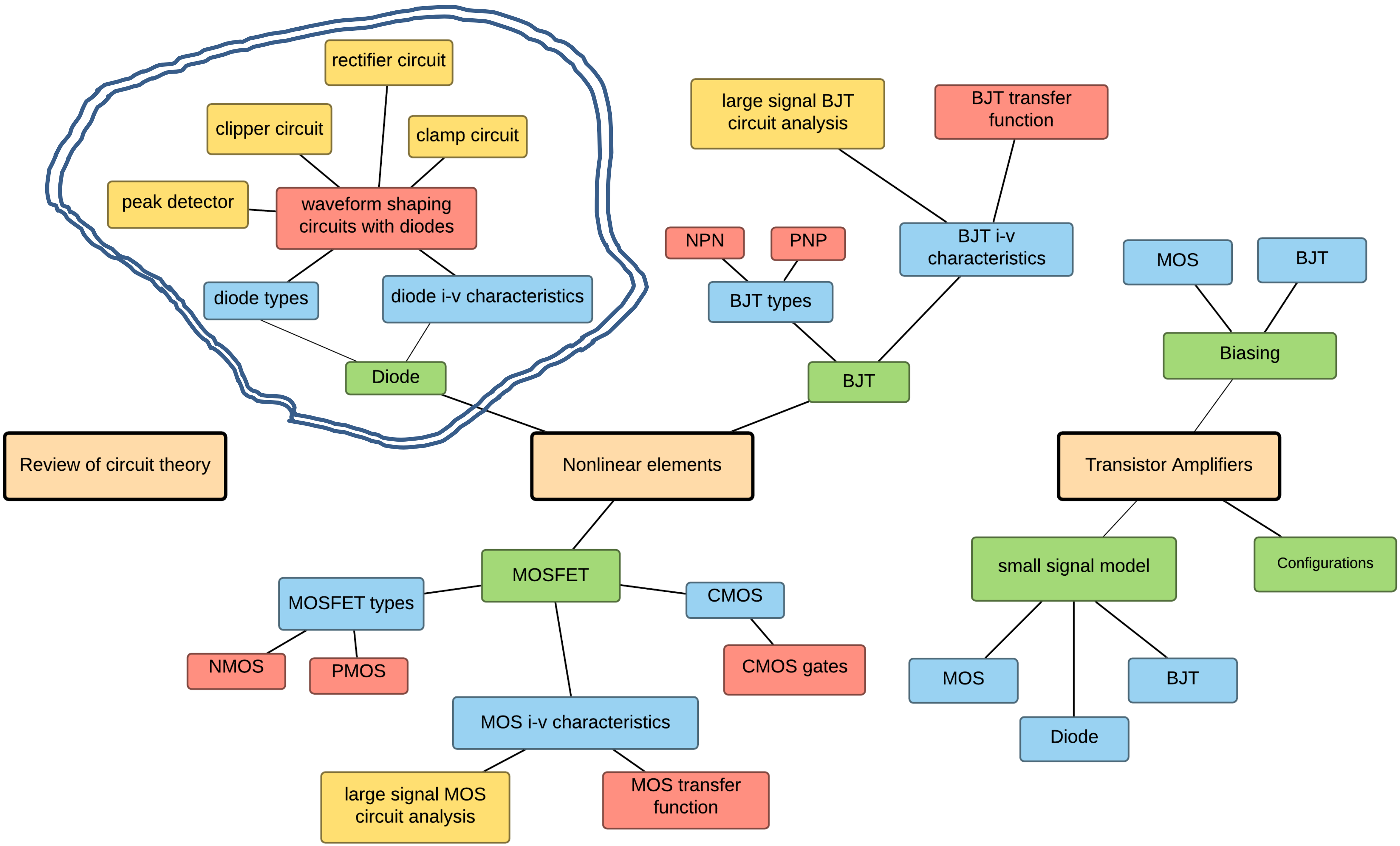
Reference notes: sections 2.9

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

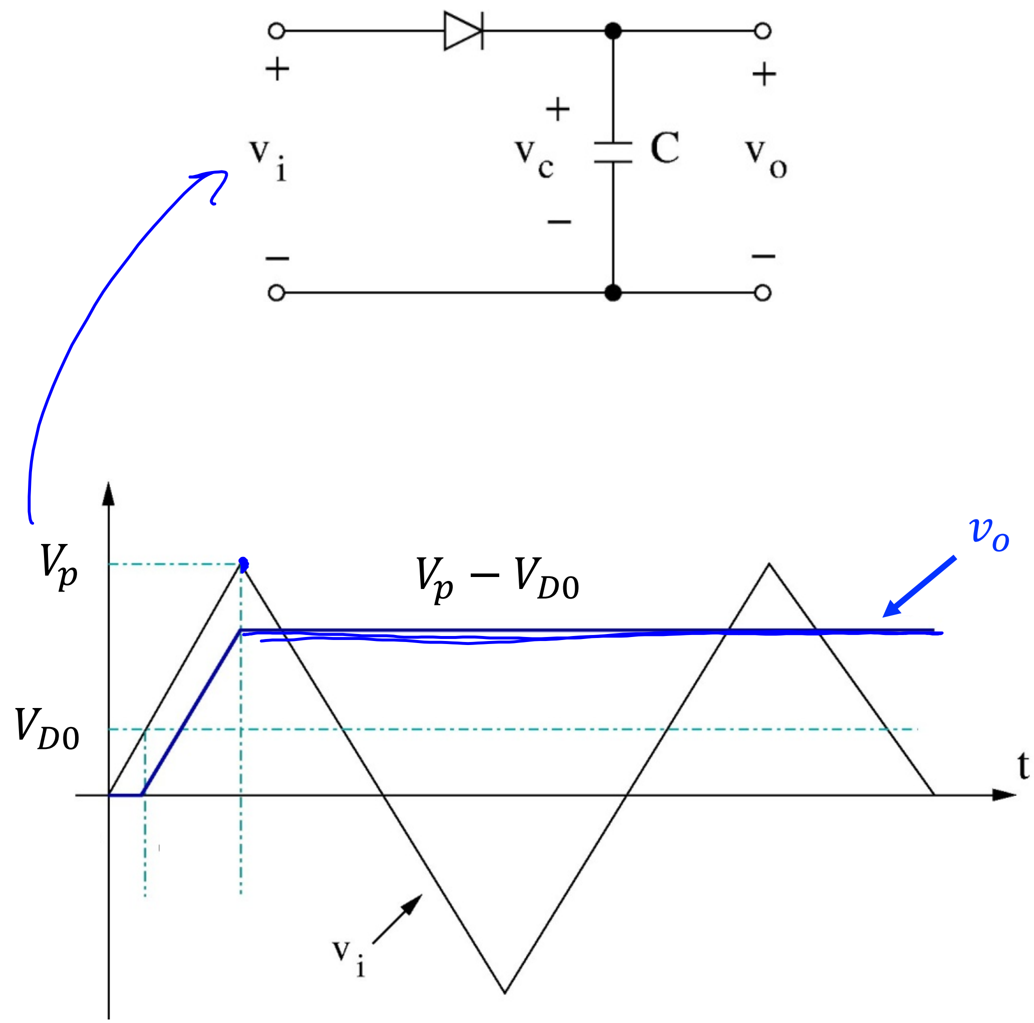
Saharnaz Baghdadchi

Course map

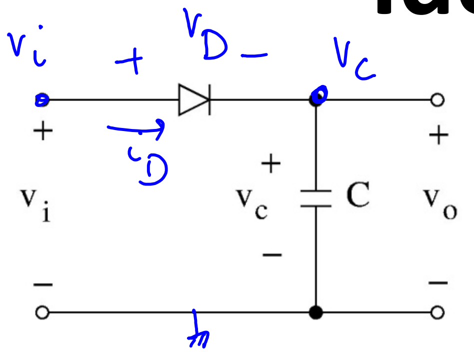
2. Diodes



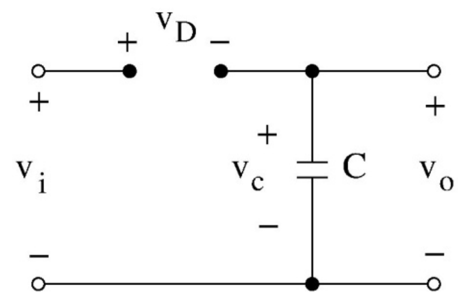
Ideal Peak Detector Circuit



Ideal Peak Detector Circuit



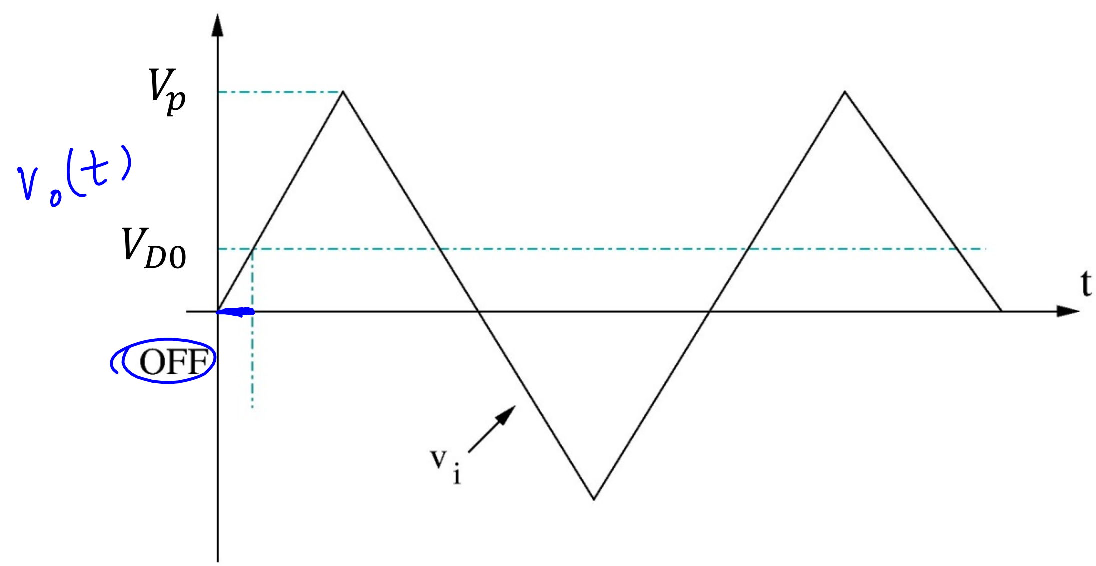
When the Diode is initially OFF:



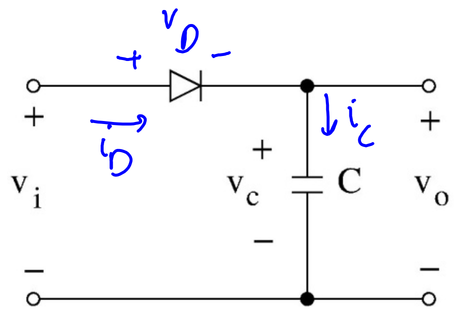
$V_D = V_i - V_c = V_i$

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

