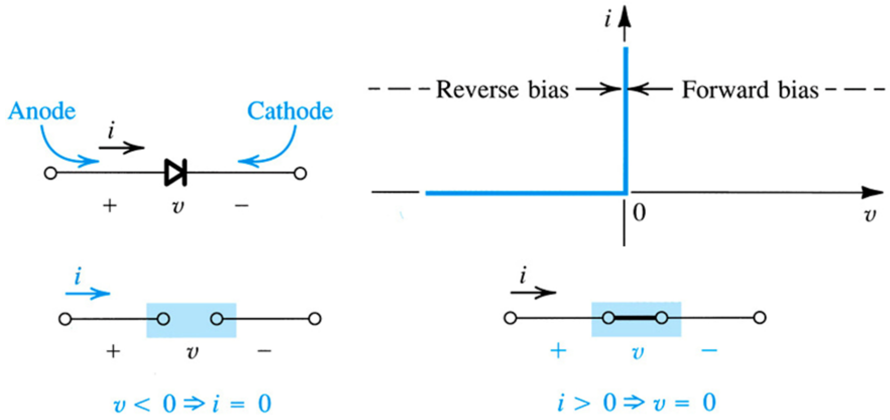
CHAPTER 3 DIODES

Chapter Outline

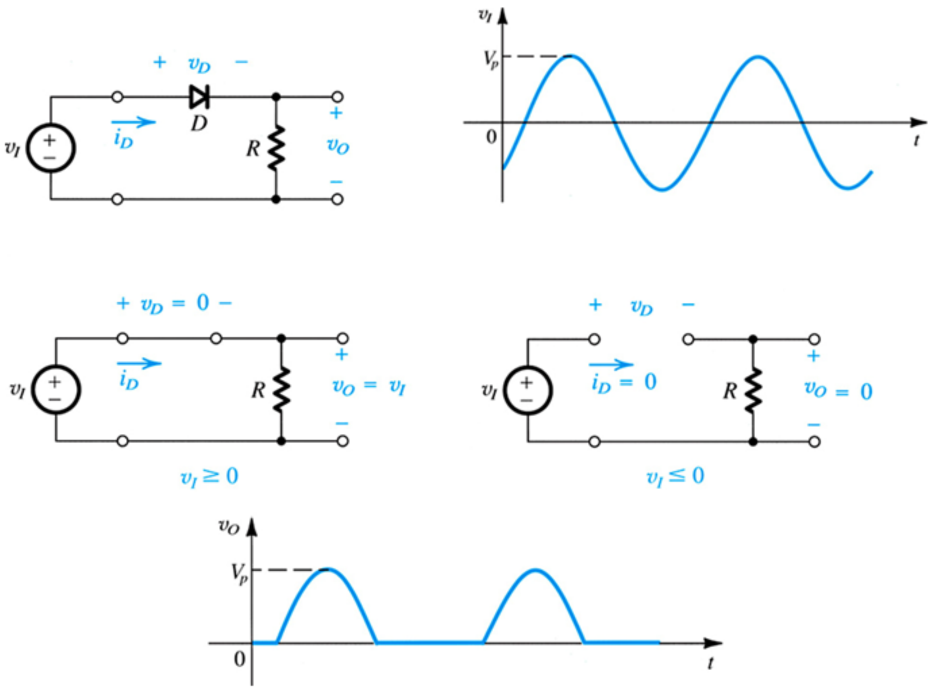
3.1 Ideal Diode

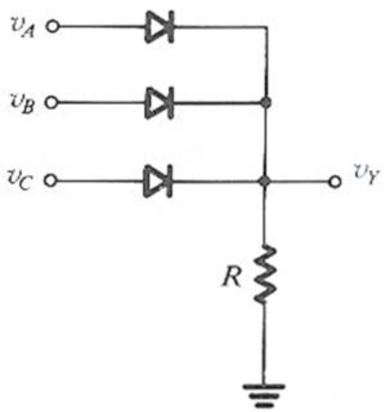
Ideal diode characteristics

- ❑ An diode is a two-terminal device:
  - ■ **Anode**: the positive terminal
  - ■ **Cathode**: the negative terminal
- ❑ Forward biased → turned on → short
- ❑ Reverse biased → turned off → open

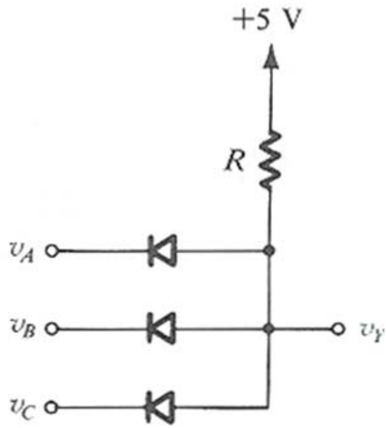


Circuit applications





$Y = A + B + C$

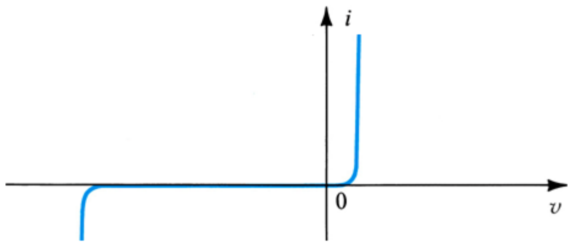


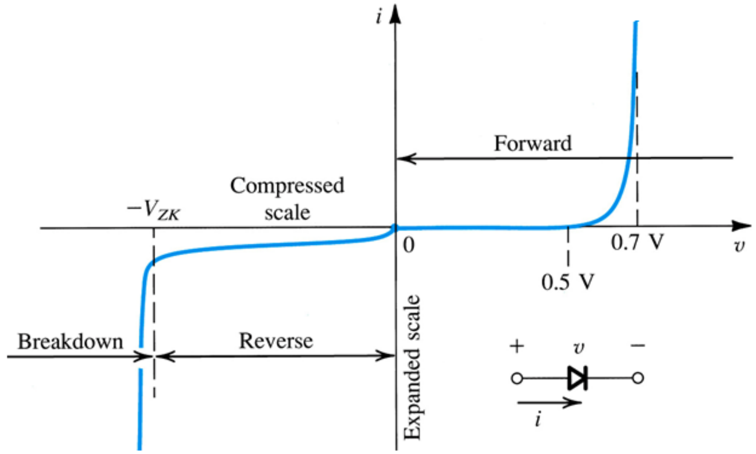
$Y = A \cdot B \cdot C$

3.2 Terminal Characteristics of Junction Diodes

I-V characteristics of junction diodes

- ❑ Diode current: $i = I_S(e^{v/nV_T} - 1)$
  - ■ I_S (saturation current): proportional to diode area
  - ■ n (ideality factor): between 1 and 2
  - ■ V_T (thermal voltage) ≈ 25 mV at room temperature
- ❑ The forward-bias region, determined by $v > 0$
- ❑ The reverse-bias region, determined by $v < 0$
- ❑ The breakdown region, determined by $v < -V_{ZK}$