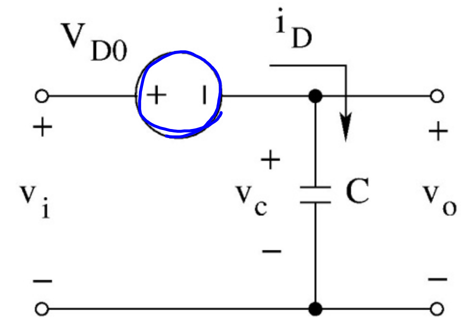
$\Rightarrow V_i < V_{D0}$



Ideal Peak Detector Circuit



When the Diode is ON:

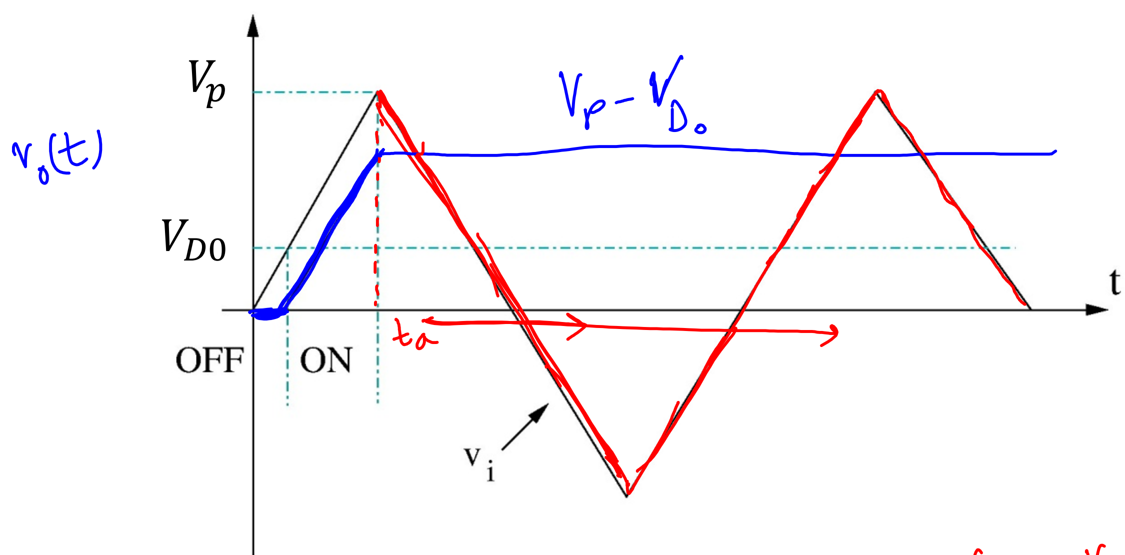


$$V_D = V_{D_o}$$

$$i_D \geq 0$$

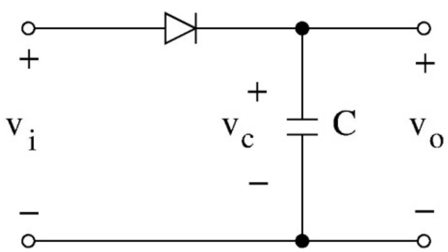
$$V_o = -V_D + V_i = -V_{D_o} + V_i \quad , \quad i_D = i_C = C\frac{dv_C}{dt} = C\frac{d(v_i - V_{D_o})}{dt}$$

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

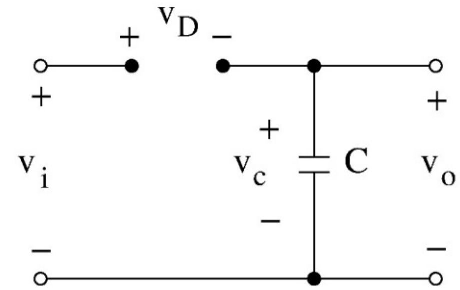


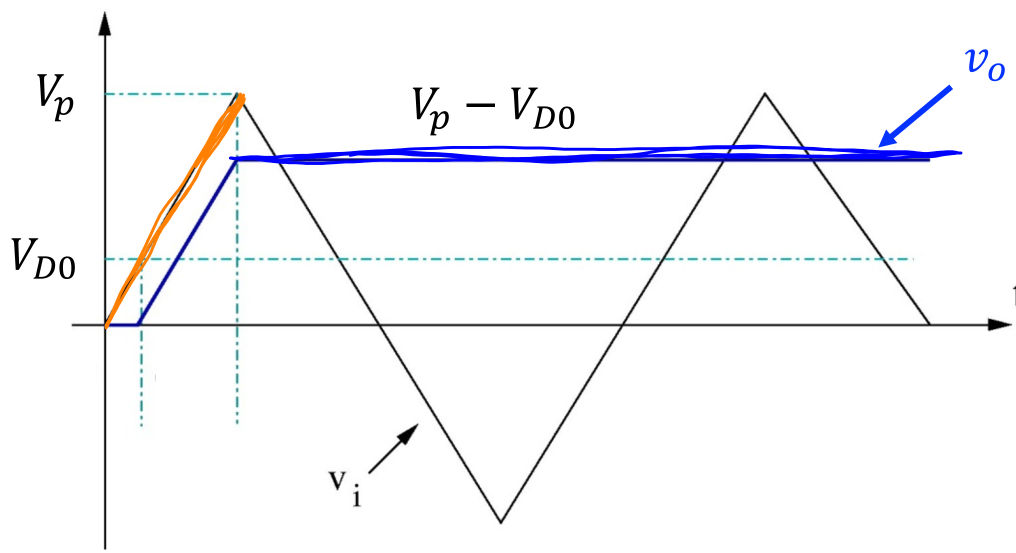
at $t = t_a$, $v_i = V_p$, $v_C = V_p - V_{D_o}$, $V_D = V_i - V_C = V_i - (V_p - V_{D_o})$

Ideal Peak Detector Circuit

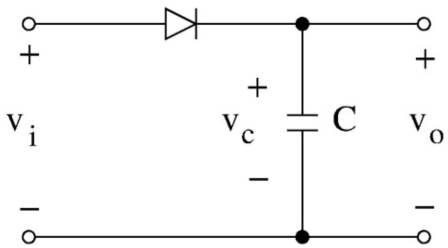


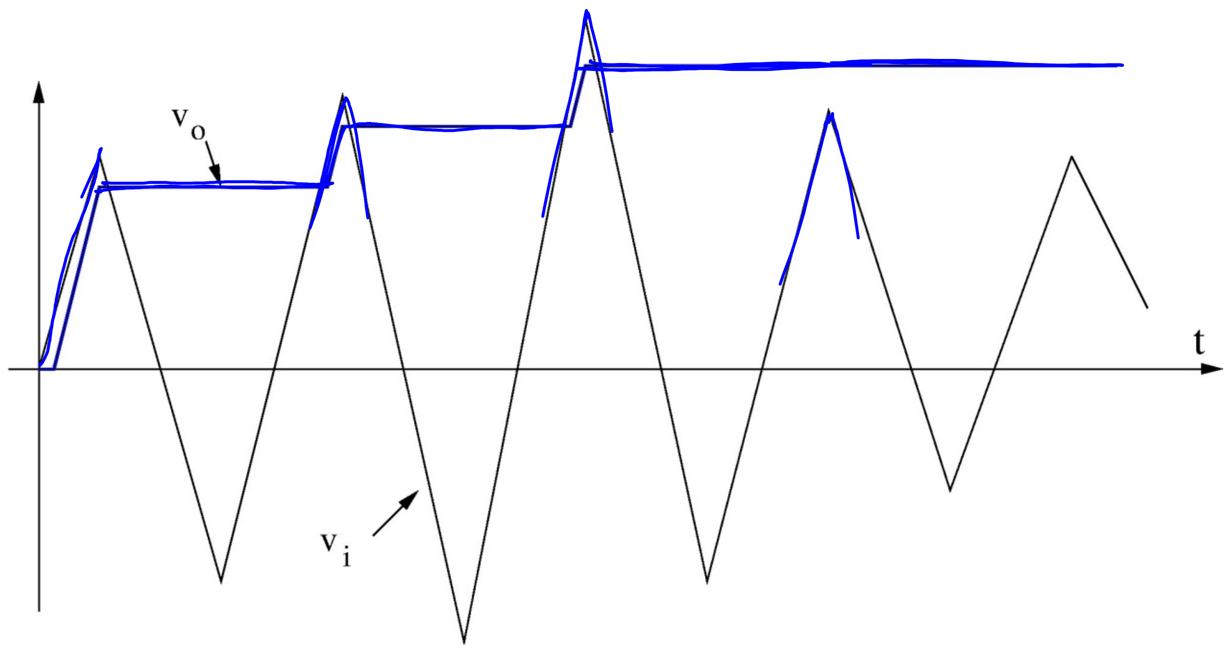
After v_i reached its peak value, the diode does not turn ON anymore.





Response of the Ideal Peak Detector (v_i amplitude changes)

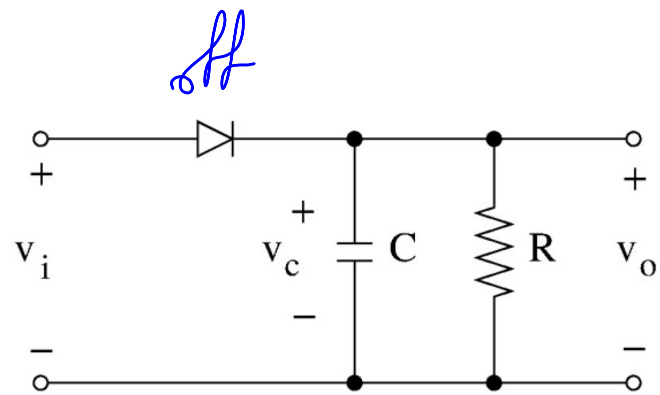


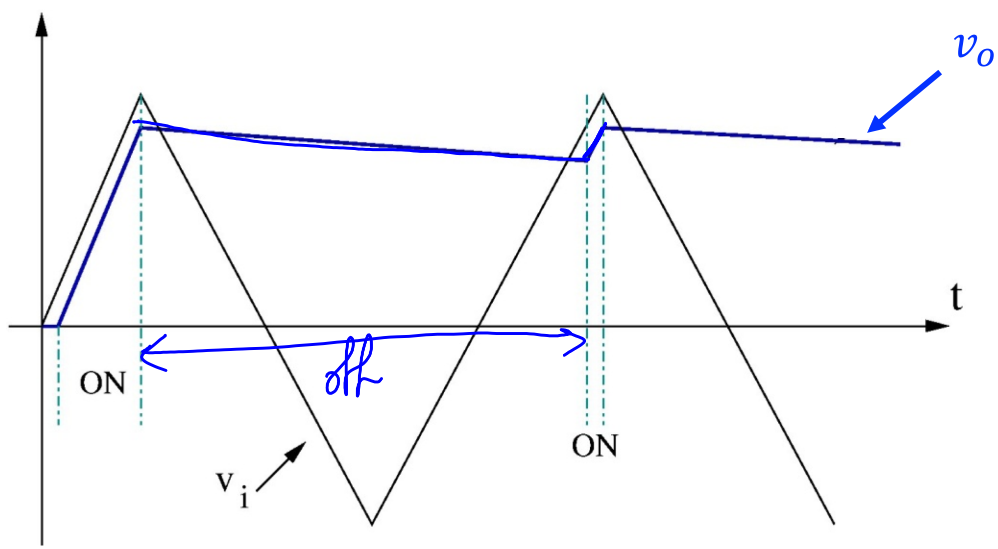


v_o is the "peak" value of input waveform ($V_p - V_{D0}$):

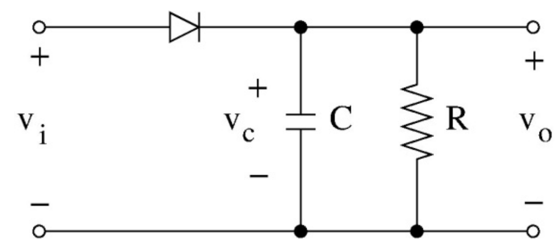
Note v_o did not "drop" after the peak was decreased in the 3rd cycle.

Practical Peak Detector Circuit

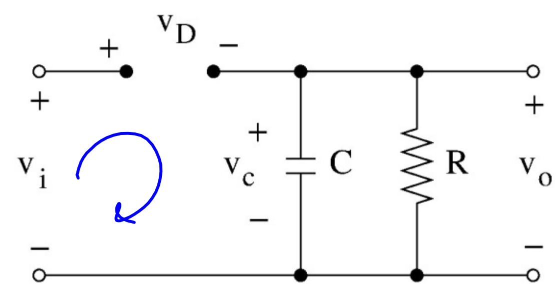




Practical Peak Detector Circuit



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

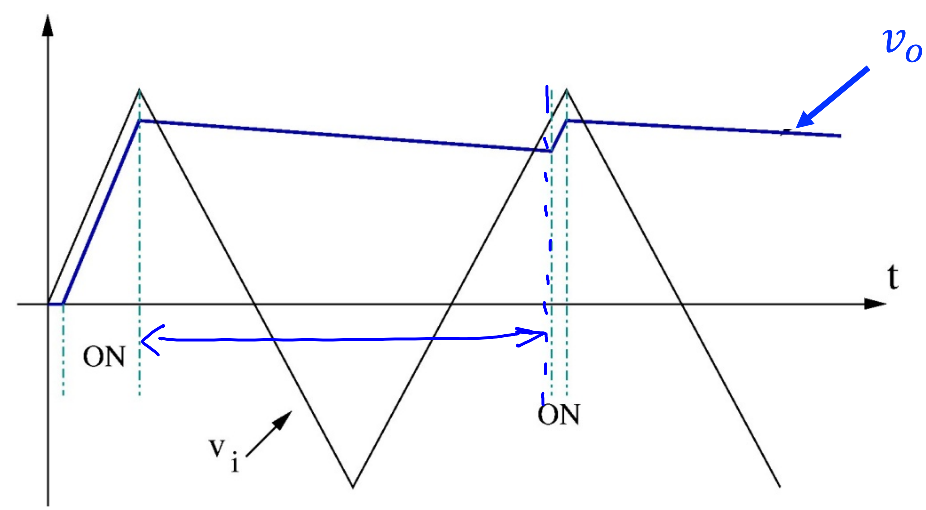


Capacitor discharges into the resistor with a time constant of $\tau = RC$

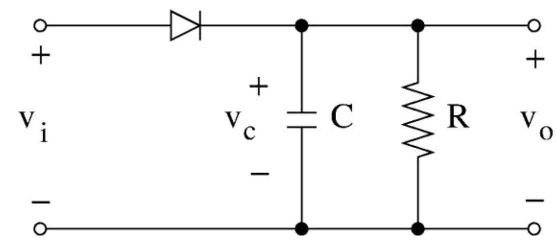
$$v_o = v_c(t) = v_{c_0}\, e^{-(t-t_0)/\tau}$$