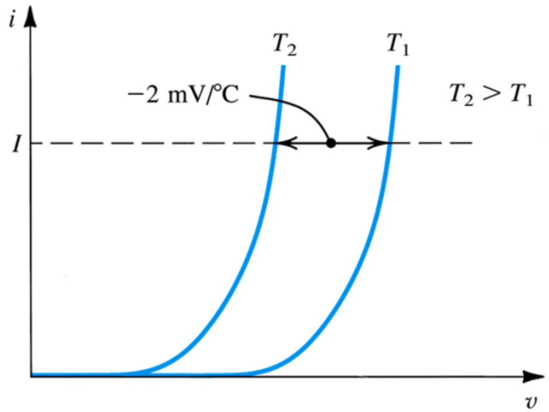


Forward-bias region

- ❑ The simplified forward-bias I-V relationship:
  - ■ For a given forward voltage: $i \approx I_S e^{v/nV_T}$
  - ■ For a given forward current: $v \approx nV_T \ln(I/I_S)$
- ❑ Due to the exponential I-V relationship
  - ■ $i \approx 0$ for $v < 0.5$V (**cut-in voltage**)
  - ■ Fully conduction for $0.6\text{V} < v < 0.8\text{V} \rightarrow V_{on} = 0.7$V

Temperature dependence

- ❑ I_S doubles for every 5°C rise in temperature
- ❑ Voltage decreases 2mV/°C for a given current
- ❑ Current increases with temperature for a given voltage



Reverse-bias region

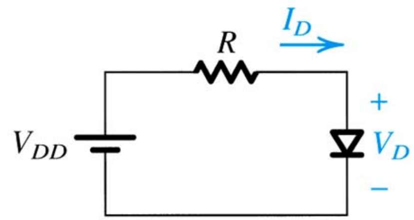
- Reverse current: $i \approx -I_S$
- Ideally, the reverse current is independent of reverse bias
- In reality, reverse current is larger than I_S and also increases somewhat with the reverse bias
- Temperature dependence: reverse current doubles for every 10°C rise in temperature

Breakdown region

- The knee of the I-V curve is specified as breakdown voltage V_{ZK} for Zener breakdown mechanism
- In breakdown region, the reverse current increases rapidly with a small increase in the reverse bias
- Normally, the reverse current is specified by external circuitry to assure the power dissipation within a safe range (non-destructive operation)

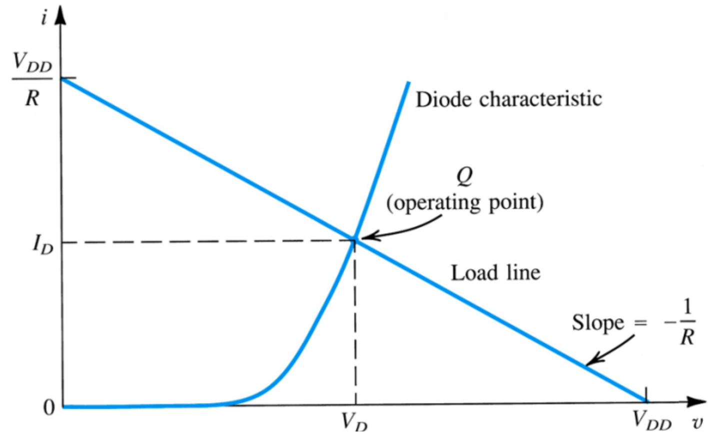
3.3 Modeling the Diode Forward Characteristics

Circuit analysis



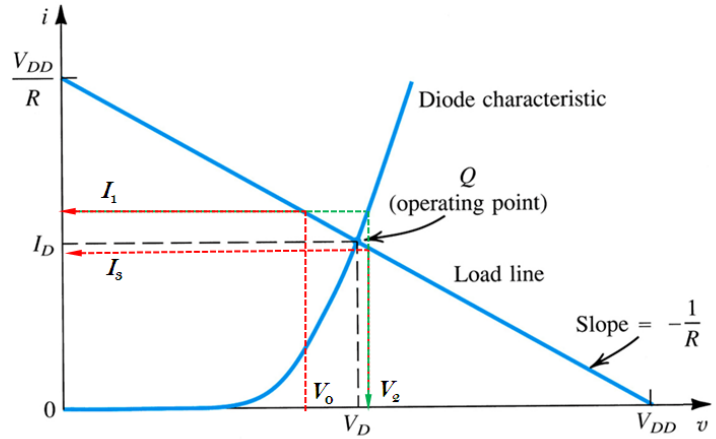
- ❑ Determine the diode current I_D and voltage V_D for circuit analysis
- ❑ The equation required for the analysis:
  - ➔ $I_D = I_S \exp(V_D/nV_T) \rightarrow$ doide I-V characteristics
  - ➔ $I_D = (V_{DD}-V_D)/R \rightarrow$ Kirchhoff loop equation
- ❑ Need to solve non-linear equations

Graphical analysis



- ❑ Plot the two equations in the same I-V coordination
- ❑ The straight line is known as **load line**
- ❑ The intersect is the solution for I_D and V_D