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

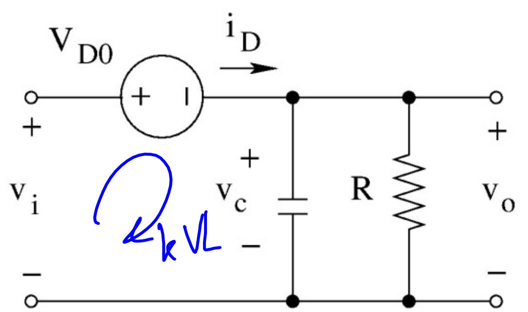
$$\rightarrow v_i < v_c(t) + V_{D0}$$



Practical Peak Detector Circuit

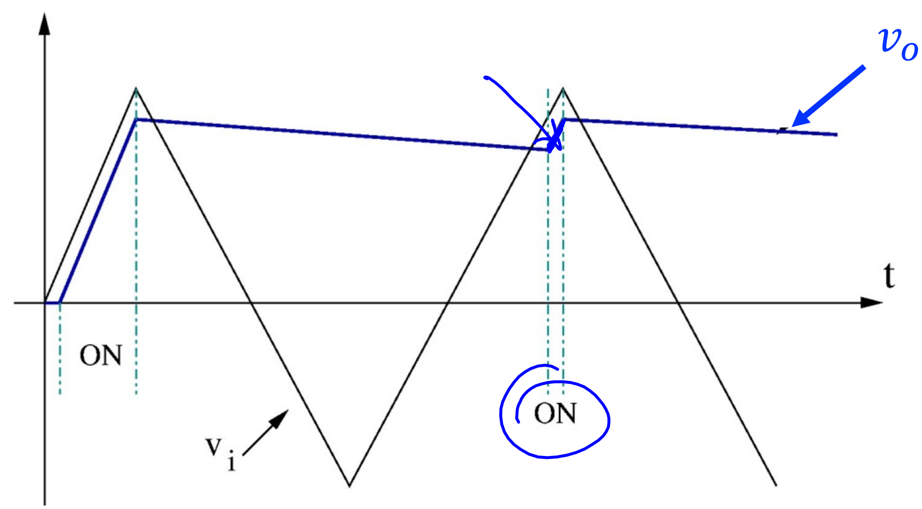


Diode ON: $v_D = V_{D0}$ and $i_D \geq 0$



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

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



Response of the Practical Peak Detector

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

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

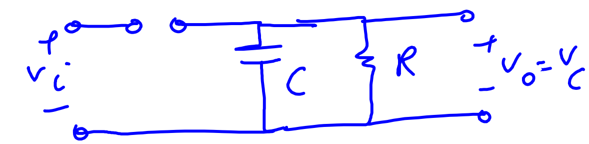
"Good" peak detector: $\tau/T >> 1$

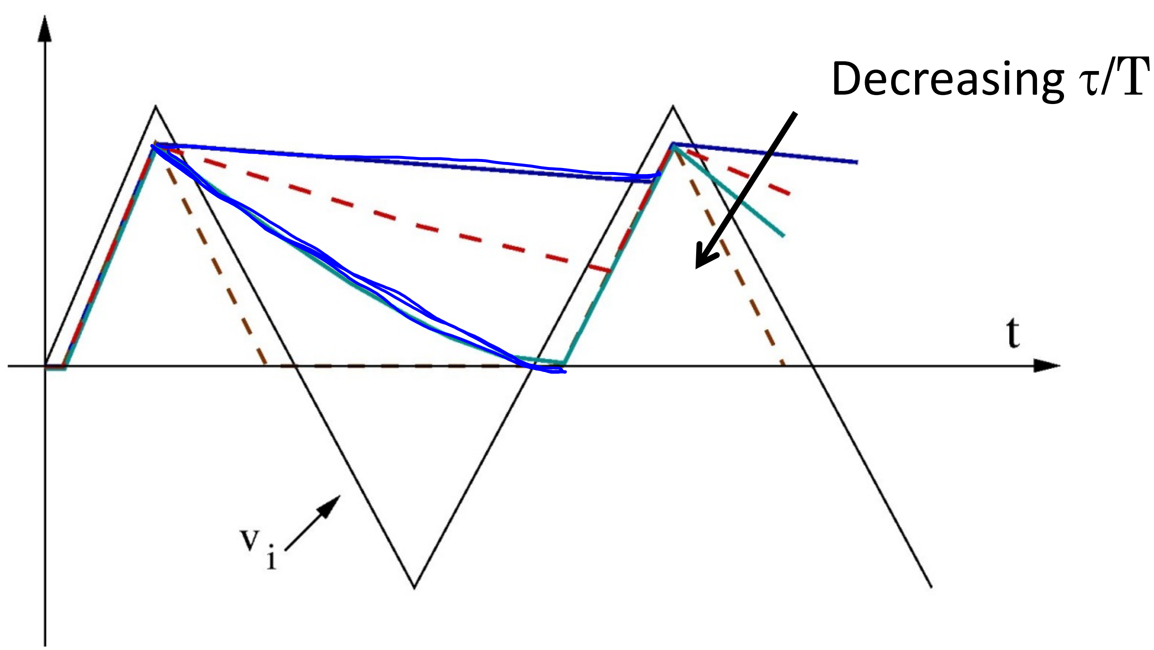
As τ/T decreases, the circuit departs from a peak detector.

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

τ : time constant $= RC$

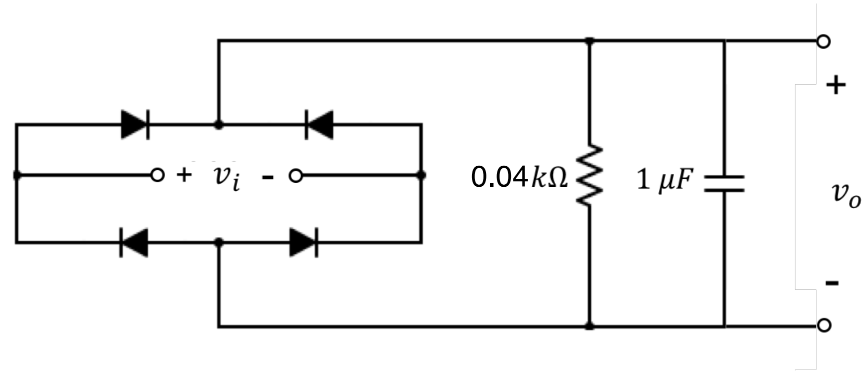
T : period of $v_i(t)$



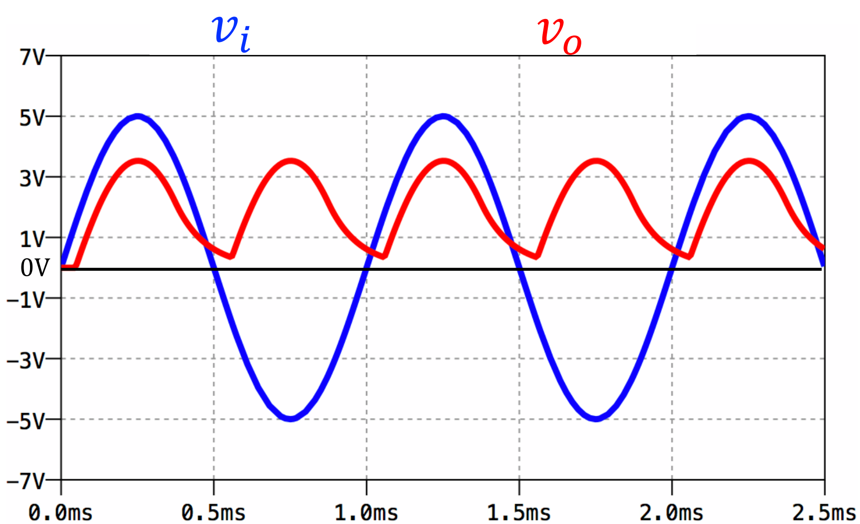


Lecture 8 reading quiz.

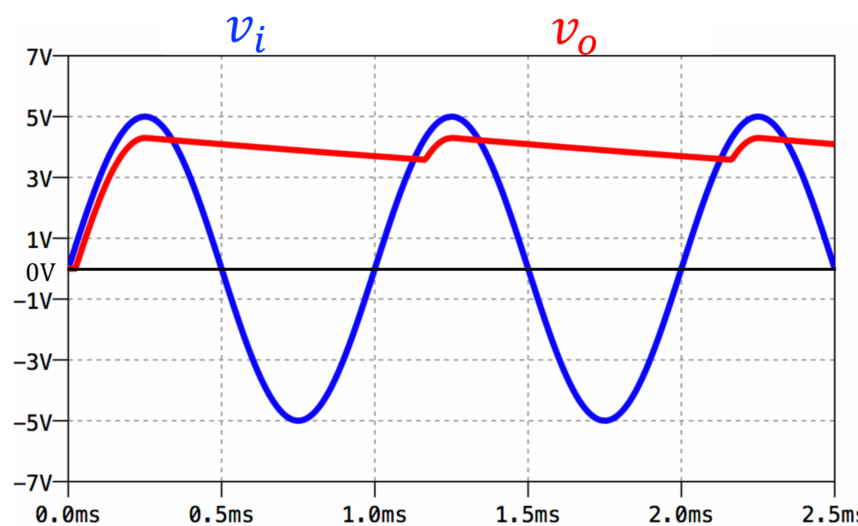
In the following diode circuit, which one of the options could be the input and output voltages for this circuit? $V_{D0} = 0.7\ V$.



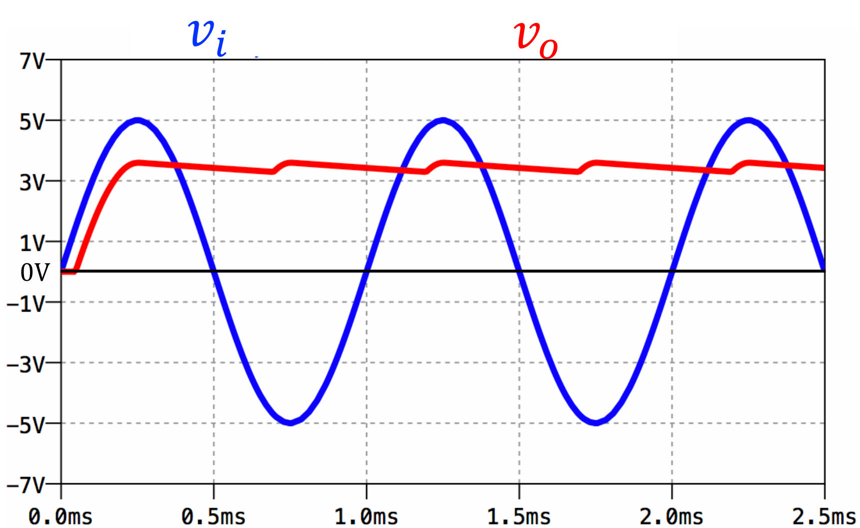
A.



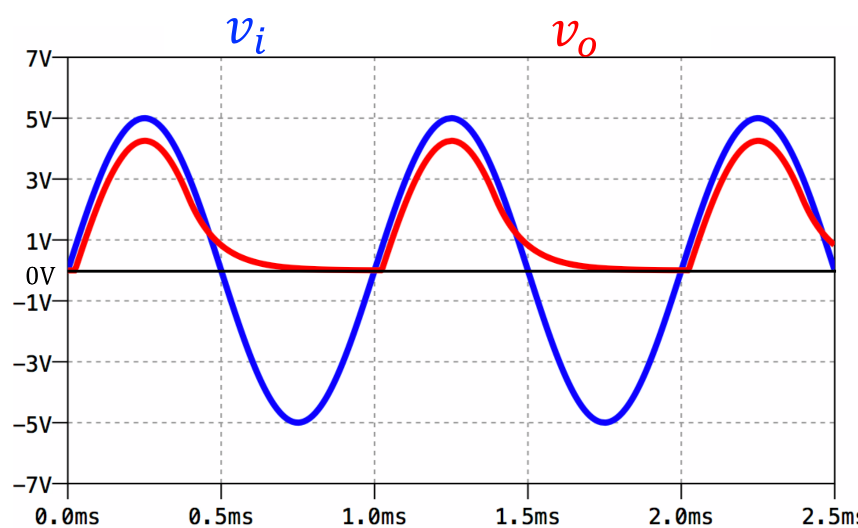
C.



B.



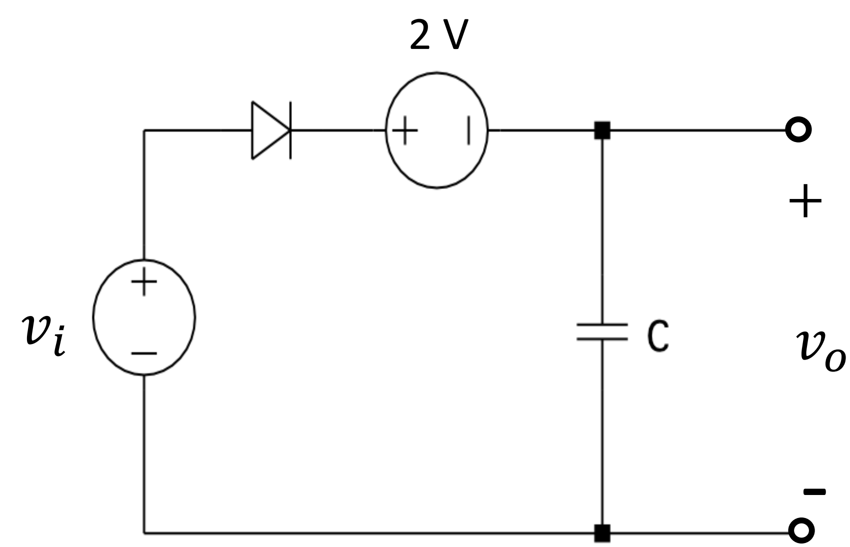
D.



Discussion question 1.

In the circuit below, $v_i(t) = 10\ \sin(\omega t)$ where ω=1000 rad/s, $v_c(0) = 0$.

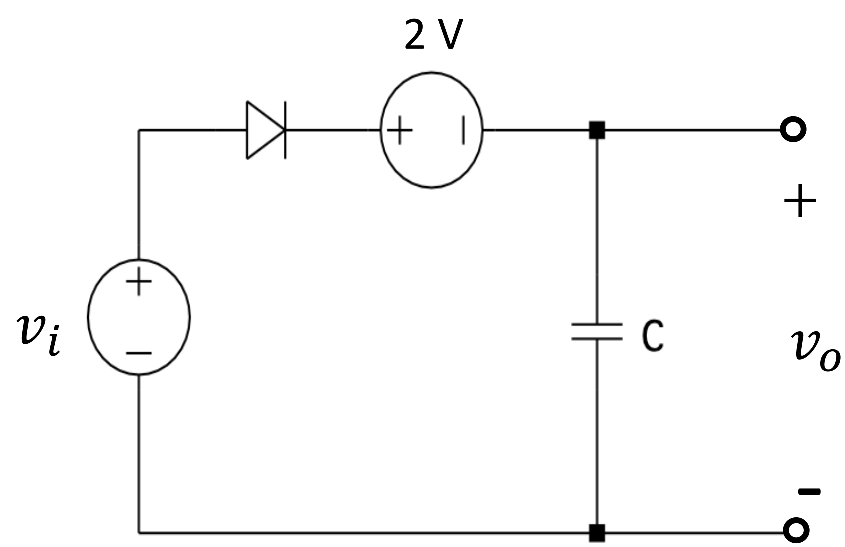
$V_{D0} = 0.7\ V$. What is the value of $v_o(t)$ at t = 1ms and t=2 ms? Draw one cycle of the input and output waveforms.



Hints:

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.



- Find the period of the input sinusoidal waveform.
T = 2pi/w

- Find the minimum amplitude of vi to turn the diode ON. You should write a KVL in the circuit to get the answer. Note that Vc(0)=0

- The diode will conduct until vi reaches its peak amplitude. Then, it will disconnect.

- Find the time point at which vi reaches it's peak amplitude and compare it with the given time points, t = 1ms and 2ms. The relationship between vout and vi will be different at different time points.

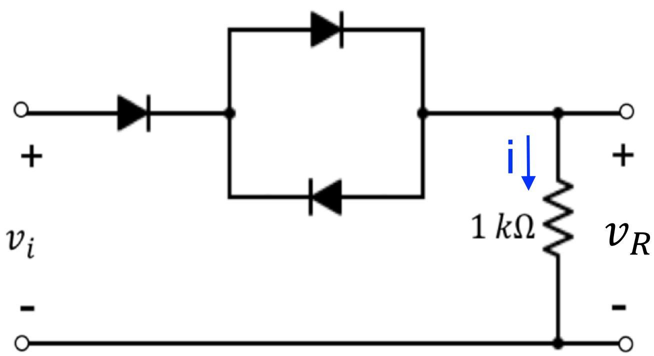
Discussion question 2.

Design a clipper circuit that limits voltages above 6 V. You can use any combination of regular PN junction diodes, Zener diodes or DC sources.

Extra problem for practice

Find v_R and i in the below circuit for $-5\text{ V} \le v_i \le 5\ V$.