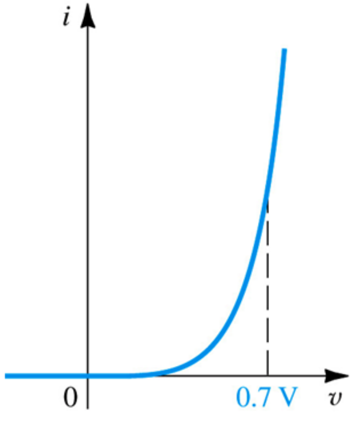
Iterative analysis

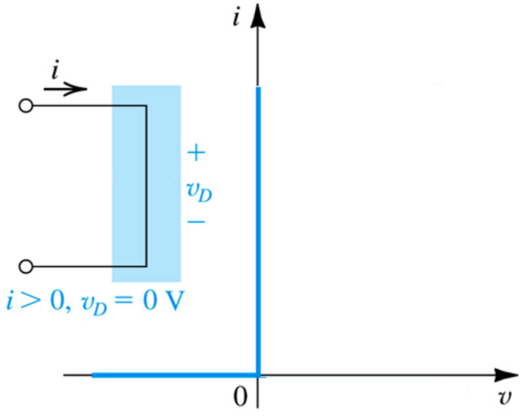


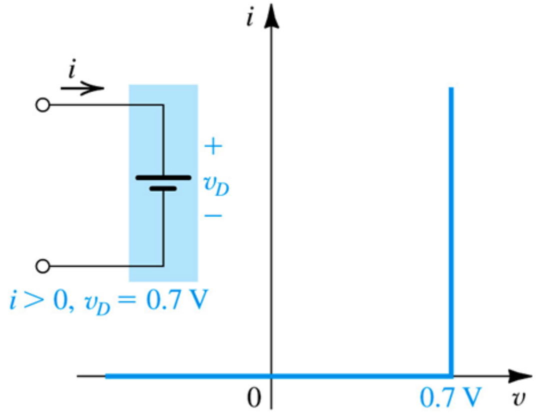
- ❑ Set initial value $V_D = V_o$
- ❑ Use $I_D = (V_{DD}-V_D)/R$ to obtain I_1
- ❑ Use $V_D = nV_T \ln(I_D/I_S)$ to obtain V_2
- ❑ Repeat until it converges (I_3, V_4, I_5, V_6…)
- ❑ Iterations are needed to solve the nonlinear circuit

The need for rapid analysis

- ❑ Rapid analysis using simplified models for initial design
- ❑ Accurate analysis (iterative analysis or computer program) for final design
- ❑ Rapid analysis (I): ideal-diode model
  - ■ The most simplified model used when supply voltage is much higher than the diode voltage
  - ■ Diode on: v_D = 0 V and $i > 0$
  - ■ Diode off: $i = 0$ and v_D < 0 V
  - ■ Equivalent circuit model as an ideal diode
- ❑ Rapid analysis (II): constant-voltage-drop model
  - ■ The most widely used model in initial design and analysis phases
  - ■ Diode on: v_D = 0.7 V and $i > 0$
  - ■ Diode off: $i = 0$ and v_D < 0.7 V
  - ■ Equivalent circuit model as an ideal diode with a 0.7-V voltage source







Small-signal approximation

❑ The diode is operated at a dc bias point and a small ac signal is superimposed on the dc quantities:

$$v_D(t) = V_D + v_d(t)$$

$$i_D(t) = I_S e^{v_D/nV_T} = I_S e^{(V_D+v_d)/nV_T} = I_S e^{V_D/nV_T} e^{v_d/nV_T} = I_D e^{v_d/nV_T}$$

❑ Under small-signal condition: $v_d / nV_T \ll 1$

$$i_D(t) \approx I_D(1+\frac{v_d}{nV_T}) = I_D + \frac{I_D}{nV_T}v_d = I_D + i_d$$

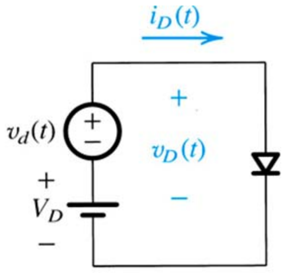
- I_D associates with $V_D \rightarrow$ dc operating point Q
- i_d associates with $v_d \rightarrow$ small signal response

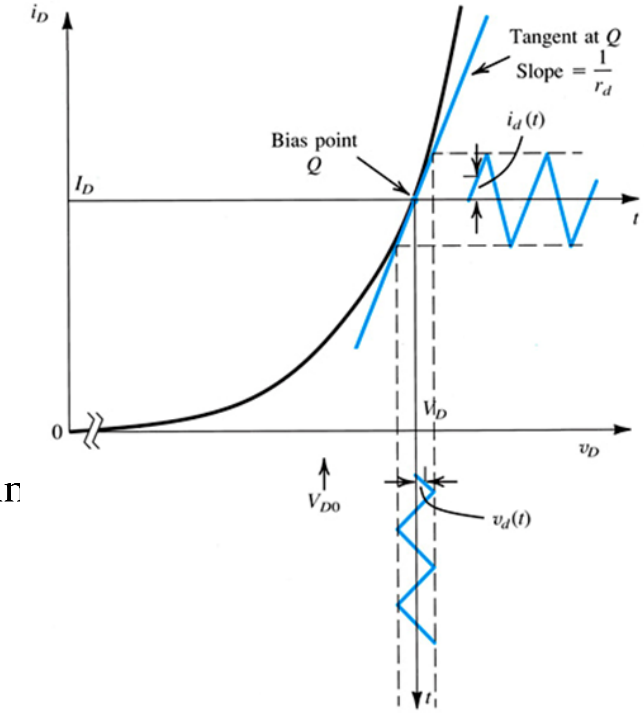
❑ The diode exhibits linear I-V characteristics under small-signal conditions ($v_d \leq 10$mV)

❑ Diode **small-signal resistance** and **conductance** at operating poir

$$i_d = \frac{I_D}{nV_T}v_d = g_d v_d = v_d / r_d \quad \rightarrow g_d = \frac{I_D}{nV_T} = [\frac{\partial i_D}{\partial v_D}]_{i_D=I_D}$$

$$\rightarrow r_d = \frac{nV_T}{I_D} = 1/[\frac{\partial i_D}{\partial v_D}]_{i_D=I_D}$$





The diode small-signal model

❑ Choose proper dc analysis technique or model to obtain the operation point Q

❑ The small-signal model is determined once Q is provided

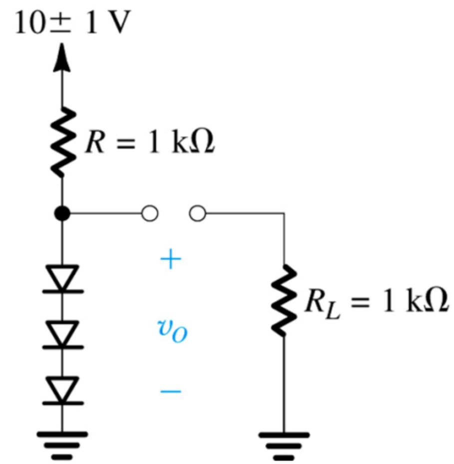
❑ The small-signal model is used for circuit analysis when the diode is operating around Q