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



ECE 65: Components & Circuits Lab

Lecture 9

Diode waveform shaping circuits

Clamp circuits

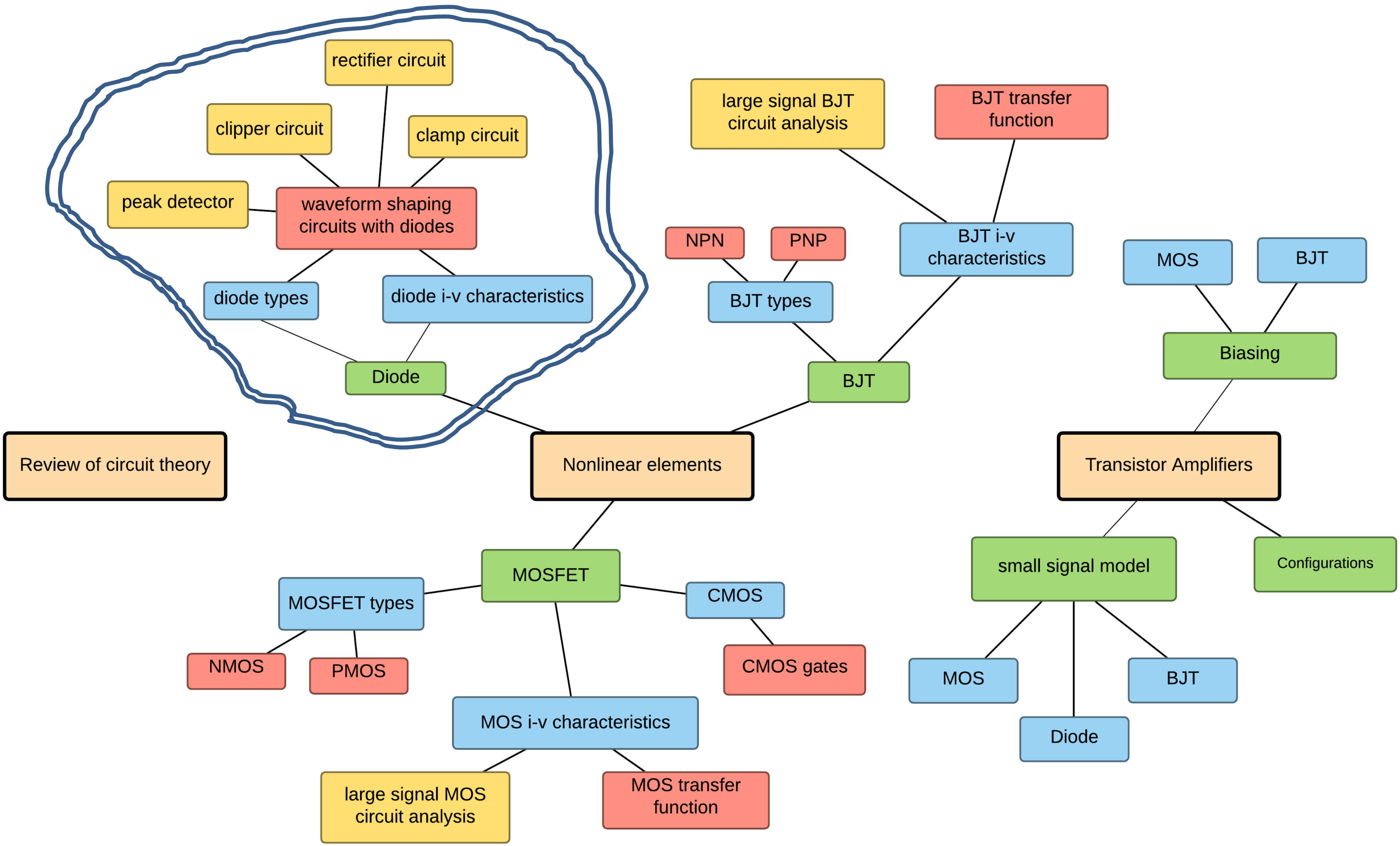
Reference notes: sections 2.9

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

Saharnaz Baghdadchi

Course map

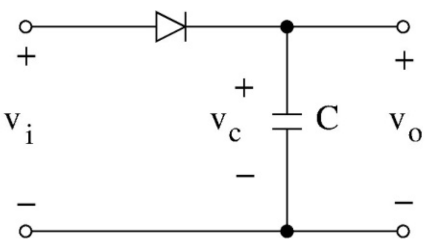
2. Diodes

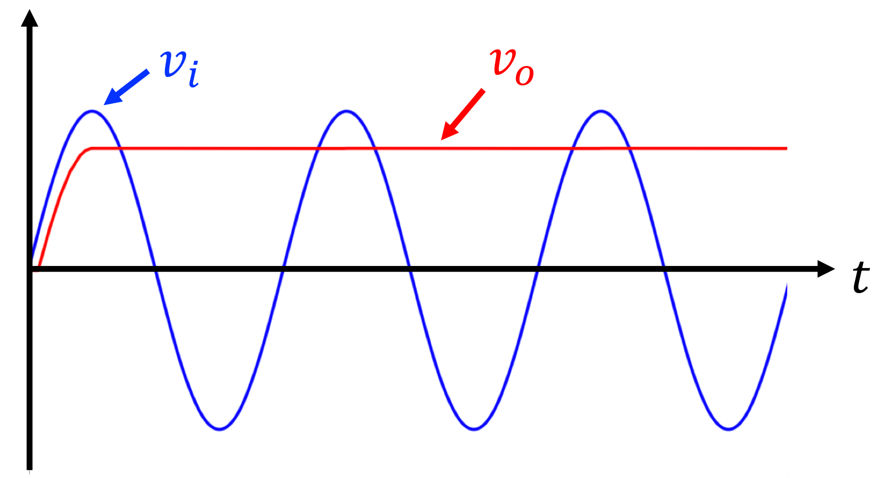


Clamp circuit and peak detector circuit

Ideal peak detector:

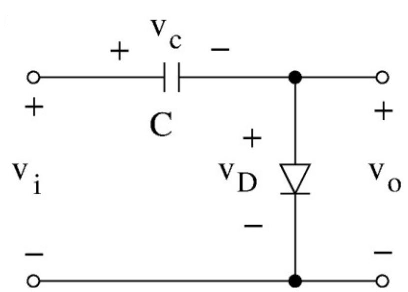
$$v_o = V_p - V_{D0}$$

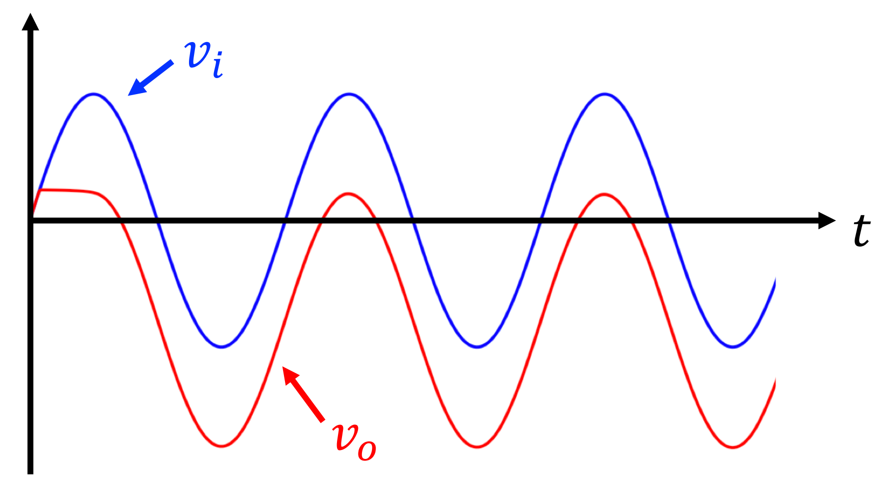




Clamp circuit:

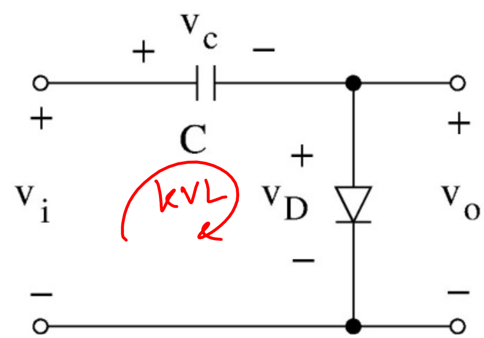
$$v_o = v_i - (V_p - V_{D0})$$



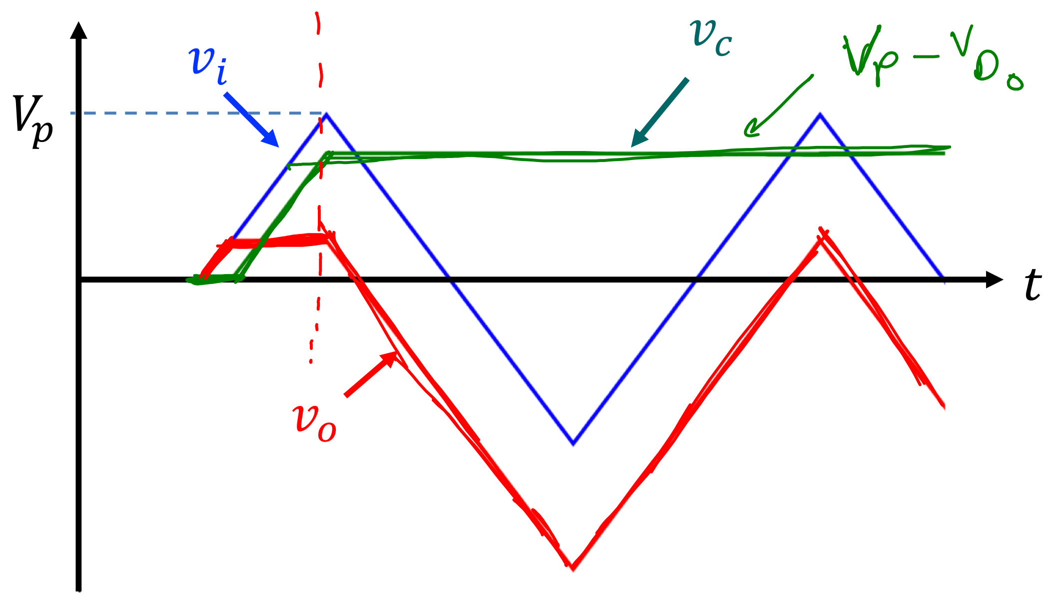


Clamp Circuit

$v_D = -v_c + v_i$



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



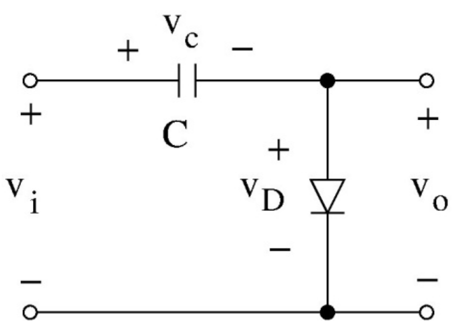
$$v_o = v_D = v_i - v_c$$

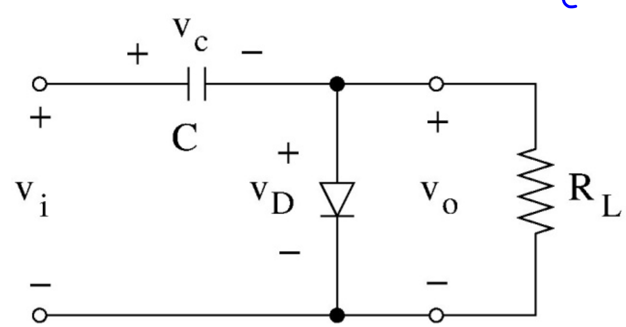
Diode off:

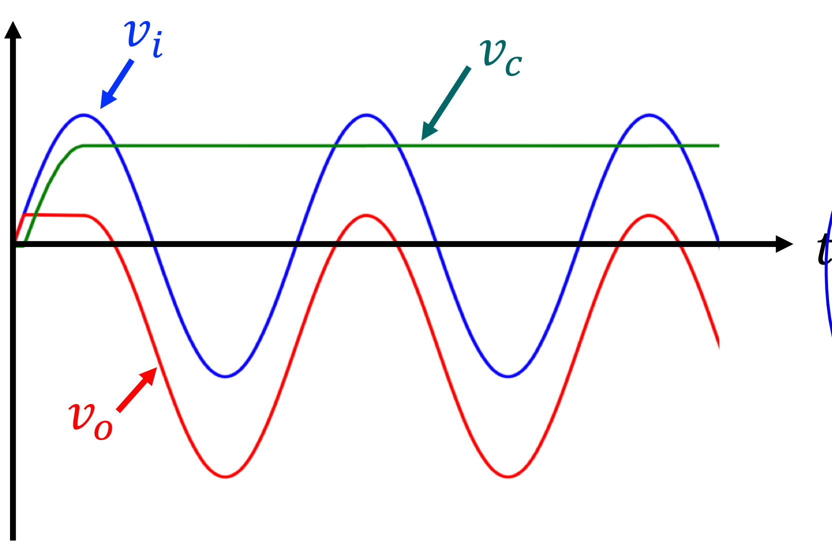
$$v_o = v_i - (V_p - V_{D0})$$

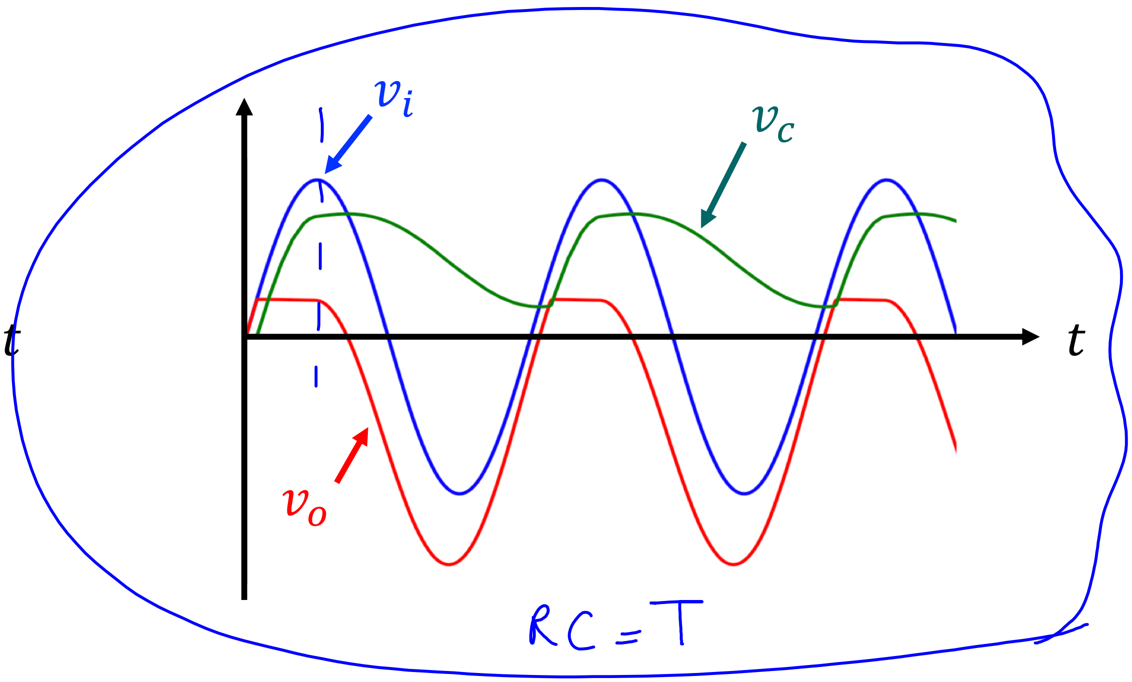
Clamp Circuit with a Load

$\tau = CR_L$



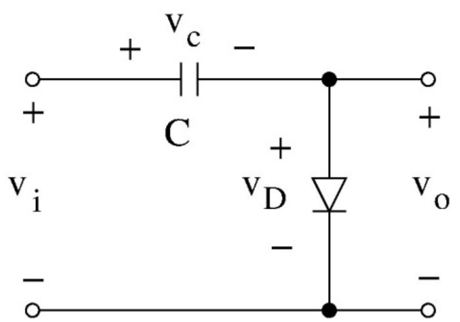






If $\tau = R_L C >> T$ capacitor does not discharge substantially and clamp circuits works fine

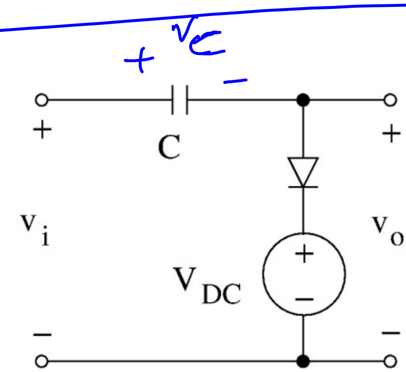
Voltage shift in a clamp circuit can be adjusted



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

$$V_o = -V_C + V_i$$

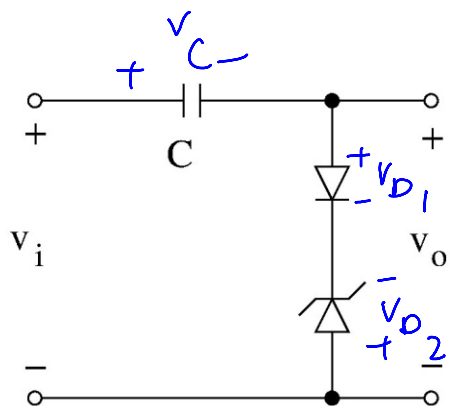
$$V_o = V_i - \boxed{(V_p - V_{D_0})}$$



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

$$V_o = -V_C + V_i$$

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

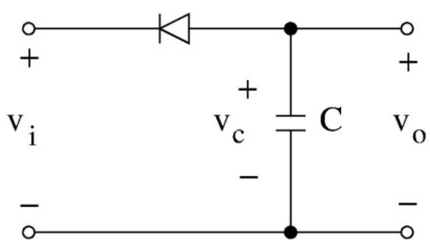


$$V_o = -V_C + V_i$$

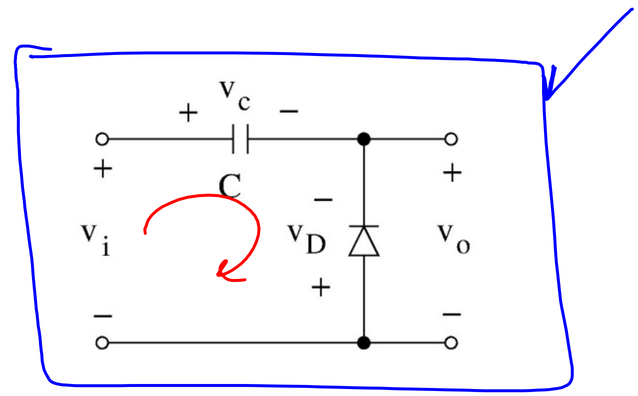
$$= V_i - (V_p - V_{D_0} - V_Z)$$

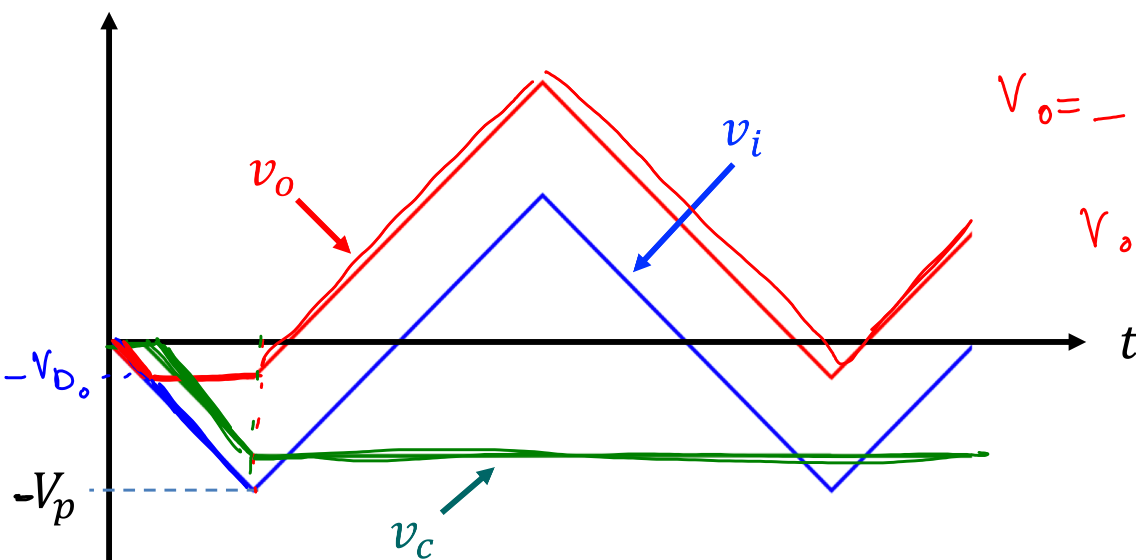
Clamp circuit can introduce a "positive" shift by reversing the diode terminals

Peak detector (diode is reversed):



Clamp circuit (diode reversed):





$V_o = -V_c + V_i$

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

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

$V_D = -V_i + V_c = -V_i$

$V_o = -V_D$

$\Rightarrow V_o = +V_i$

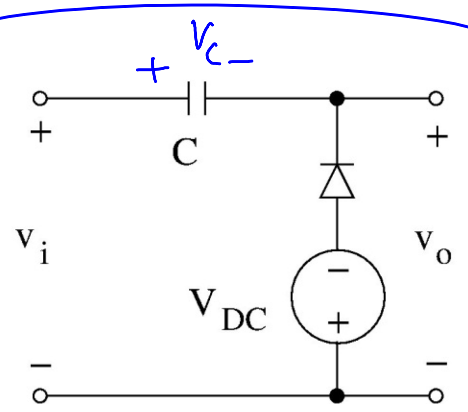
$V_o = -V_{D_o}$

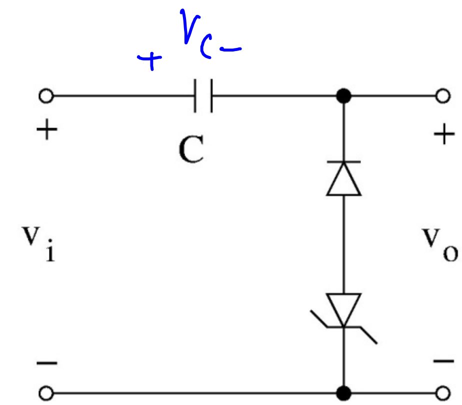
$V_c = V_i + V_{D_o}$

After the diode turned off

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

The positive shift can also be adjusted.





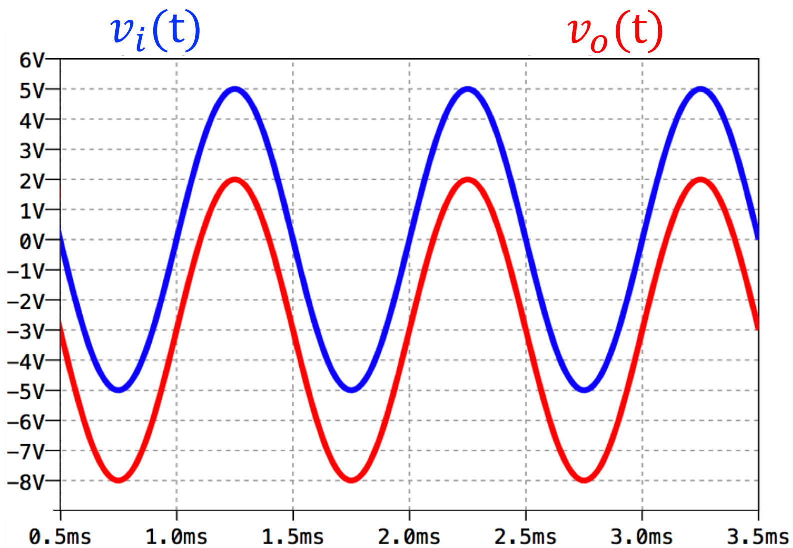
$V_c = -V_p + V_{DC} + V_{D_o}$

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

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

Lecture 9 reading quiz

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



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.

Hints:

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.

- Check the lecture notes to see the structure of the clamp circuit that can add a positive DC shift to input signals.

- You can use the equations included in the lecture notes to find the required amplitude of VDC to have the +5V DC shift.

-After drawing the circuit structure, solve the circuit to find vout as a function of vi for different time intervals.

- You need to find the minimum value of vi to turn on the diode. You also need to find out for how long the diode can stay on and what happens when the diode turns off.

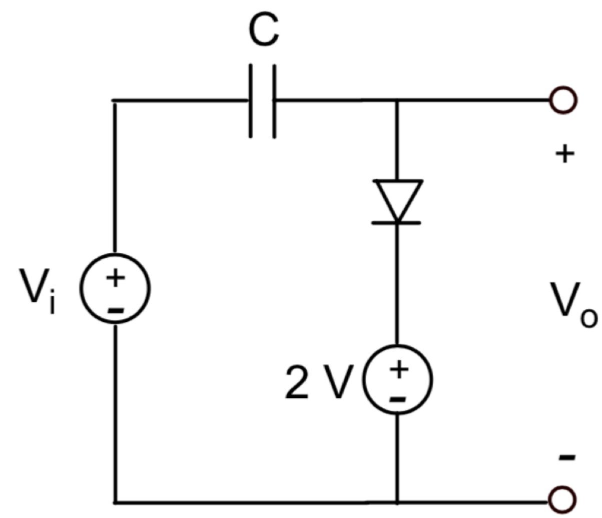
- Draw vi(t) and vout(t) on the same graph.

- You can also draw the clamp circuit structure with a DC source with an unknown amplitude and solve the circuit to find the amplitude of the DC source.

Clicker question 1.

In the circuit below, $v_i(t) = 10\sin(\omega t)$ where ω=1000rad/s, $v_o(0) = 0$. $V_{D0} = 0.7\ V$

What is the value of $v_o(t)$ at t = 2 ms?



A. $v_o(t = 2\ ms)$ = 1.8 V

B. $v_o(t = 2\ ms)$ = 6.4 V

C. $v_o(t = 2\ ms)$ = 2.7 V