Circuit analysis techniques for total quantities (AC+DC)

- ❑ Eliminate all the time varying signals (ac voltage and current sources) for operation point analysis
- ❑ Use rapid analysis or accurate analysis to obtain dc voltage and current at operating point Q
- ❑ Determine the parameters of small-signal models from Q
- ❑ Replace the devices with small-signal models and eliminate all the dc sources
- ❑ Circuit analysis under small-signal approximation
- ❑ The complete response of the circuit is obtained by superposition of the dc and ac components

Voltage regulator by diode forward drop

- ❑ A regulator is to provide a constant dc voltage regardless changes in load and power-supply voltage
- ❑ The forward-voltage drop remains almost constant at 0.7 V within a wide current range
- ❑ Multiple diodes in series to achieve the required voltage drop
- ❑ Better regulation can be provided for higher bias current and smaller r_d



Example 3.5 (Textbook)

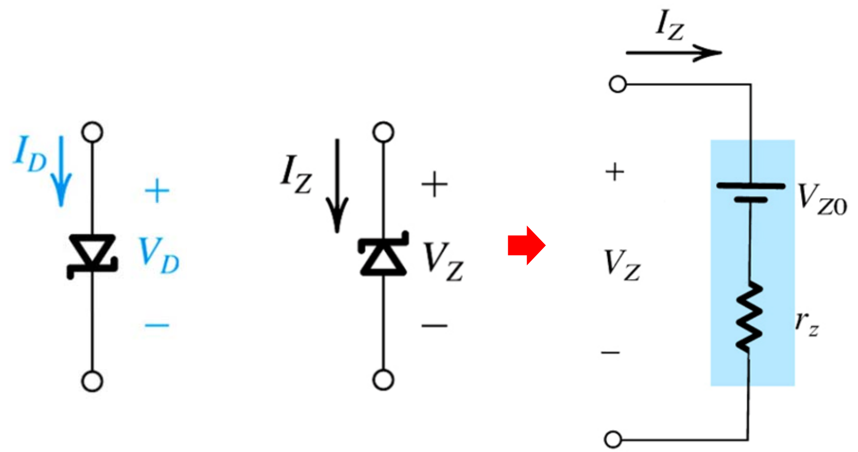
Example 3.6 (Textbook)

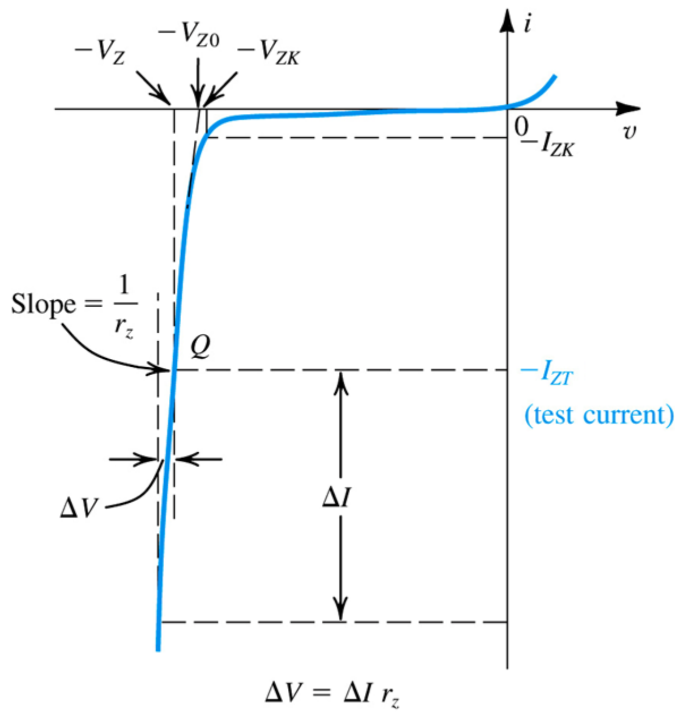
Exercise 3.14 (Textbook)

3.4 Operation in the Reverse Breakdown Region – Zener Diodes

Symbol and circuit model for the Zener diode

- ❑ In breakdown region, a reverse bias (V_Z) beyond the knee voltage (V_{ZK}) leads to a large reverse current (I_Z).
- ❑ The diode in breakdown region is given by $V_Z = V_{Zo} + r_z I_z$
  - ■ The breakdown diode is modeled by a voltage source V_{Zo} in series with an incremental resistance r_z
  - ■ Incremental voltage versus current: $\Delta V = r_z \Delta I$
  - ■ The simplified model is only valid for $I_Z > I_{ZK}$ (knee current)
  - ■ Equivalent r_z increases as I_Z decreases
- ❑ Diode types:
  - ■ Diode: only forward and reverse regions are considered
  - ■ Zener diode: forward, reverse and breakdown regions



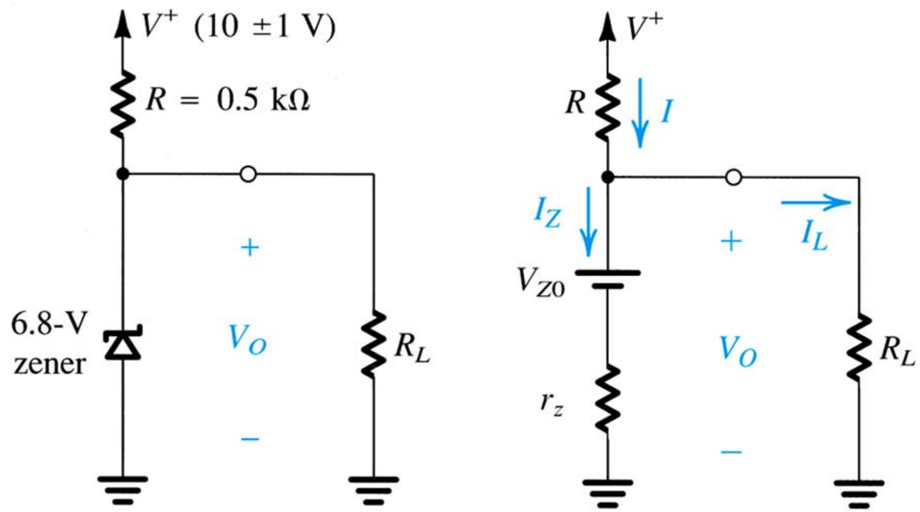


Design of the Zener shunt regulator

- Output voltage of the regulator:

$$V_O = \frac{R}{R+r_z}V_{Z0} + \frac{r_Z}{R+r_Z}V^+ - \frac{Rr_Z}{R+r_Z}I_L$$

  - **Line regulation**: $\frac{\Delta V_O}{\Delta V^+} = \frac{r_Z}{R+r_Z}$
  - **Load regulation**: $\frac{\Delta V_O}{\Delta I_L} = -\frac{Rr_Z}{R+r_Z}$



- Line and load regulation should be minimized
- For r_z << R, line regulation can be minimized by choosing small r_z
- Load regulation can be minimized by choosing small r_z and large R
- There is an upper limit on the value of R to ensure sufficiently high current I_Z (r_z increases if I_Z is too low)
- R should be selected from $R = \frac{V_{S\min} - V_{Z0} - r_z I_{Z\min}}{I_{Z\min} + I_{L\max}}$

Example 3.7 (Textbook)

Exercise 3.16 (Textbook)

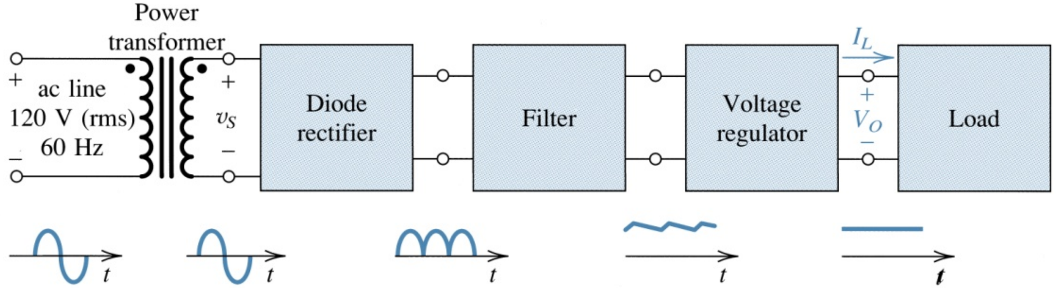
Exercise 3.17(Textbook)

Exercise 3.18 (Textbook)

3.5 Rectifier Circuits

Block diagram of a dc power supply

- DC power supply
  - Generate a dc voltage from ac power sources
  - The ac input is a low-frequency **large-signal** voltage

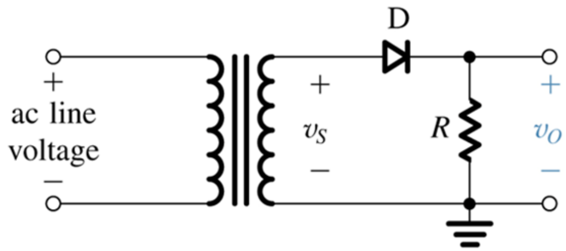


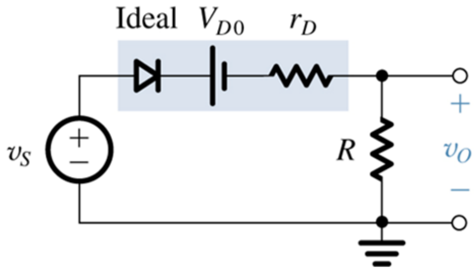
- Power transformer
  - Step the line voltage down to required value and provides electric isolation
- Diode rectifier
  - Converts the input sinusoidal to a **unipolar output**
  - Can be divided to **half-wave** and **full-wave rectifiers**
- Filter
  - Reduces the magnitude variation for the rectifier output
  - Equivalent to time-average operation of the input waveform
- Voltage Regulator
  - Further stabilizes the output to obtain a constant dc voltage
  - Can be implemented by Zener diode circuits

The half-wave rectifier

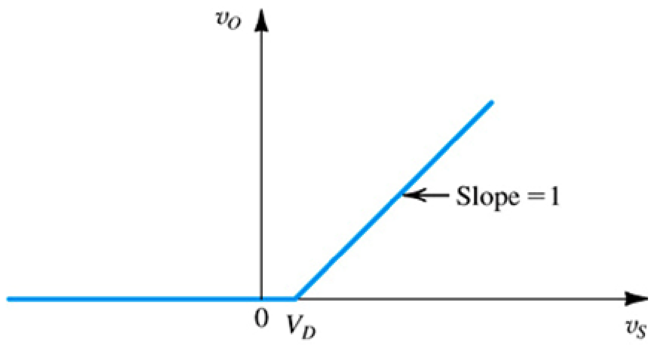
- Voltage transfer curve:

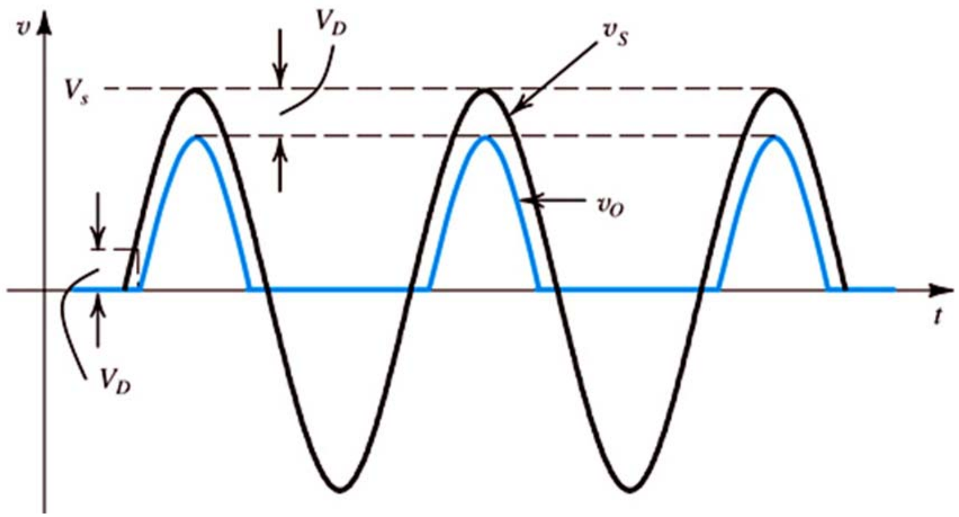
$$v_S < V_{D0} \rightarrow v_O = 0$$
$$v_S \geq V_{D0} \rightarrow v_O = v_S - V_{D0}$$





- Rectifier diode specifications:
  - Current-handling capability: the largest current the diode is expected to conduct
  - **Peak inverse voltage** (PIV): the largest reverse voltage the diode can stand without breakdown
- PIV = V_s (input voltage swing) and the diode breakdown voltage is selected at least 50% higher





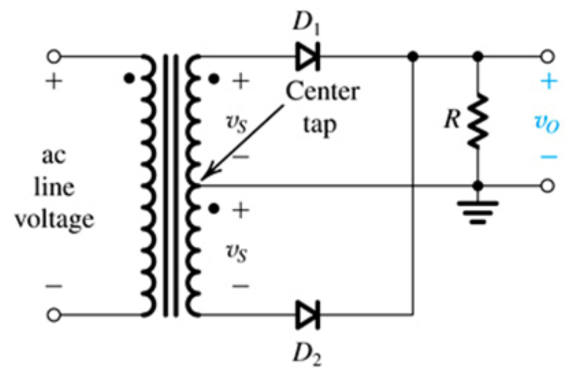
The full-wave rectifier (center-tapped transformer)

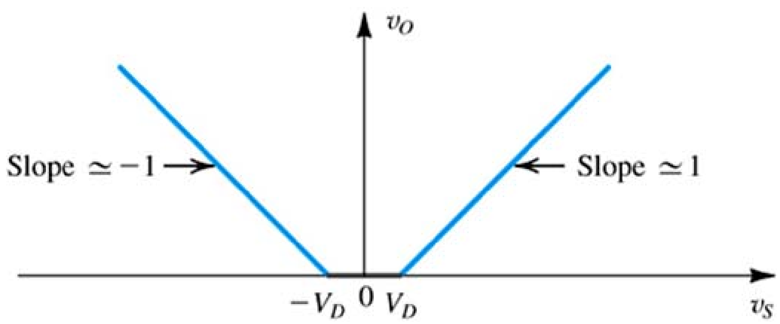
- Voltage transfer curve:

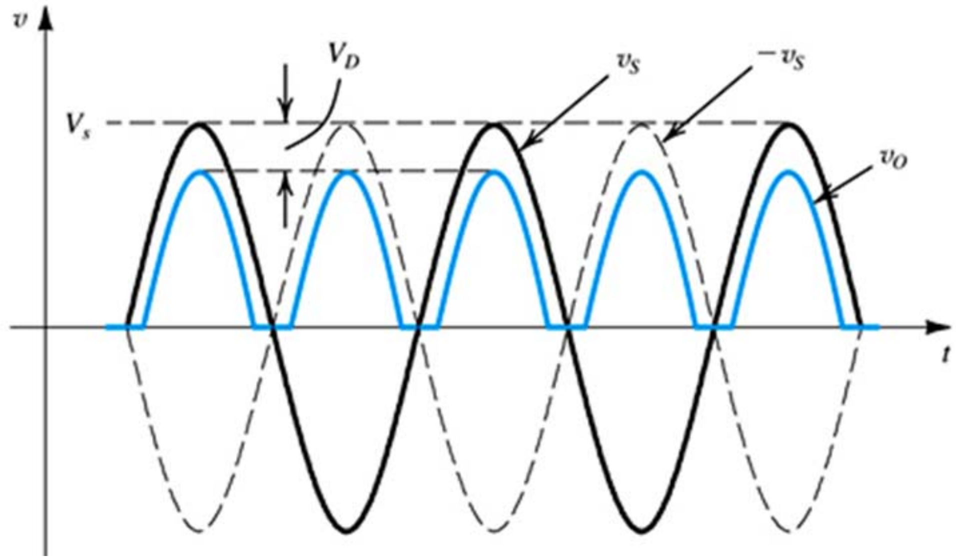
  $|v_S| < V_{D0} \rightarrow v_O = 0$

  $v_S \leq -V_{D0} \rightarrow v_O = -v_S - V_{D0}$

- Transformer secondary winding is center-tapped
- Peak inverse voltage (PIV) = $2V_s - V_{Do}$
- Rectified output waveform for both positive and negative cycles







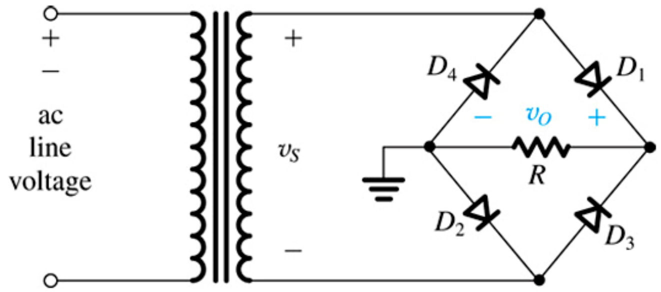
Full-wave rectifier (Bridge rectifier)

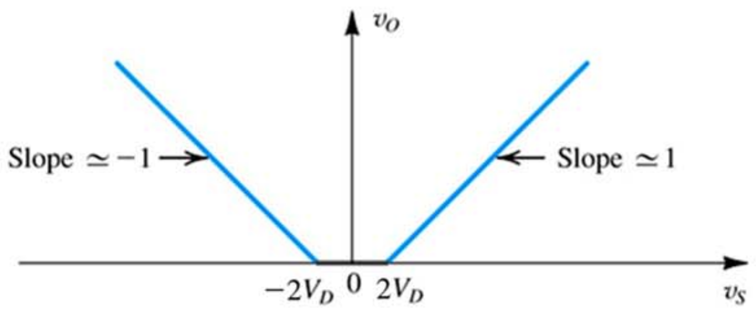
- Voltage transfer curve:

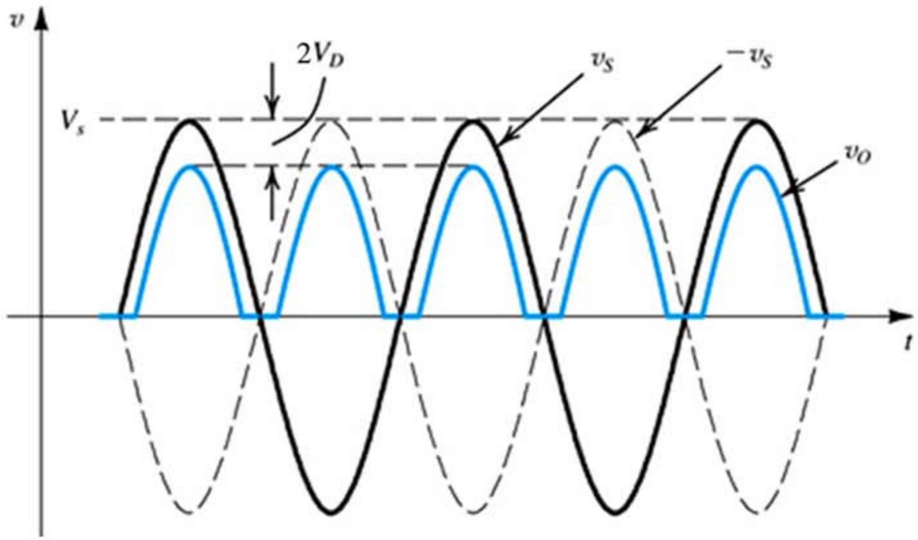
  $|v_S| < 2V_{D0} \rightarrow v_O = 0$

  $v_S \geq 2V_{D0} \rightarrow v_O = v_S - 2V_{D0}$

  $v_S \leq -2V_{D0} \rightarrow v_O = -v_S - 2V_{D0}$
- Does not require a center-tapped transformer
- Higher turn-on voltage ($2V_{Do}$)
- Peak inverse voltage (PIV) = $V_s - V_{Do}$
- Most popular rectifier circuit configuration







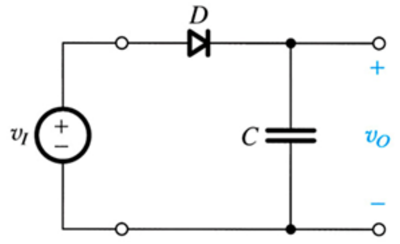
Exercise 3.19 (Textbook)

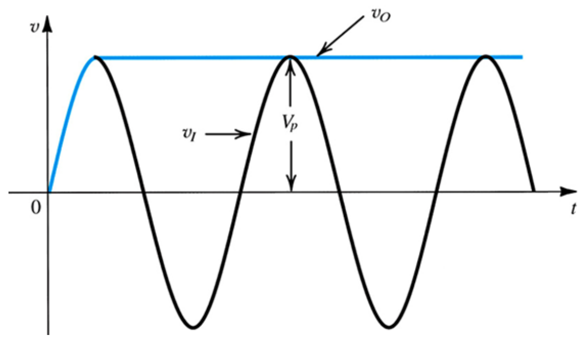
Exercise 3.20(Textbook)

Exercise 3.21 (Textbook)

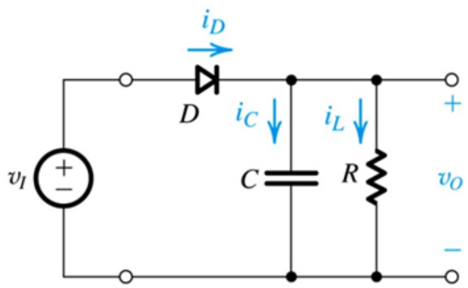
Rectifier with a filter capacitor – the peak rectifier

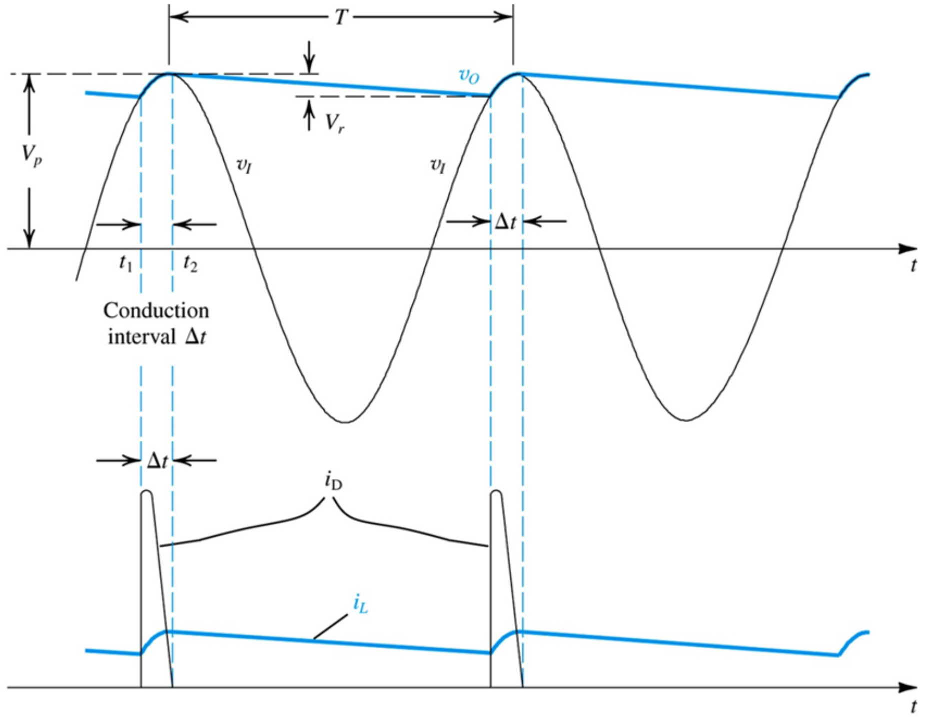
- Output unloaded case:





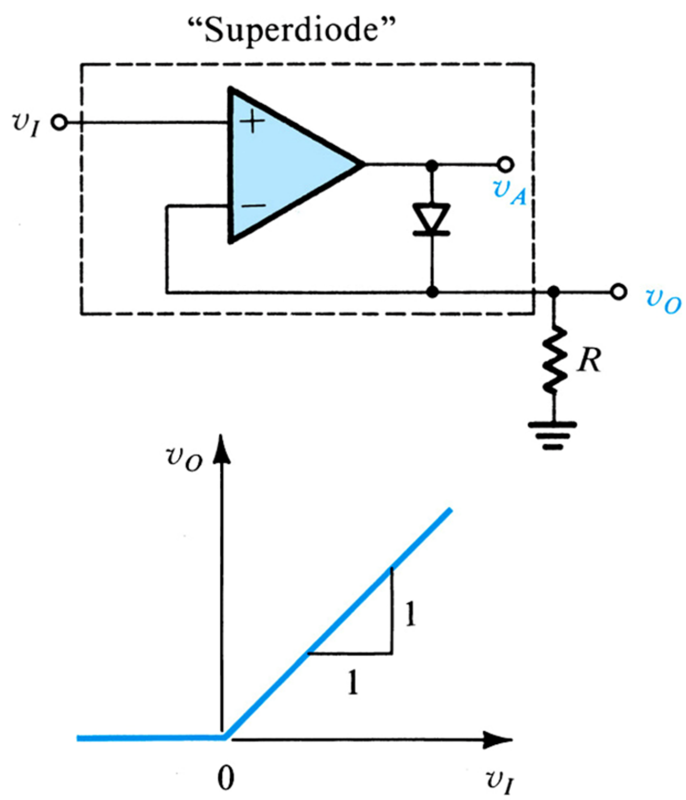
- Output loaded case:





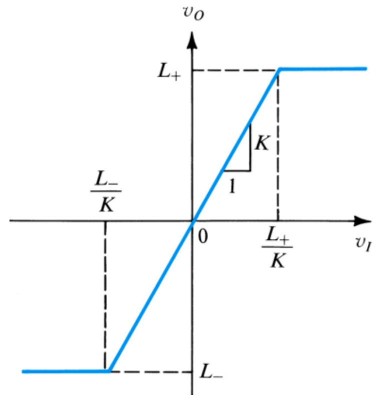
Precision half-wave rectifier – the superdiode

- ❑ Superdiode is composed of a op amp and a diode
- ❑ Superdiode works as an ideal diode with zero turn-on voltage
  - ■ Positive input voltage:
    - ➔Diode turns on
    - ➔Closed-loop op amp with virtual short at input
    - ➔Output voltage follows input voltage
  - ■ Negative input voltage:
    - ➔Diode turns off
    - ➔Op amp in open loop
    - ➔Output voltage is 0 V
- ❑ Rectifier with superdiode can demonstrates better efficiency

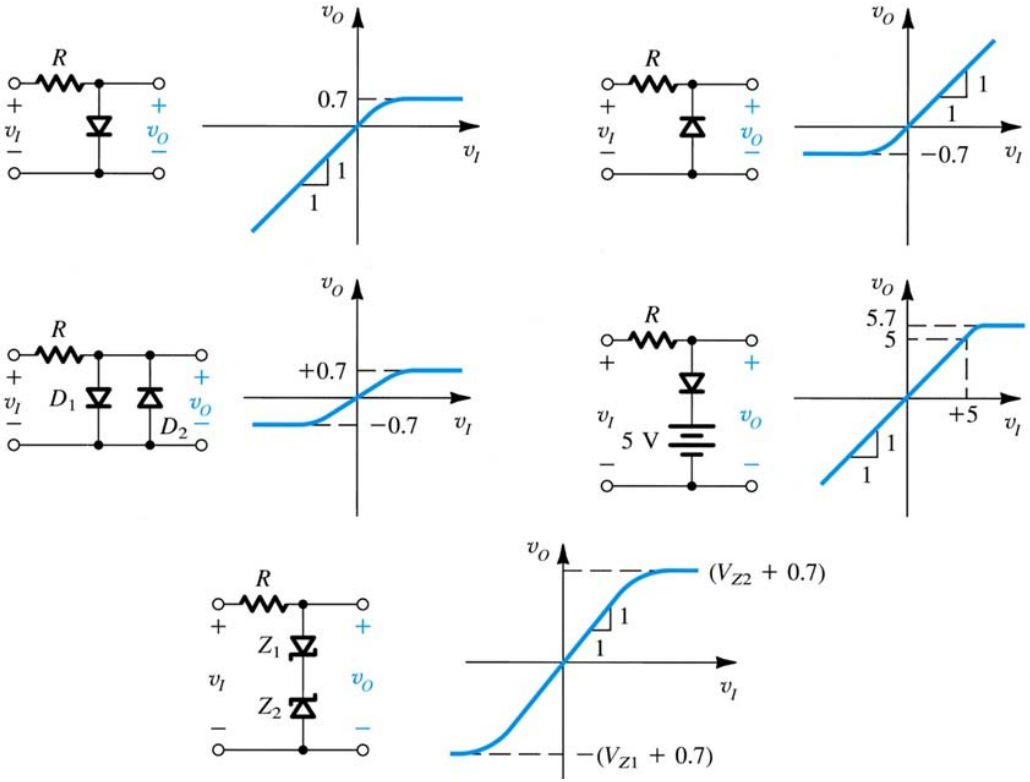


3.6 Limiting and Clamping Circuits

Limiter circuits

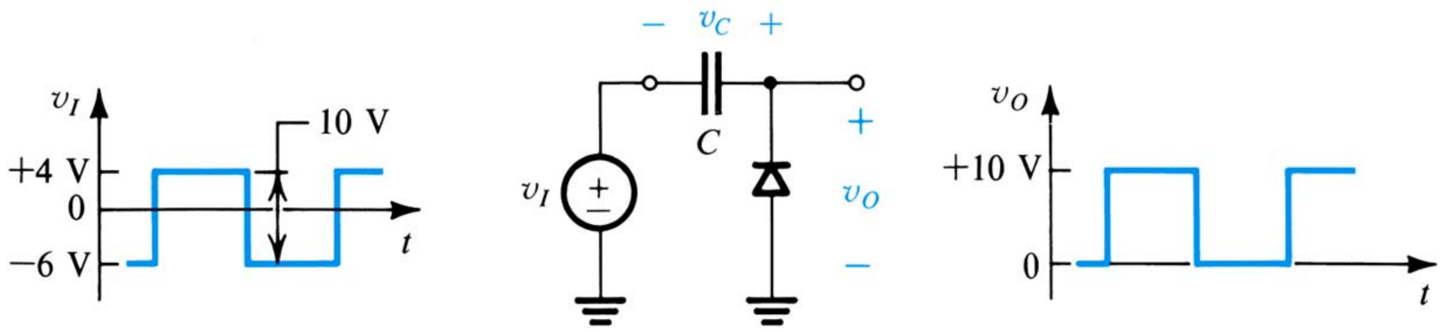


- ❑ For input in a certain range, the limiter acts as a linear circuit.
- ❑ For input exceeds the threshold, the output voltage swing is limited.
- ❑ Classification:
  - ■ Based on transfer characteristics: **hard limiter** and **soft limiter**
  - ■ Based on the polarity: **single limiter** and **double limiter**
- ❑ A variety of limiting circuits by diodes:



Clamped capacitor or DC restorer

❑ Output unloaded case:



❑ Output loaded case: