EEE109: Diode Circuit

Chapter 2

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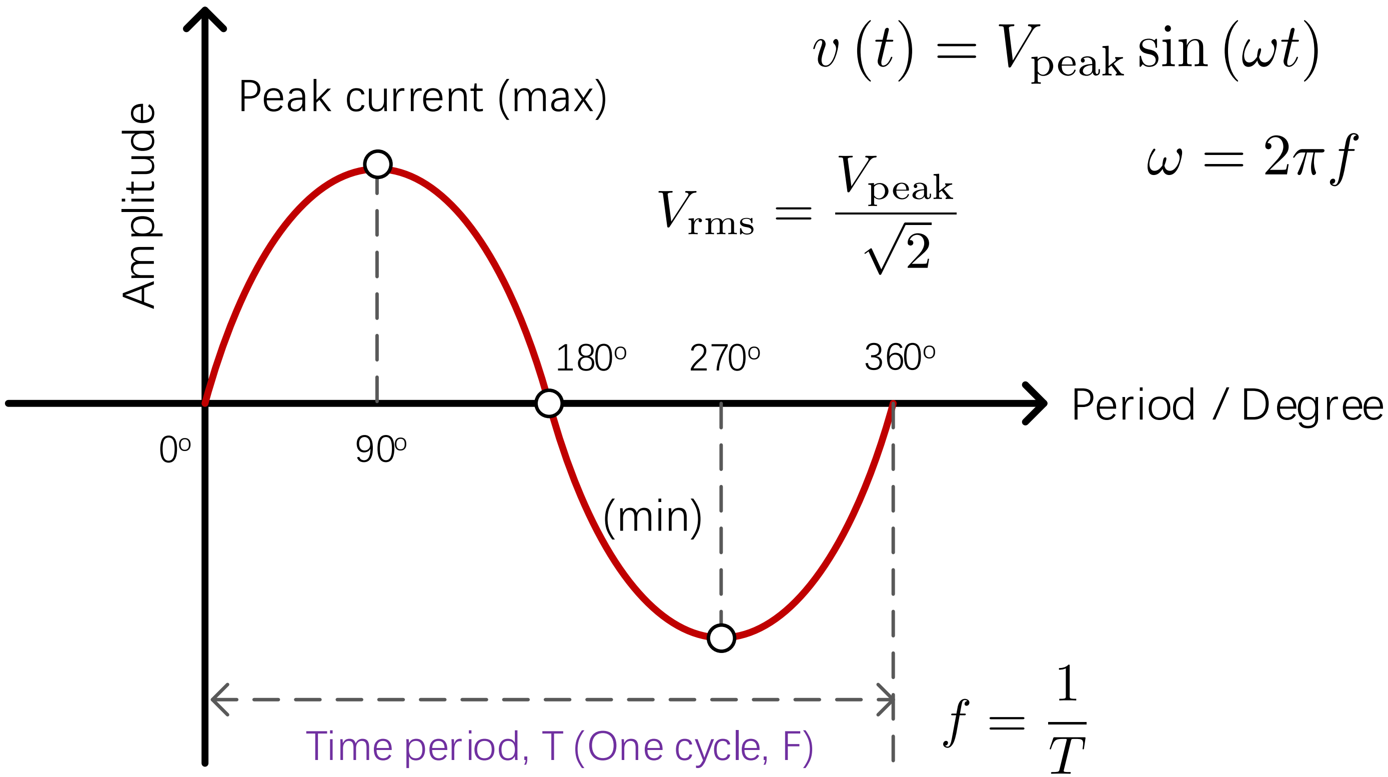
- Apply the features of diodes to create wave shaping circuit such as clippers circuit (限幅电路) and clamper circuit (钳位电路)
- Understand the operation and features of specialized LED circuit

RECTIFIER CIRCUIT (整流电路)

Determine the operation and characteristics of diode rectifier circuits, which form the first stage in the process of converting an **AC** signal into a **DC** signal in the electronic power supply.

AC & DC

- **Alternating Current (AC)** power is the standard electricity and is defined as a flow of the charge that presents a **periodic** change in direction.

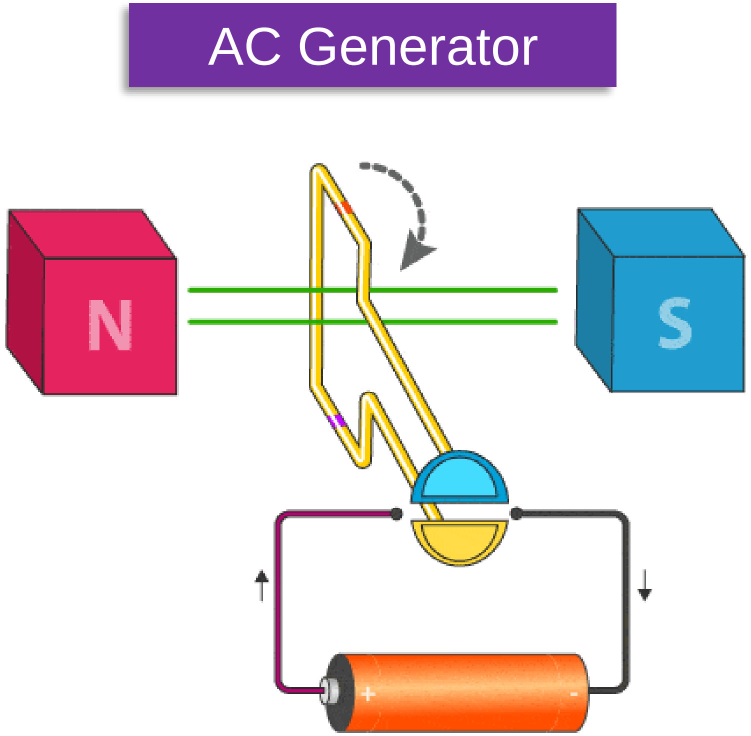


$$v\left(t\right) = V_{\text{peak}} \sin\left(\omega t\right)$$

$$\omega = 2\pi f$$

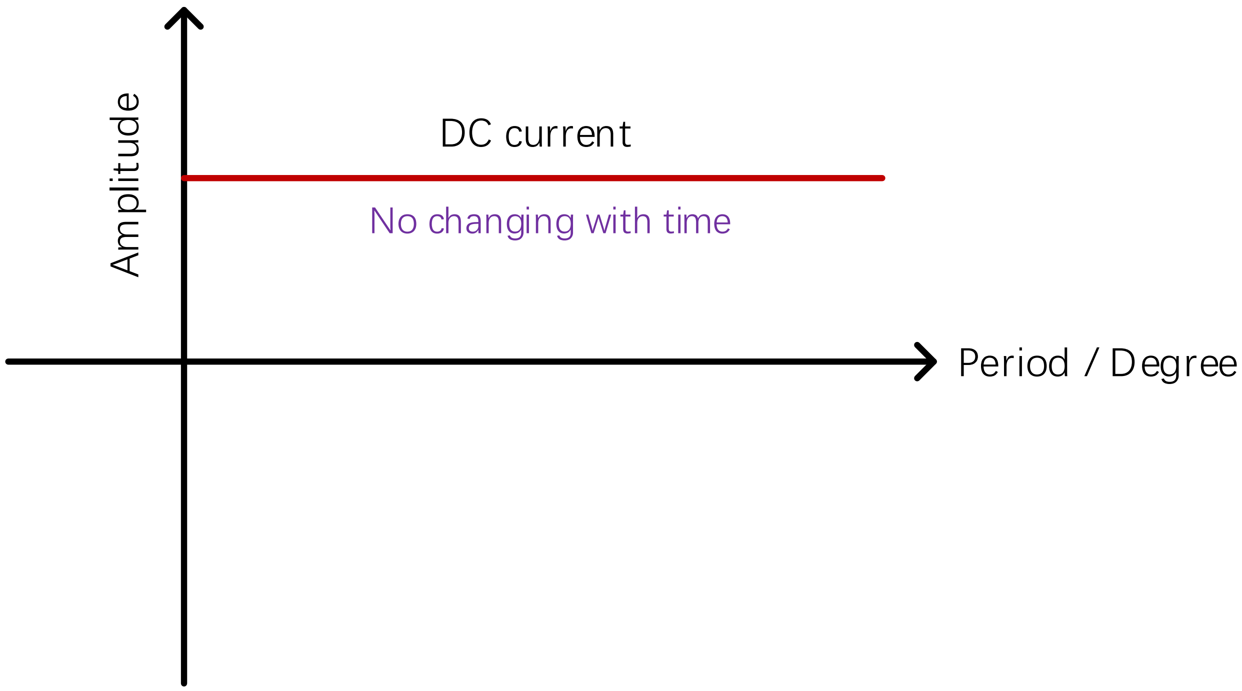
$$V_{\text{rms}} = \frac{V_{\text{peak}}}{\sqrt{2}}$$

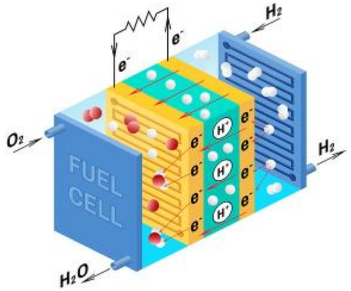
$$f = \frac{1}{T}$$



AC & DC

- **Direct Current (DC)** power is a linear electrical current, it moves in a straight line. DC current can come from multiple sources, including batteries, solar cells, fuel battery and so on. DC power can also be 「made」 from AC power by using a **rectifier**.





rectifier

AC & DC

- Why do we need two different power types?
- One for long-distance delivery (远距离传输), and one for daily use
- **DC**: Most electronics and electrical devices prefer DC power because of its smooth flow and even charging voltage.
- **AC**: It owns the electricity market (电力市场); all power outlets bring power into buildings (school, home or stores) in the form of AC. Since DC is not capable of traveling the same long distances from power plants to the building.

AC for long distance delivery → **rectifier** → **DC for people's daily use**

AC & DC

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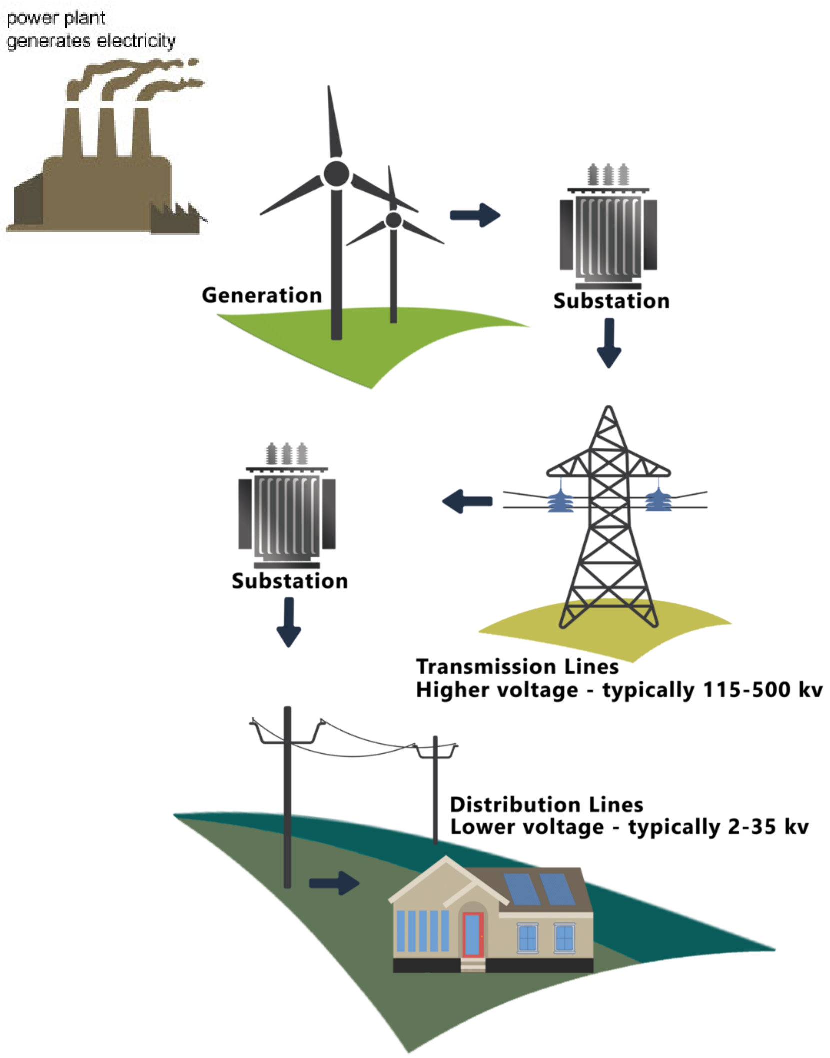

- Transmission lines move large volumes of high-voltage electricity across long distance
- Transmission lines create a networked system by interconnecting a variety of load centers to generating resource.
- Most generators are located long distances from the town and cities.
- Video

Extension of AC & DC

- According the report of International Energy Agency (IEA, 国际能源署), there are still **1** (thousand, million, billion?) people still don't have access to electricity in 2019.

- Why can't we build high voltage power lines there? Because the cost is too high, and the project is too complicated. Many of these people lives in remote villages, mountains and backward counties.

Extension of AC & DC

- But now, we have the distributed solar and wind energy for these remote village.
- The output of the PV system is DC current and voltage. Since the village is small, we can transfer the DC energy directly.

Smart Microgrid
智能微网 or 分布式微网

Electronic Power Supply

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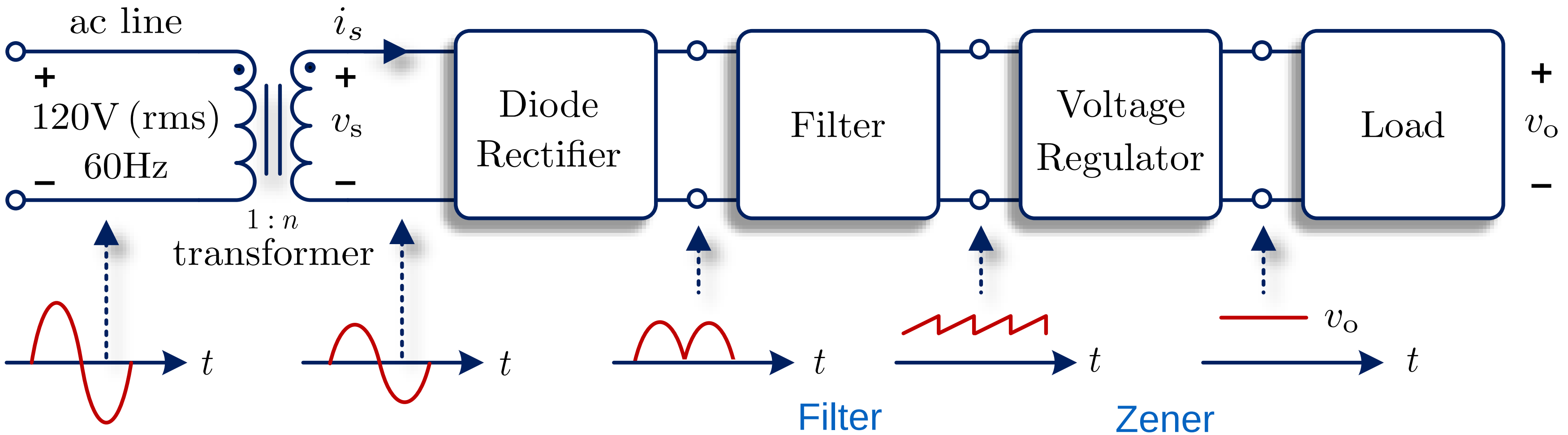
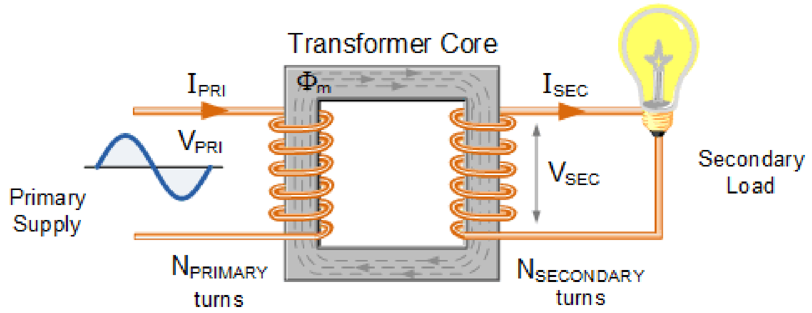
- A DC voltage is required to power essentially electronic device, such TV and phone.
- One application of diode is in the design of rectifier circuit. The whole electronic power supply contains diode **rectifier** **filter** and **voltage regulator**.
- Rectifier is classified as 「**Half-wave**」 and 「**Full-wave**」. Half-wave is being the **simpler** but full-wave being more **efficient**.



Filter Zener

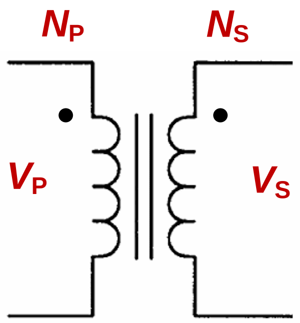
Electronic Power Supply

- A transformer is a passive component that transfers electrical energy from one electrical circuit to another circuit.
- Transformers are used to change AC voltage levels that step-up (升压) or step-down (降压) the voltage level.

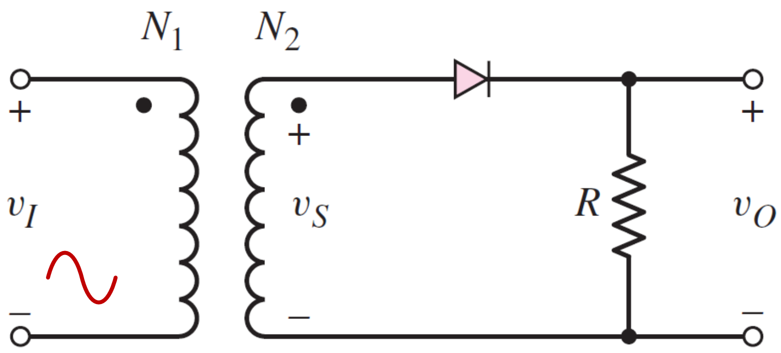


$$\frac{V_P}{V_S} = \frac{N_P}{N_S} \Rightarrow V_S = V_P \frac{N_S}{N_P}$$

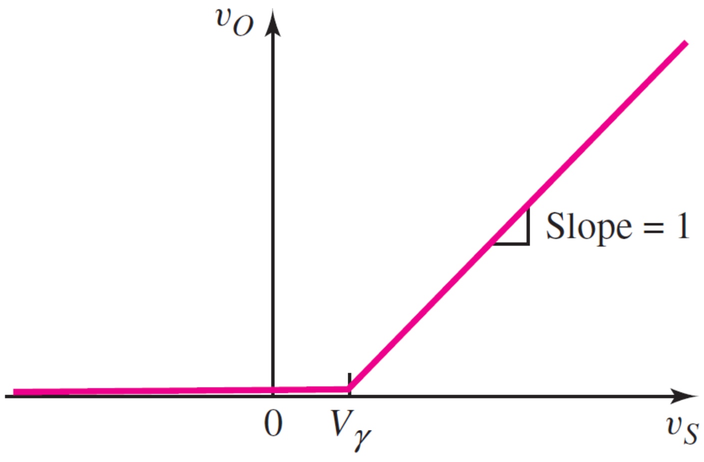
Voltage ratio equation



Half-Wave Rectifier



Half-wave rectifier



Voltage transfer feature

V_I: **I** here is for input, input voltage

V_S: **S** here is for secondary side voltage of transformer

V_o: **O** here is for output, output voltage

We using piecewise linear model to analyze it, and assume the forward resistance of diode is zero $r_f = 0$

- For $V_s \le V_\gamma$ — the diode is "OFF"
  - Open circuit, output voltage $V_o = 0$
- For $V_s > V_\gamma$ — the diode is "ON"
  - Output voltage $V_o = V_s - V_\gamma$ ⇨ $I_D = \dfrac{V_s - V_\gamma}{R}$

Half-Wave Rectifier

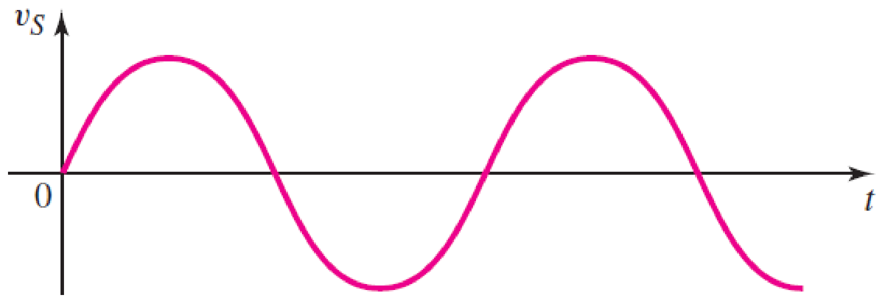
- If V_s is a sinusoidal signal

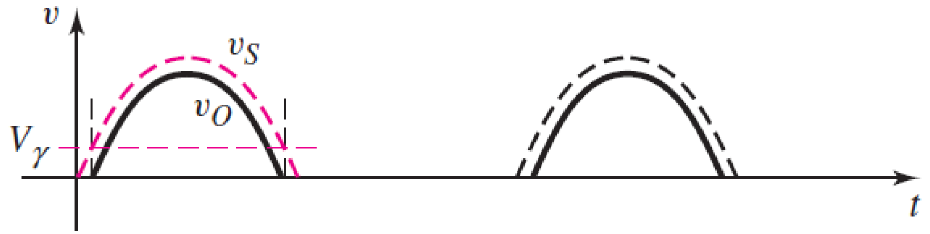
$$V_s \leq V_\gamma \rightarrow V_o = 0$$

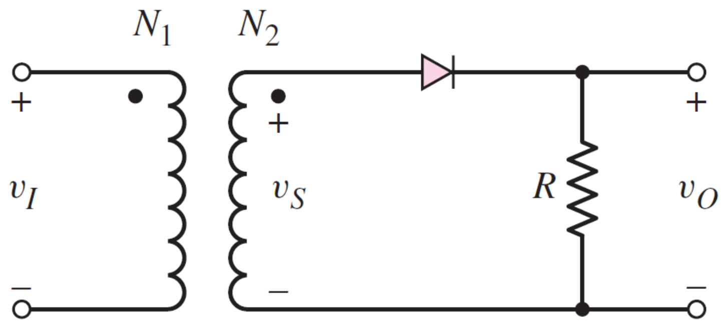
$$V_s > V_\gamma \rightarrow V_o = V_s - V_\gamma$$

- The input signal value is rectified, since the output voltage appears only during the positive cycle, the circuit is called a half-wave rectifier.

- **Drawback**: The load lost half of the power, whole circuit is low efficient

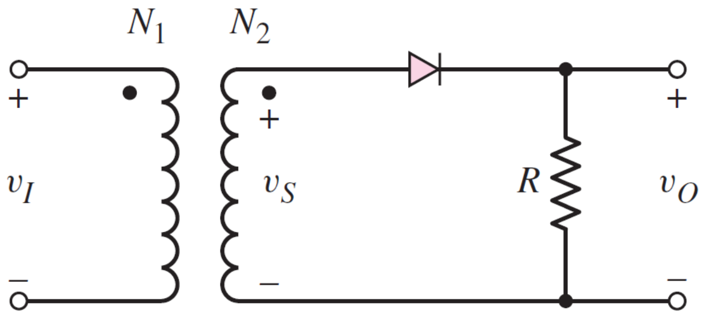






Reinforce Your Learning 🤖

- A half-wave rectifier such as shown below has 2kΩ load. The input source is 120V (rms), 60Hz signal and the transformer is a 10:1 step down transformer. The diode has a cut-in voltage V_γ=0.7V (inside resistance is r_f = 0Ω)

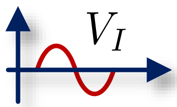


(a) What is the peak output voltage and peak diode current ?

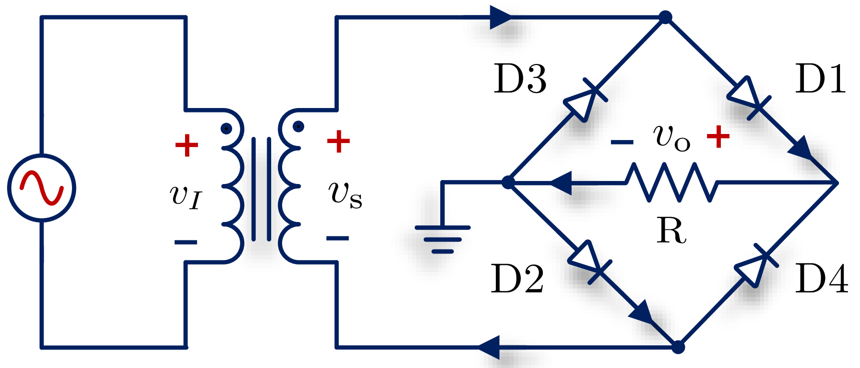
- **Solution (a)**

Full-Wave Rectifier - Type I

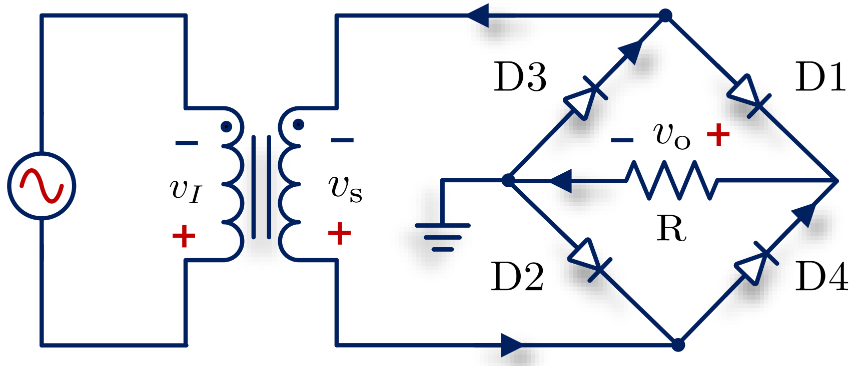
- The full-wave rectifier inverts the negative portions of the sine wave, a full-wave power can reach terminal load. The following architecture is called 「 **bridge rectifier** 」

- If the input voltage is a sine-wave signal 

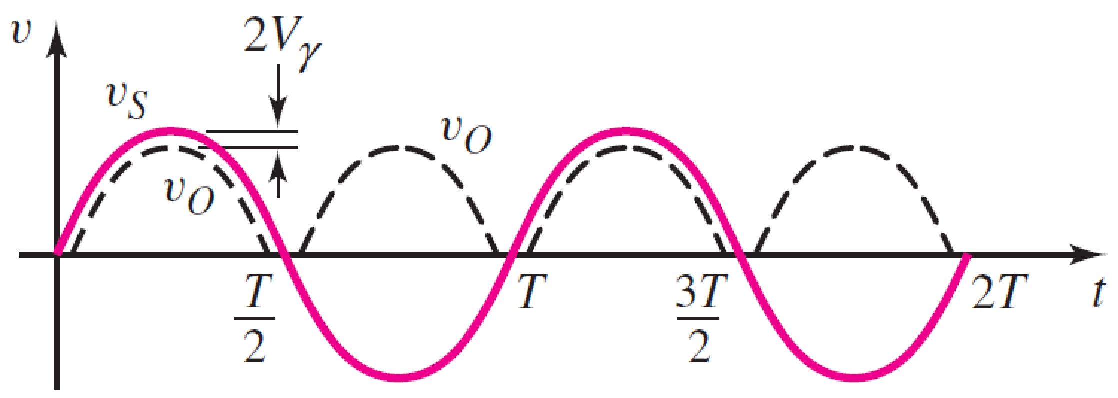
- When V_I is positive
  - D1 and D2 are "ON" state
  - D3 and D4 are "OFF" state

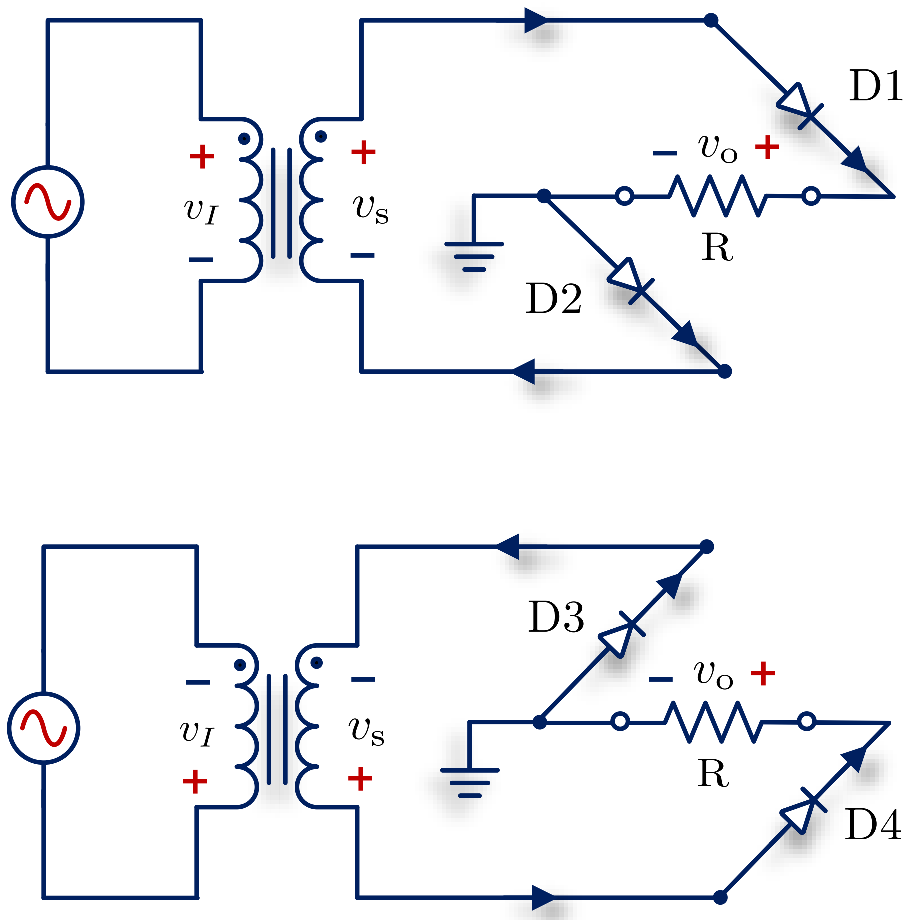


- When V_I is negative
  - D1 and D2 are "OFF" state
  - D3 and D4 are "ON" state



Full-Wave Rectifier - Type I





- The current flows through load ***R*** in the **same** direction, result in an output voltage:

$$V_o = V_s - 2V_\gamma$$

Full-Wave Rectifier - Type I

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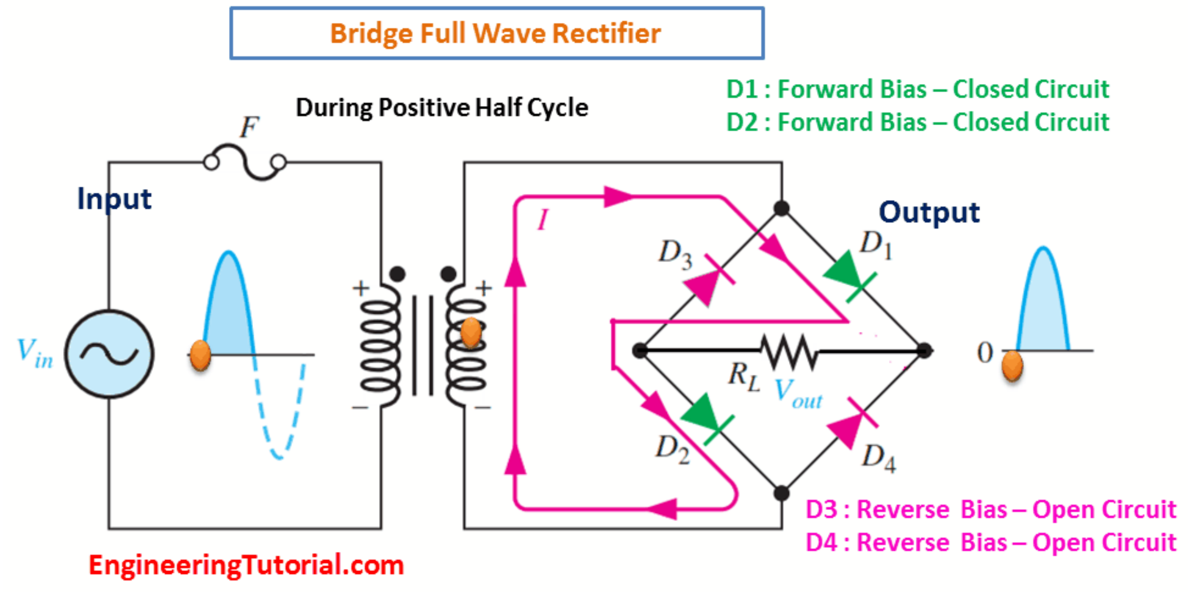
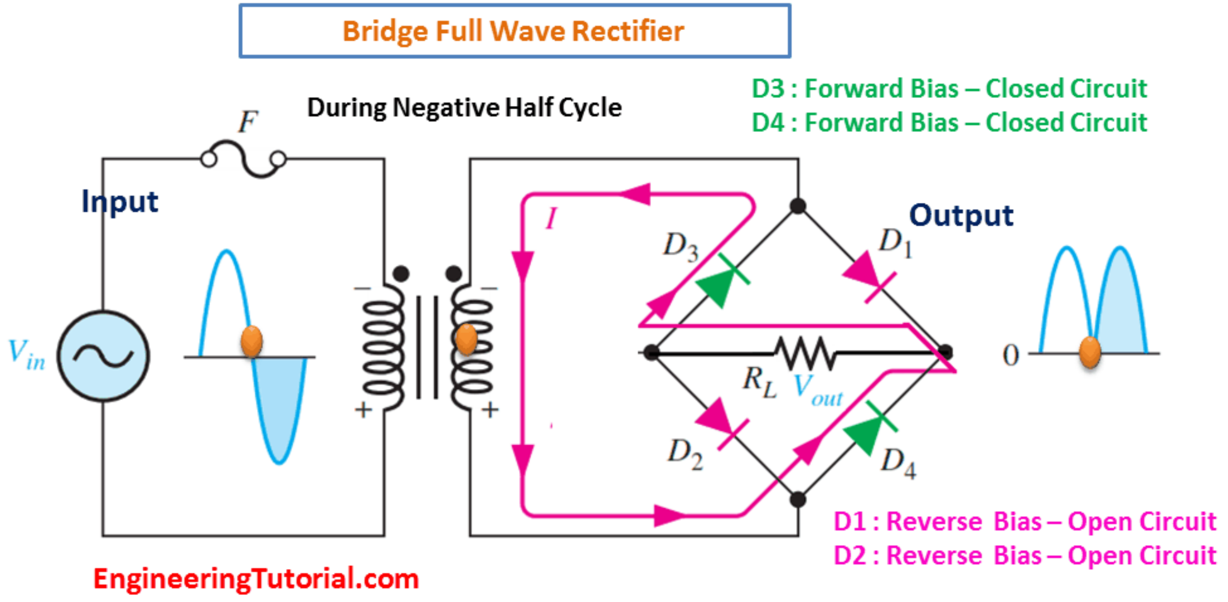
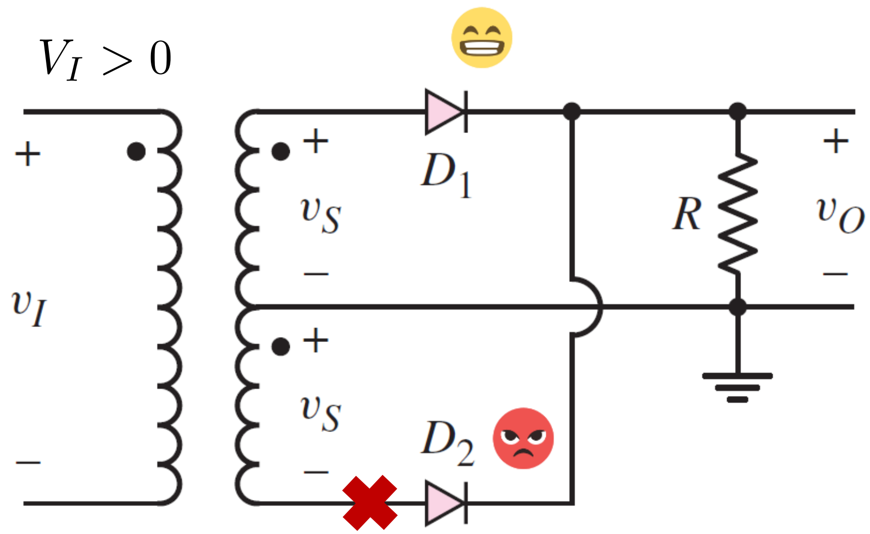


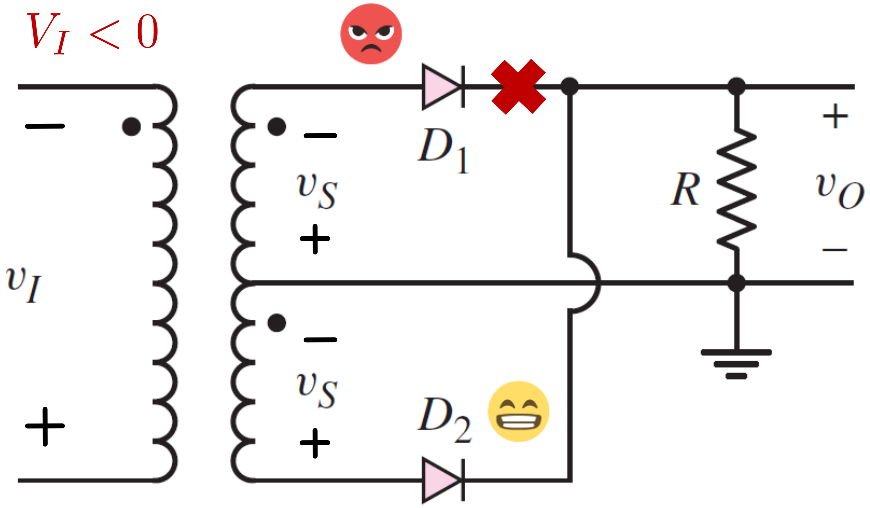


- Source from: https://engineeringtutorial.com/bridge-full-wave-rectifier-operation/
- Author: Bharadwaj

Full-Wave Rectifier - Type II

- A full wave rectifier circuit with center-tapped transform, providing a **equal** voltage on secondary side. This architecture is called 「**Centre-tapped rectifier**」
- When V_I is positive
  - V_s is positive, D1 is “ON”, D2 is “OFF”
  - V_o is positive
- When V_I is negative
  - V_s is negative, D1 is “OFF”, D2 is “ON”
  - V_o is still positive





Full-Wave Rectifier - Type II

- For $V_s > V_\gamma$: D1 is “ON”

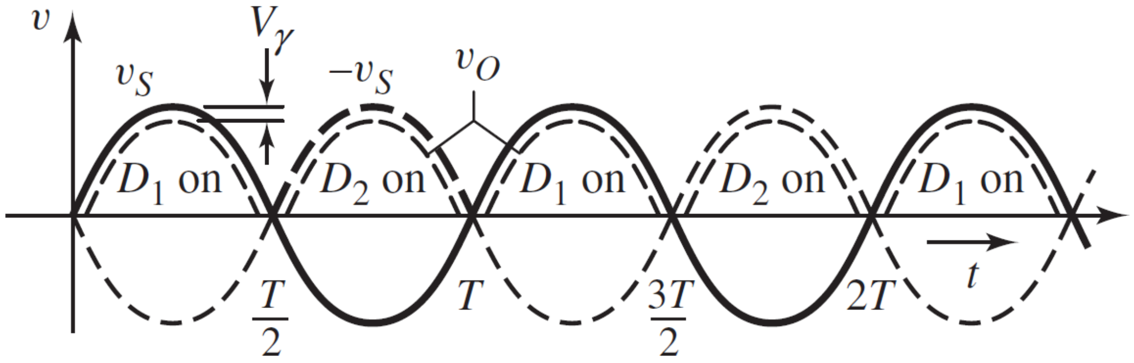
$$\Rightarrow \quad V_o = |V_s| - V_\gamma$$

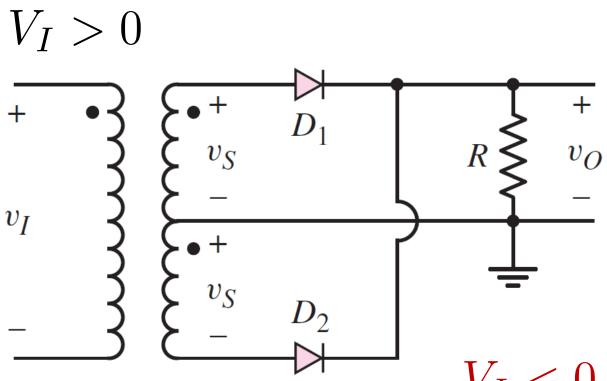
- For $V_s < -V_\gamma$: D2 is “ON”

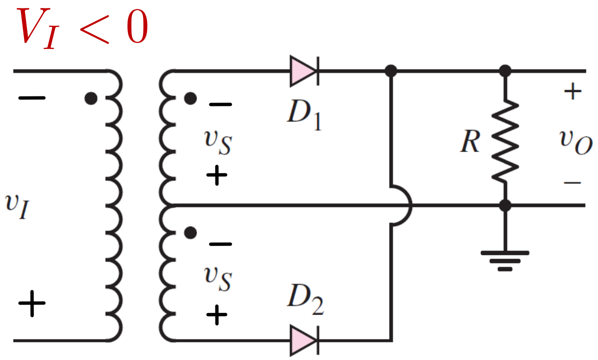
$$\Rightarrow \quad V_o = |V_s| - V_\gamma$$

- For $-V_\gamma \le V_s \le V_\gamma$: D1 and D2 are “OFF”

$$\Rightarrow \quad V_o = 0$$







Full-Wave Rectifier - Type II

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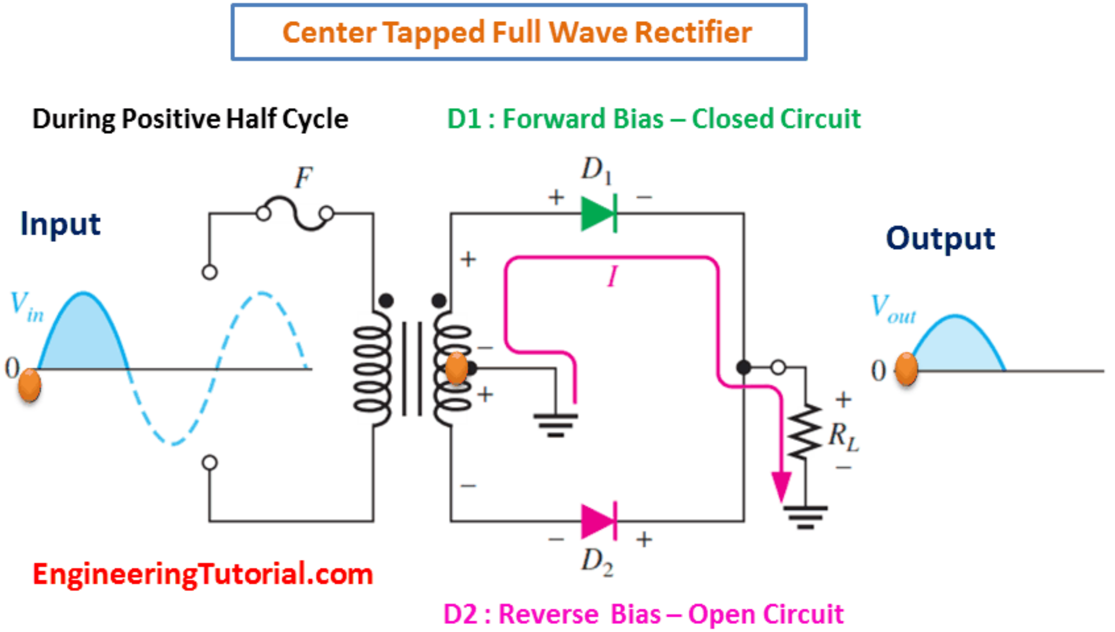

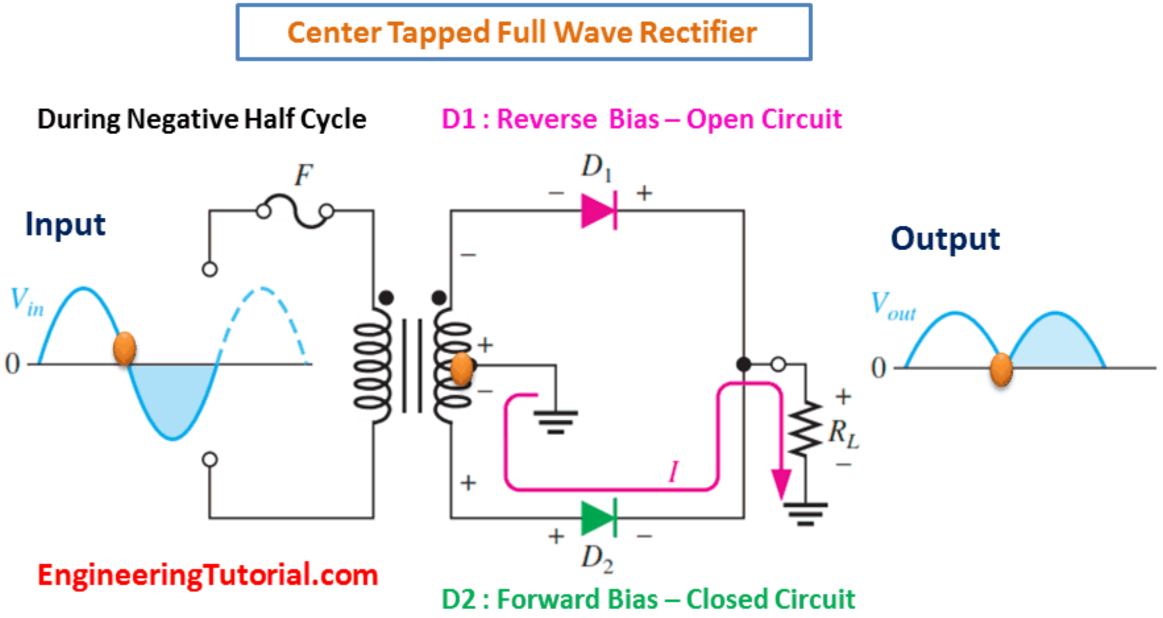

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Reinforce Your Learning 🤖

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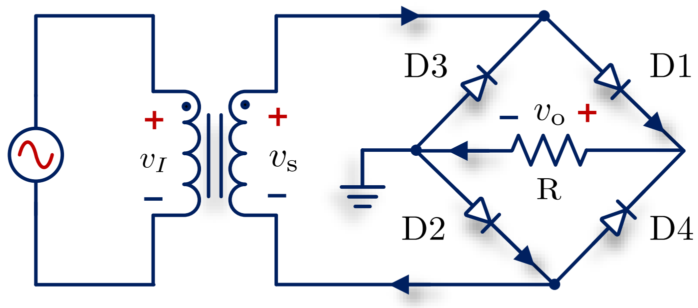
(a) What is the peak output voltage and peak output current ?



- **Solution (a)**

RECTIFIER CIRCUIT (整流电路)

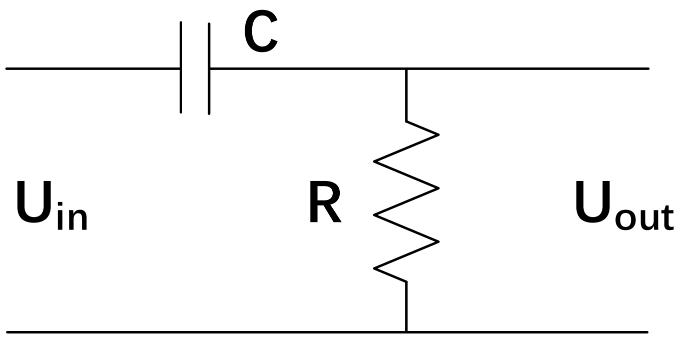
Understand the working theory of filter circuit, including the content of ripple voltage and diode current

Capacitor

- DC current can not flow through the capacitor, but AC current can (通交流，阻直流). Why? Back to the equation

$$C = \frac{Q}{U} \Rightarrow Q = It \Rightarrow I_c = C\frac{dU_c}{dt}$$

$$X_c = \frac{1}{2\pi f C} \Rightarrow$$ Capacitive reactance (容抗), the unit is Ω

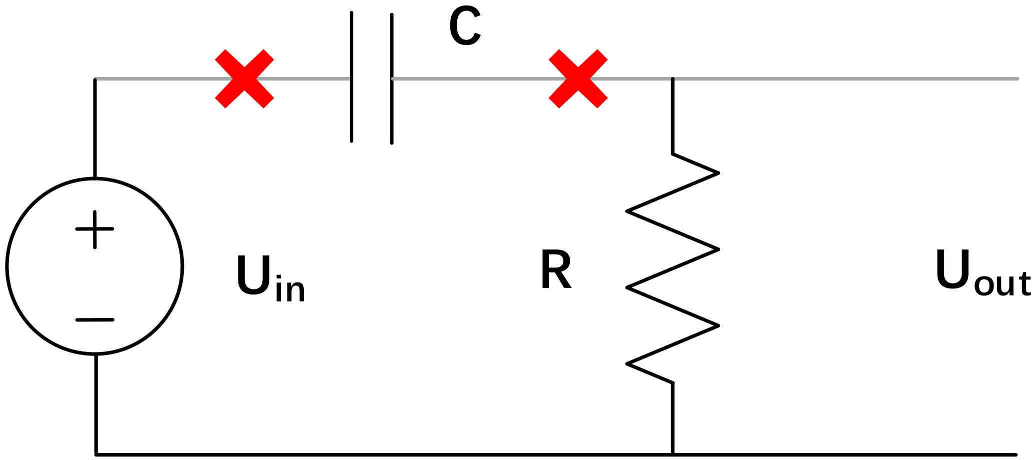


$$U_{out} = \frac{R}{R + X_c} U_{in} \Rightarrow \boxed{U_{out} = \frac{R}{R + \frac{1}{2\pi f c}} U_{in}}$$

Capacitor

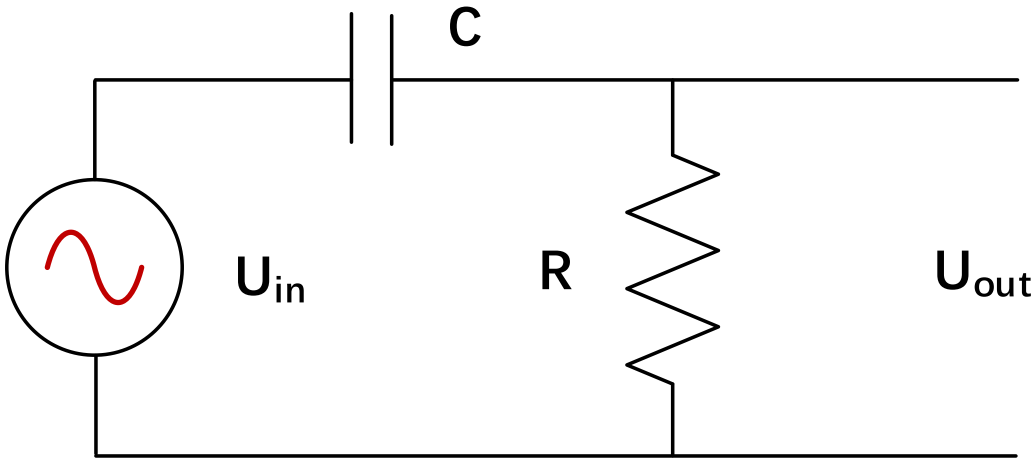
- If U_{in} is DC source, the frequency is infinity approaches **0**

$$U_{out} = \lim_{f \to 0} \frac{R}{R + \frac{1}{2\pi f c}} U_{in} = 0$$



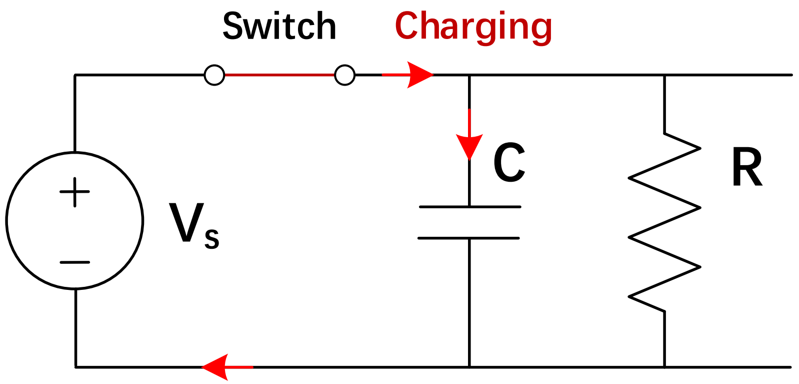
- If U_{in} is AC source, the frequency is a certain number or to infinite

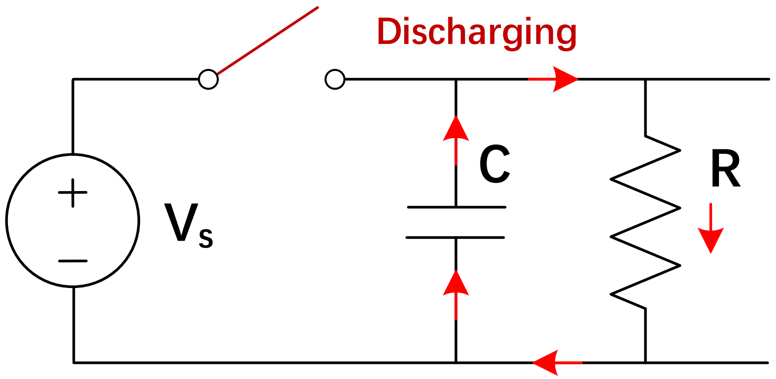
$$U_{out} = \lim_{f \to \infty} \frac{R}{R + \frac{1}{2\pi f c}} U_{in} = U_{in}$$



Capacitor

- Capacitor can store energy in the form of an electrical charge producing a **potential difference** (V) across the plate. It likes a small rechargeable battery. Since it is a "battery", it must has two processes: Charging (充电) and Discharging (放电)





V_S Source voltage

V_C Voltage across capacitor

t Time in seconds

τ Time constant

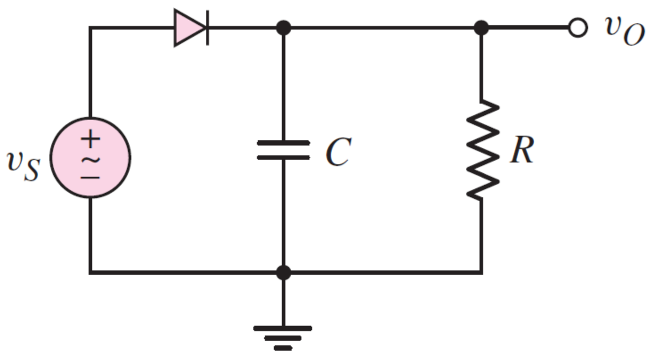
$$V_C = V_S \left(1 - e^{\frac{-t}{\tau}}\right)$$

$$V_C = V_S e^{\frac{-t}{\tau}}$$

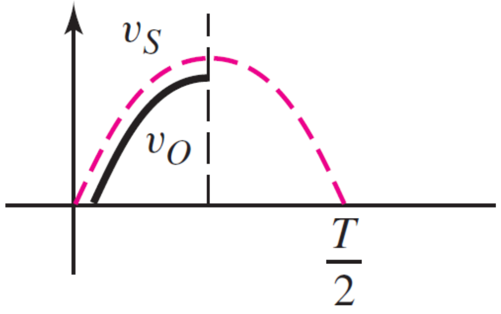
$$\tau = RC$$

Filter Circuit

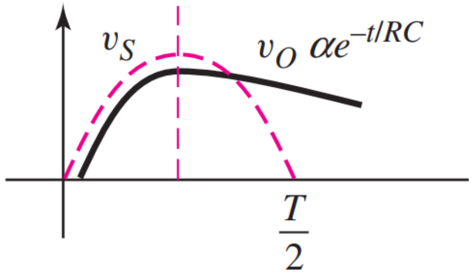
- **Filter Circuit**: A capacitor is in parallel with the load resistor with a AC input source



Charging



Discharging



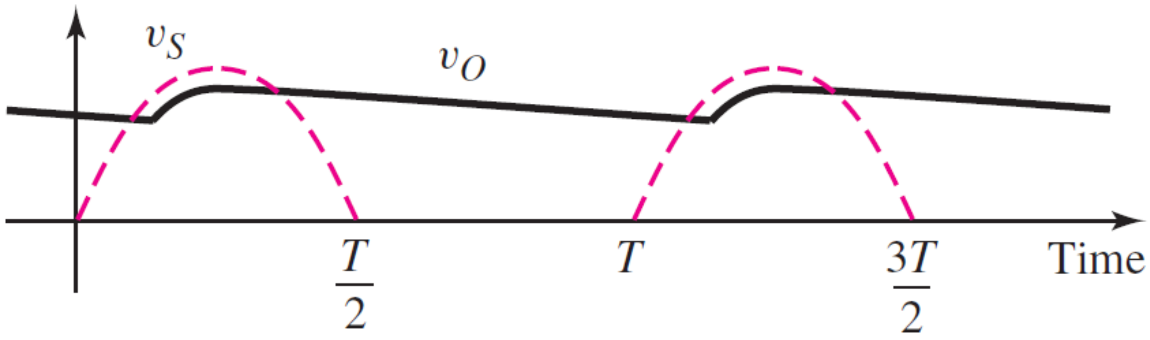
- At the very beginning, source voltage is charging the capacitor, meanwhile, the output voltage is equal to

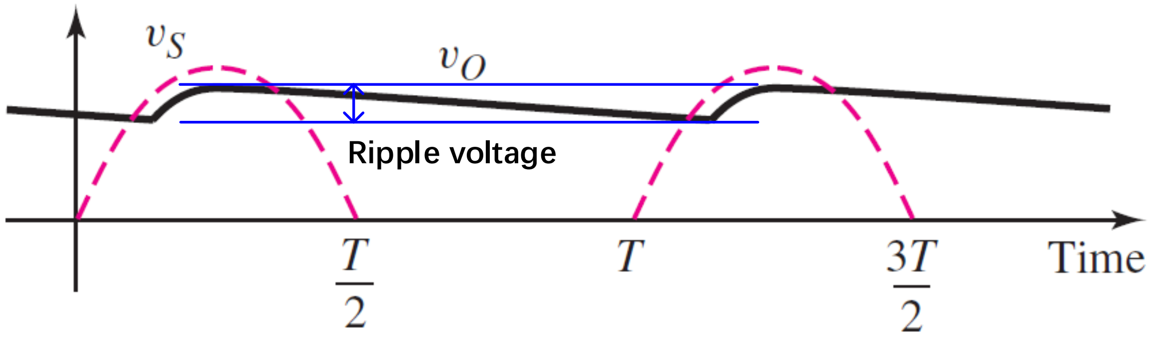
$$V_o = V_S - V_\gamma$$

- When the source voltage is going down, the capacitor is supporting the load to keep a stable voltage, diode is cut-off

$$V_o = (V_S - V_\gamma)\, e^{-\left(\frac{t}{RC}\right)}$$

Filter Circuit



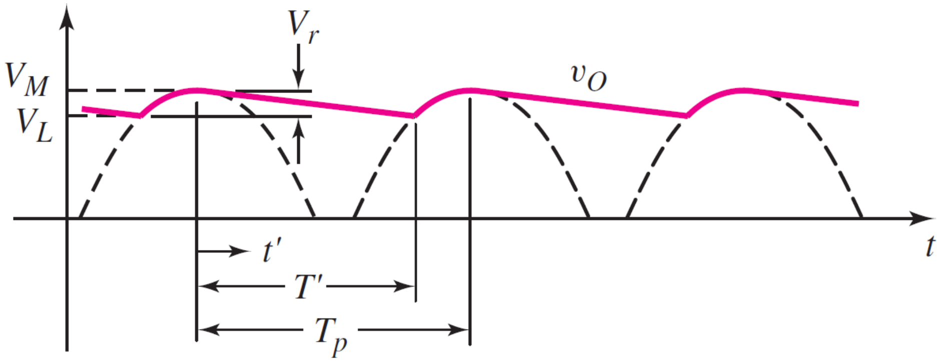


- During the next positive cycle of the input voltage, there is a point at which the input voltage is greater than the capacitor voltage, and the diode turns back on, then recharge the capacitor.

- From start of discharging to end of the discharging, there is a differential voltage, which is called **ripple voltage**

$$V_r = \frac{V_M}{2fRC}$$

How to derive it?



Example of full-wave rectifier with RC filter

$$V_o(t) = V_M e^{\frac{-t}{RC}}$$

$$V_L = V_M e^{\frac{-T'}{RC}}$$ The smallest output voltage

Ripple voltage

$$V_r = V_M - V_L = V_M \left(1 - e^{-T'/RC}\right)$$

- If we assume $T' \ll RC$

$$e^{-T'/RC} \cong 1 - (T'/RC)$$

$$V_r \cong V_M (T'/RC)$$

- Assume ripple effect is small, then as an approximation, let $T' = T_P$

$$\boxed{V_r = \frac{V_M}{2fRC}}$$

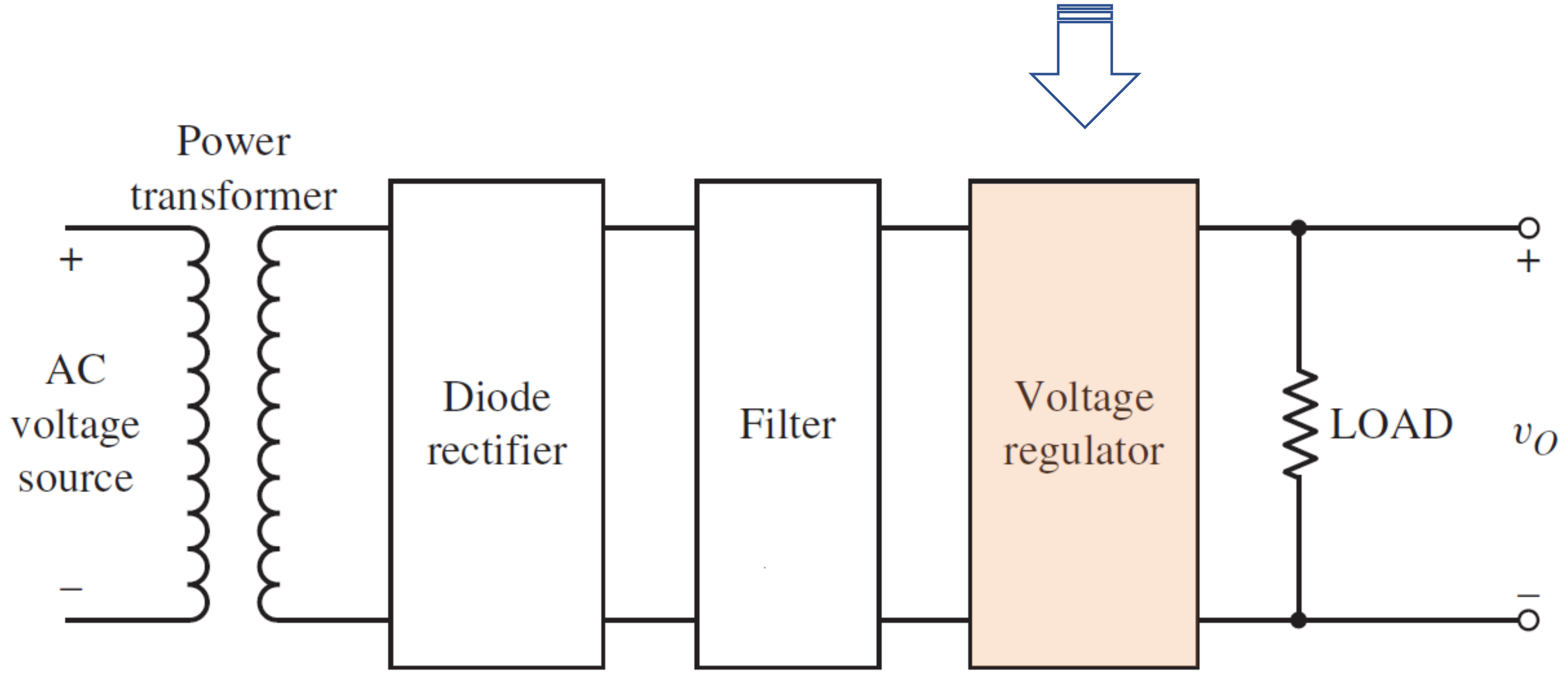
$$f = \frac{1}{2T_p}$$

VOLTAGE REGULATOR (整流电路)

Apply the characteristics of the Zener diode to a Zener diode voltage regulator circuit

Voltage Regulator

- A Zener diode has a constant breakdown voltage (nearly...)
- A **Zener diode** is useful in a voltage regulator, or a constant-voltage reference circuit

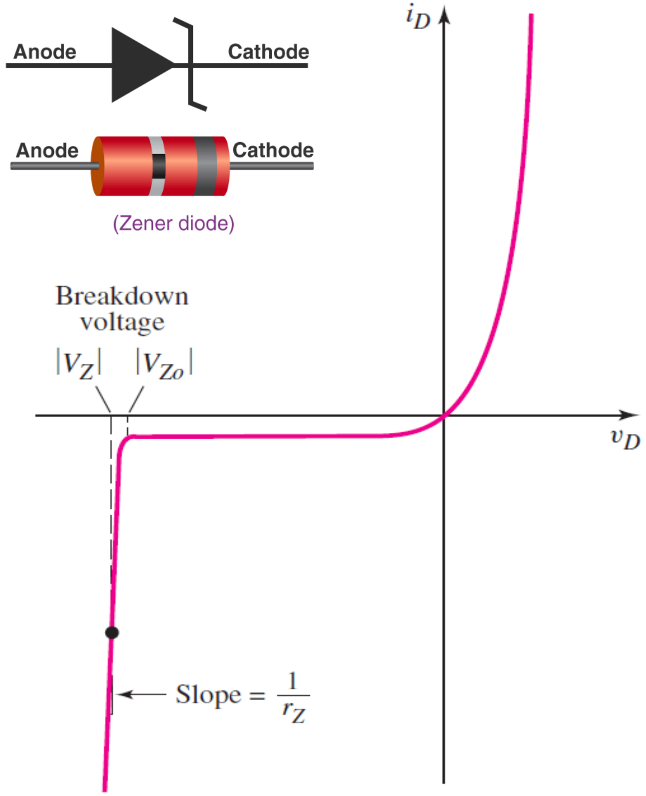


Zener Diode (齐纳二极管)

- A Zener Diode is a silicon semiconductor device that permits current to flow in either a forward or reverse direction. Usually operated in reverse bias region (反向偏置区域) near the breakdown voltage V_z

- The breakdown voltage is constant over a wide range of current and temperature

- Zener Diode can be used as a Constant-Voltage-Reference in a circuit, a voltage regulator



Voltage Regulator Circuit

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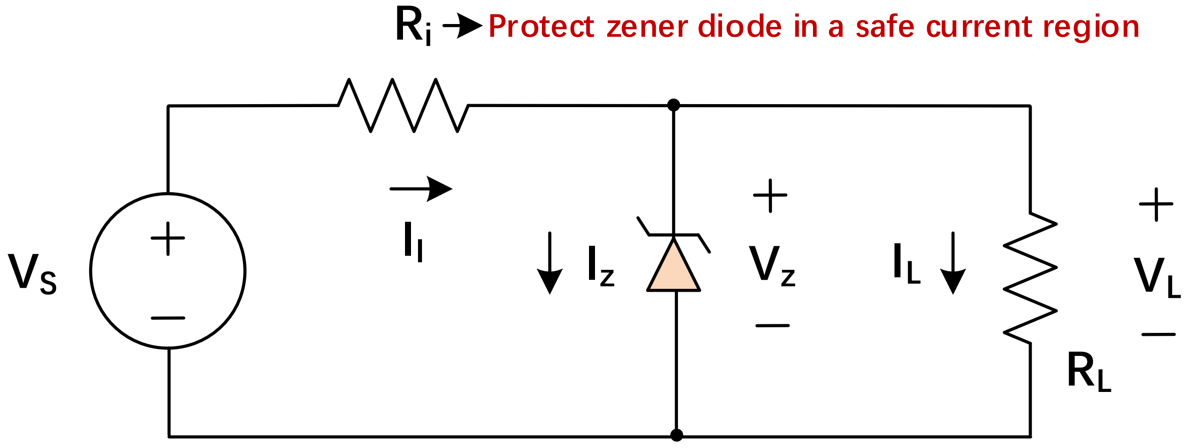
- For the voltage regulator circuit, the output voltage should remain constant, even when the output resistance and input voltage are changed.

$$I_Z = I_I - I_L$$

$$I_Z = \frac{V_S - V_Z}{R_i} - I_L$$

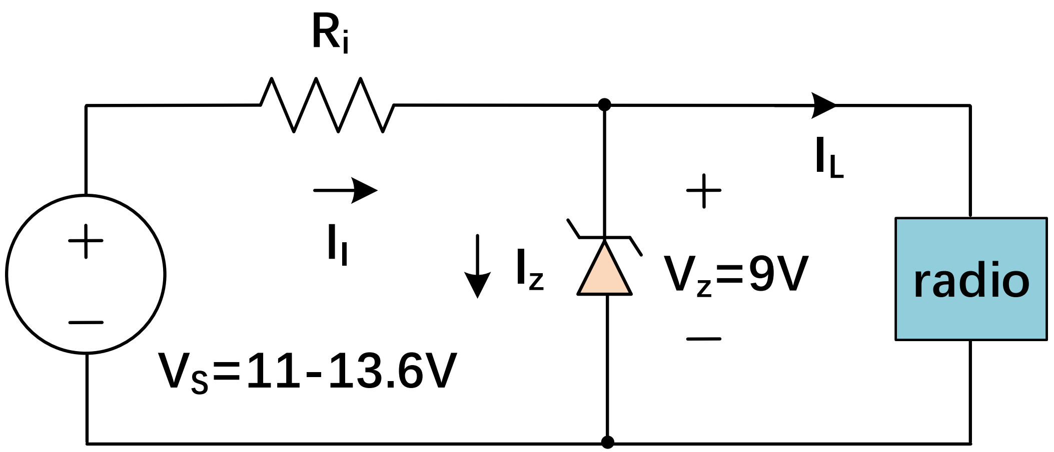


- For proper operation, diode remain in breakdown region. There should be a safe diode current region:

$$I_Z(\min) = \frac{V_S(\min) - V_Z}{R_i} - I_L(\max) \qquad I_Z(\max) = \frac{V_S(\max) - V_Z}{R_i} - I_L(\min)$$

Reinforce Your Learning 🤖

- **Demo example:** The voltage regulator is to power a car radio at V_L = 9V from an battery whose voltage may vary between 11 and 13.6V. The current in the radio will vary between (0) off to 100mA (Full volume). How to choose the value of R_i ? Assume $I_z(\min) = 0.1*I_z(\max)$



$$V_L = V_Z = 9V$$

$$I_Z(\min) = \frac{V_S(\min) - V_Z}{R_i} - I_L(\max)$$

$$I_Z(\max) = \frac{V_S(\max) - V_Z}{R_i} - I_L(\min)$$

$$\Rightarrow \boxed{R_i = 15.3\Omega}$$

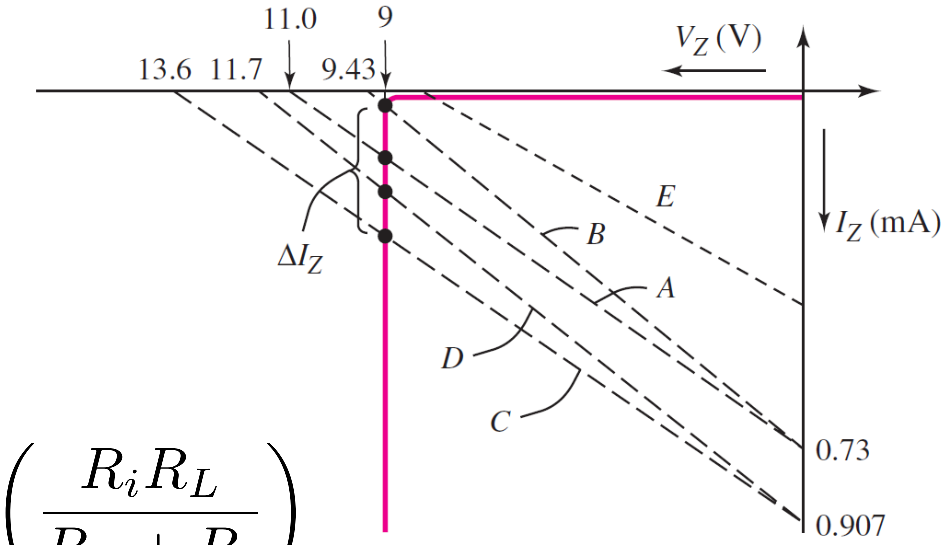
$$I_Z(\min) = \frac{11-9}{15.3} - 0.1 = 30.7mA$$

$$I_Z(\min) = \frac{13.6-9}{15.3} - 0 = 300mA$$

Breakdown Region

- How can we ensure a Zener diode in a voltage regulator circuit work in the **Breakdown region** ?

- **Load Line method**



$$\frac{V_{PS} - V_Z}{R_i} = I_Z + \frac{V_Z}{R_L} \Rightarrow V_Z = V_S \left(\frac{R_L}{R_L + R_i} \right) - I_Z \left(\frac{R_i R_L}{R_L + R_i} \right)$$

$$A: V_S = 11V, R_L = \infty, R_i = 15\Omega, V_Z = 11 - I_Z\,(15)$$

$$B: V_S = 11V, R_L = 90, R_i = 15\Omega, V_Z = 9.43 - I_Z\,(12.9)$$

$$C: V_S = 13.6V, R_L = \infty, R_i = 15\Omega, V_Z = 13.6 - I_Z\,(15)$$

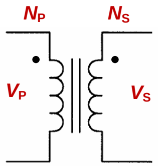
$$D: V_S = 13.6V, R_L = 90, R_i = 15\Omega, V_Z = 13.6 - I_Z\,(12.9)$$

- What about this case, in or not?

$$\Rightarrow \begin{aligned} V_S &= 11V \\ R_i &= 25\Omega \\ R_L &= 90\Omega \end{aligned}$$

$$V_Z = 8.61 - I_Z\,(19.6)$$

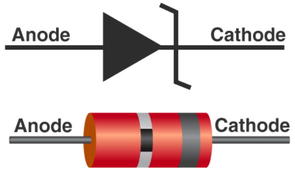
$$\frac{V_P}{V_S} = \frac{N_P}{N_S} \Rightarrow V_S = V_P \frac{N_S}{N_P}$$



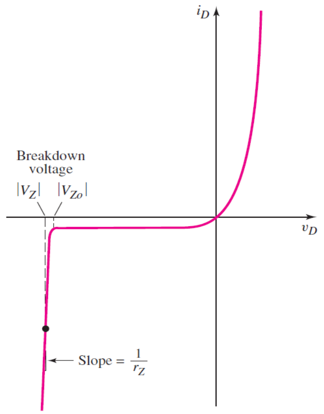
Guanying Chu

AC-DC

- **Transformer**
  - Step down and up the voltage
- **Diode Rectifier**
  - Half-wave rectifier
    - Simple
    - But Low efficient
  - Full-wave rectifier
    - Full-bridge
      - $V_o = V_s - 2V_\gamma$
    - Center-Tapped
      - $V_o = V_s - V_\gamma$
- **Filter Circuit**
  - Achieve by Capacitor
    - Ripple voltage
      - $V_r = \dfrac{V_M}{2fRC}$
- **Voltage regulator**
  - Achieve by Zener Diode
    - Work in reversed-bias region, breakdown voltage V_Z



(Zener diode)

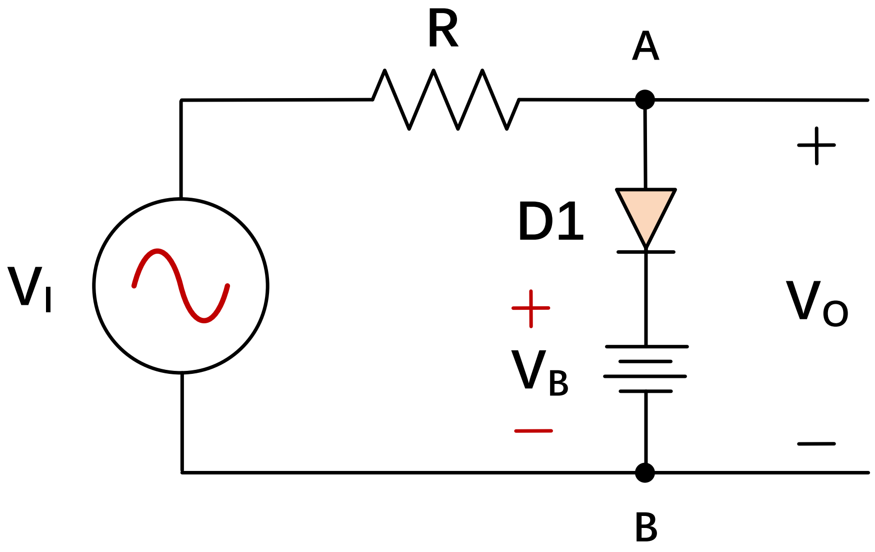


Clipper And Clamper Circuit

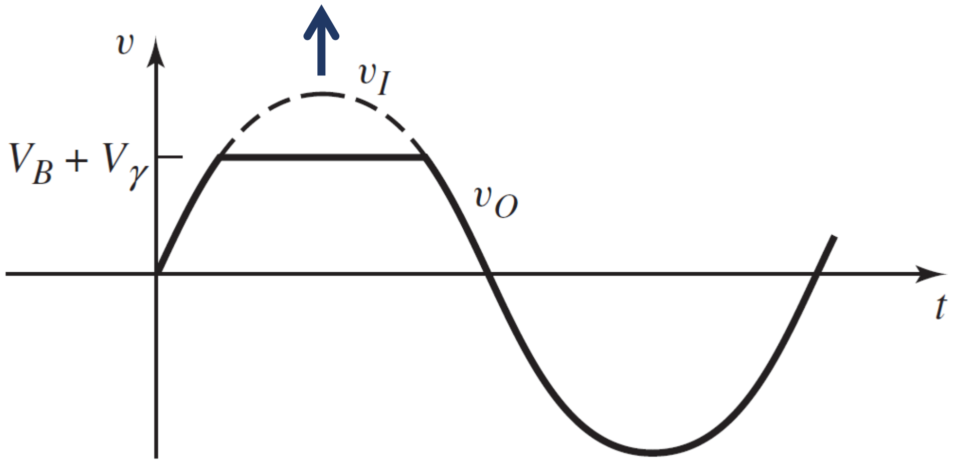
Apply the characteristics of diodes to create wave shaping circuits known as clippers and clampers.

Clipper Circuit

- Clipper circuit, also called limiter circuit, are used to eliminate portions of a signal that are above or below a specified level
- When $V_I < V_B + V_\gamma$
  - Diode D1 is "OFF"
  - No current across **R**
  - Voltage drop across **R** is zero
- When $V_I \geq V_B + V_\gamma$
  - Diode D1 is "ON"
  - V_o is clipped
  - Output voltage is ⇨ $V_o = V_B + V_\gamma$



This part is clipped

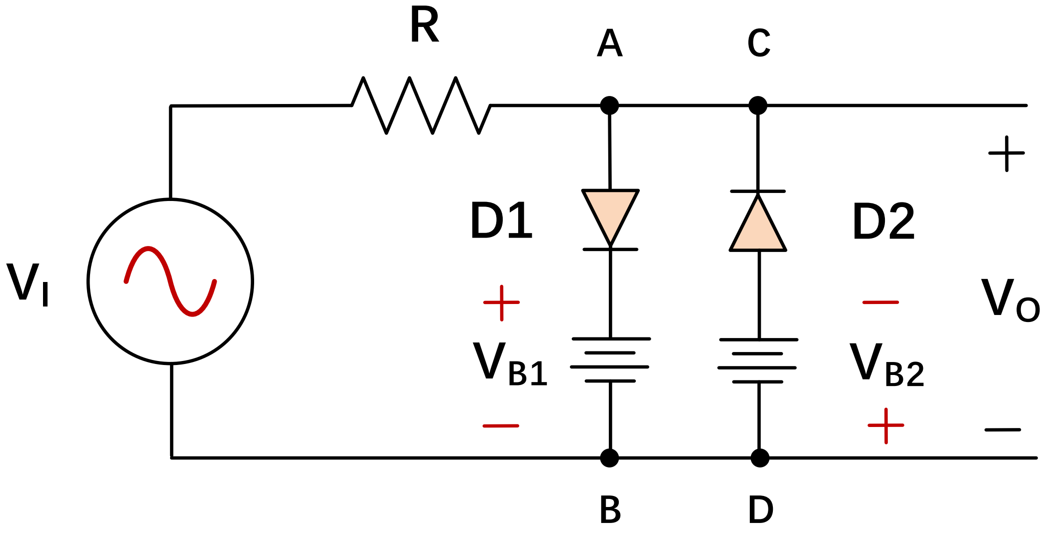


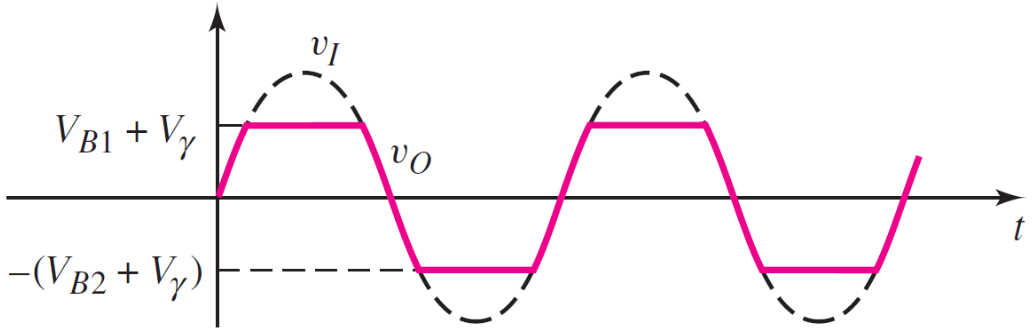
Clipper Circuit (Two parallel paths)

- Positive and negative clipping can be performed by using a double limiter or a parallel-based clipper

- When $V_I \geq -(V_{B1} + V_\gamma)$
  - Diode D2 is "OFF"
  - No current across **R**
  - Voltage drop across **R** is zero

- When $V_I < -(V_{B2} + V_\gamma)$
  - Diode D2 is "ON"
  - V_o is clipped
  - Output voltage is ⇨ $V_I = -(V_{B2} + V_\gamma)$





Clipper Circuit (Series-based)

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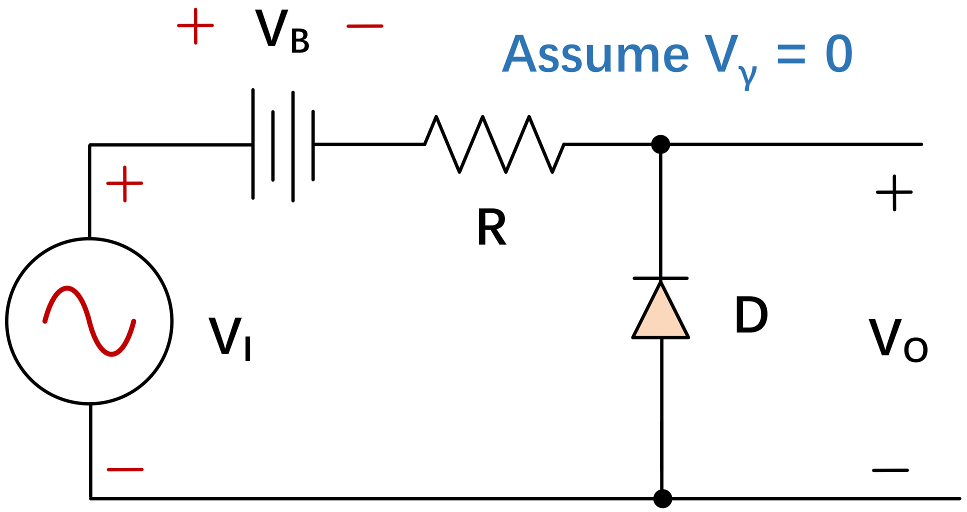
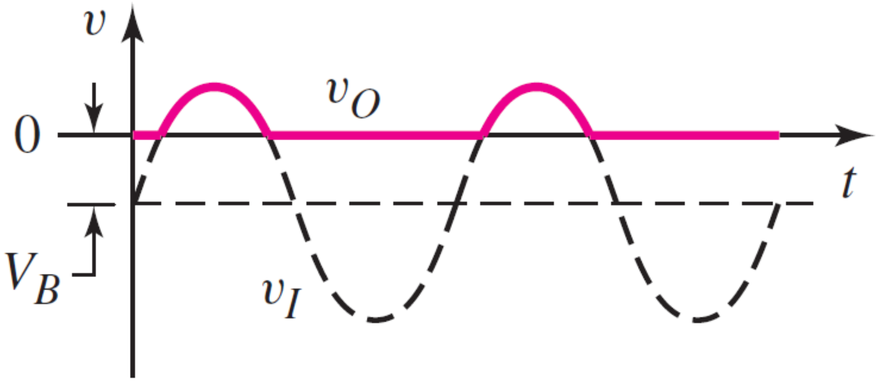
- A DC power (battery) is in series with the AC input signal
- The input signal is superimposed (叠加) on the DC voltage V_B
- When $V_I - V_B < 0$
  - Diode is "**ON**"
  - Output voltage $V_o = 0$
- When $V_I - V_B \geq 0$
  - Diode is "**OFF**"
  - Output voltage $V_o = V_I - V_B$

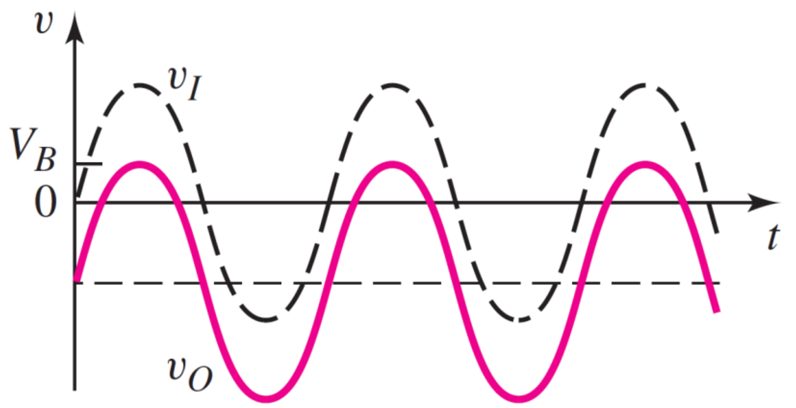




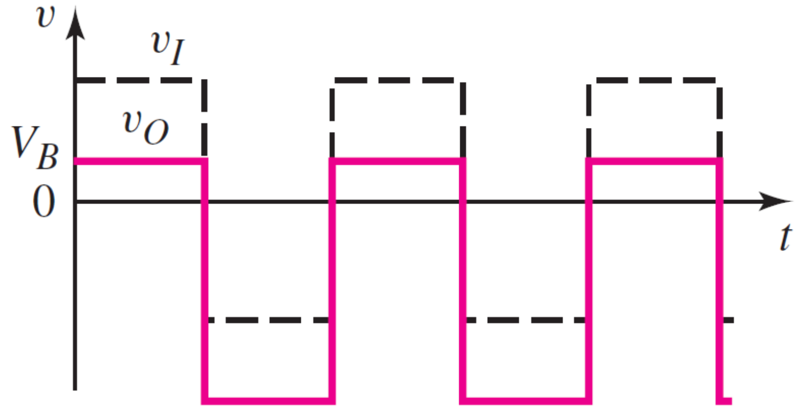
Clamper Circuit (钳位电路)

- Clamping shifts the entire signal voltage by a DC level, it doesn't change the shape of the waveform（平移输入波形，但不改变波形的形状)

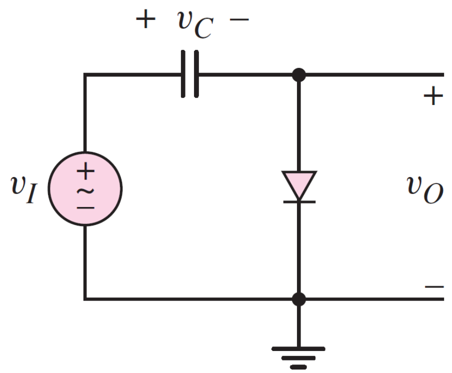
- A feature of a clamper is that it adjust the DC level without needing to know the exact waveform.



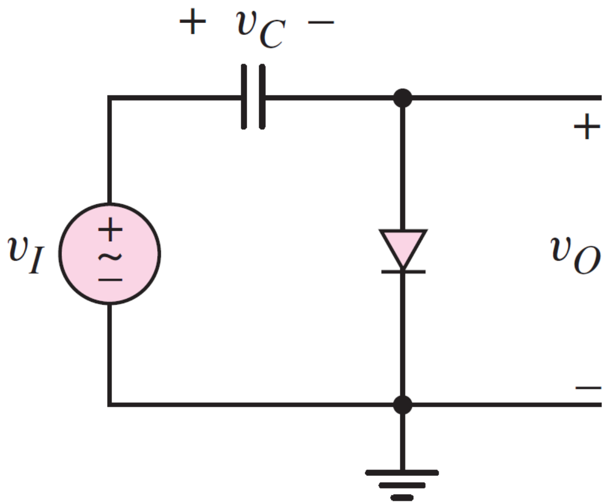
Sine-wave input and output



Square-wave input and output

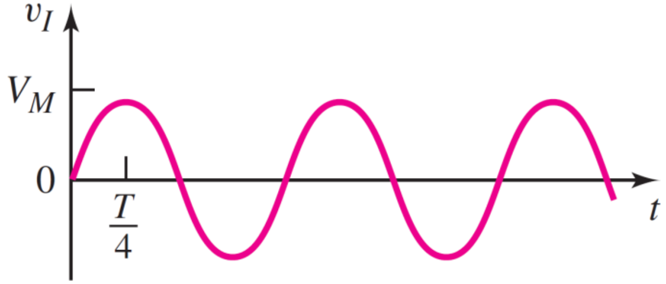


Clamper Circuit

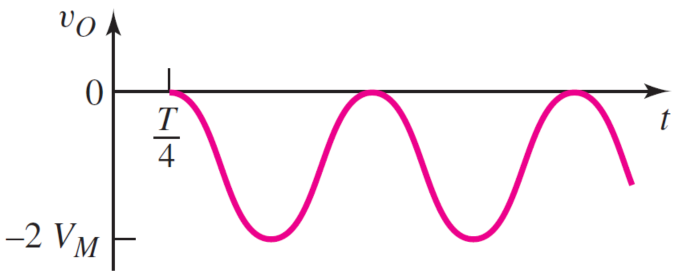


- Still...Assume the capacitor is uncharged at the very beginning, V_γ=0, and r_f = 0 A very ideal condition for simplify
- When $t \le \frac{\pi}{4}$ $V_C = V_I$ the diode is "ON"
- When $t > \frac{\pi}{4}$ V_I decrease and diode is "OFF"
- Ideally, the capacitor cannot discharge $V_C = V_M$

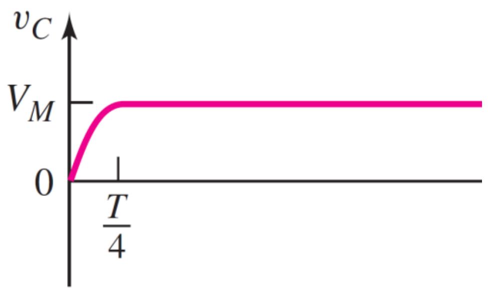
$$V_O = V_I - V_C = V_M \sin \omega t - V_M = V_M (\sin \omega t - 1)$$



Input signal



Output signal



Capacitor voltage

Clamper Circuit (With a battery)

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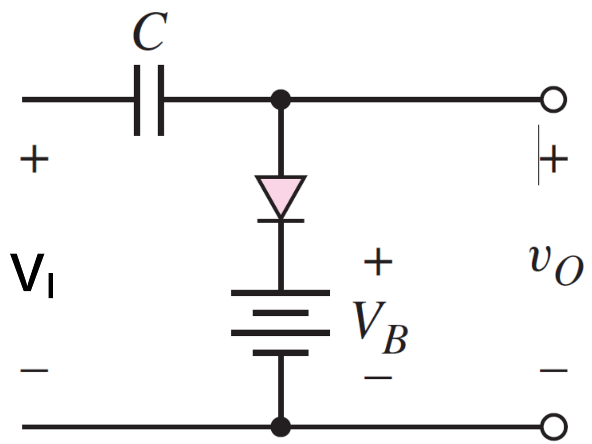
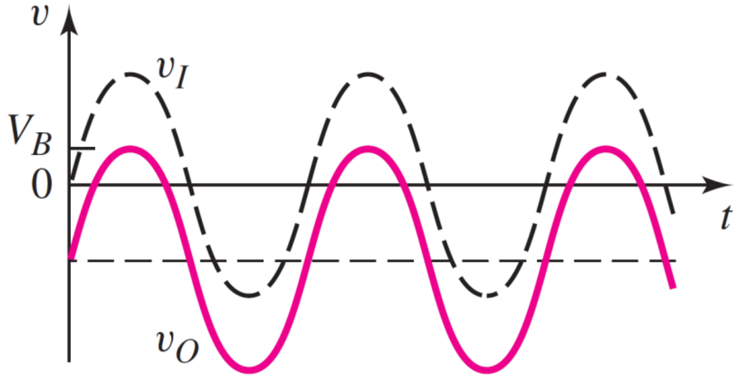


- The previous is simple, but we cannot control the shifting value. If a independent voltage source is added in, situation will change.

- The capacitor voltage is $V_M - V_C$

$$
\begin{aligned}
V_O &= V_I - V_C \\
&= V_M \sin\omega t - (V_M - V_B) \\
&= V_M (\sin\omega t - 1) + V_B
\end{aligned}
$$

$$V_O\,(\max) = V_M\,(1-1) + V_B = V_B$$

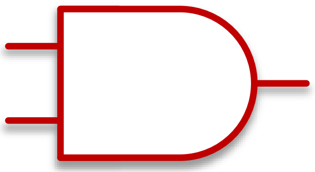


- The output voltage is clamped at $\boldsymbol{V_B}$

Diode Logic Circuit

- Diode in conjunction with other circuit elements can perform certain logic function, such as AND gate and OR gate. If we define: 0 is called "false" and 1 is called "true".

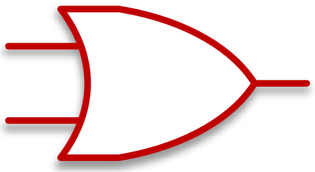
- **AND gate**: The output is "true" when both inputs are "true." Otherwise, the output is "false."
- **OR gate**: The output is "true" if either or both of the inputs are "true." If both inputs are "false," then the output is "false."



AND

Truth Table

Input 1	Input 2	Output
0	0	0
0	1	0
1	0	0
1	1	1



OR

Truth Table

Input 1	Input 2	Output
0	0	0
0	1	1
1	0	1
1	1	1

AND Logic Diode Circuit

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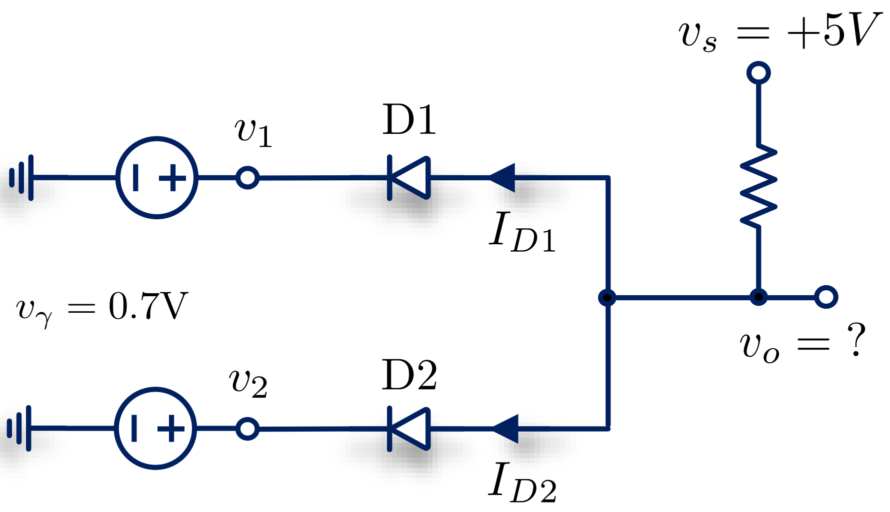
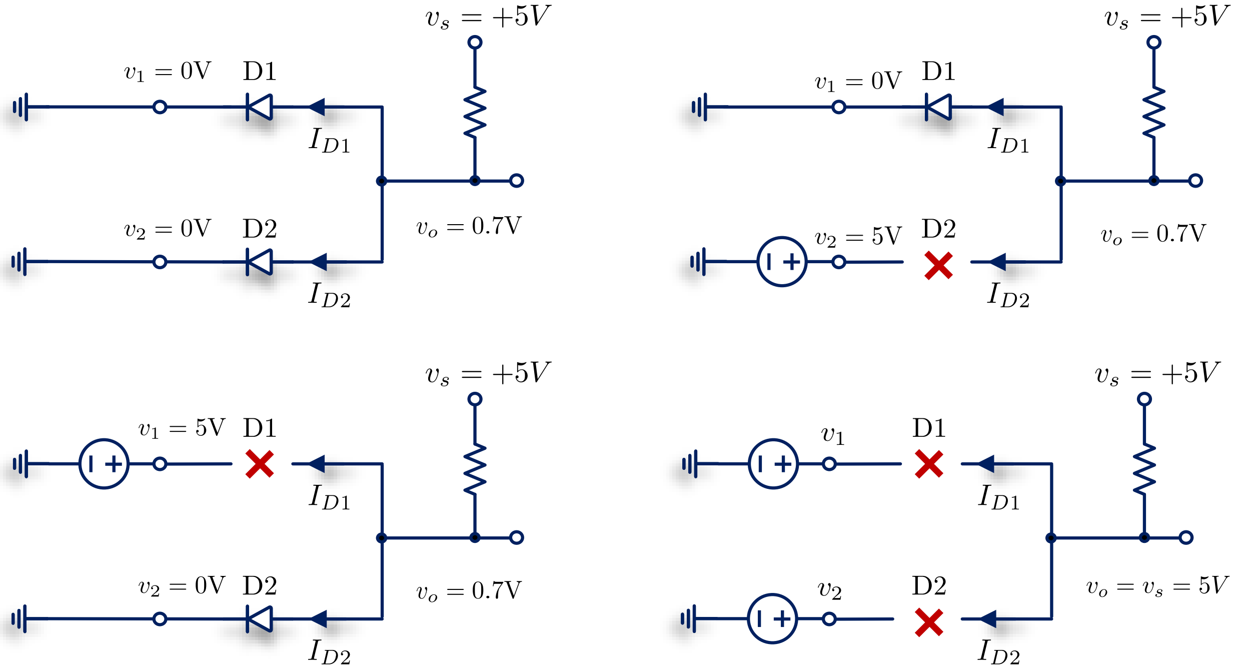
- Assume both input voltage V_1 and V_2 have two voltage levels: 0V and 5V.
- **Four** Possible state depends on the combination of input voltage



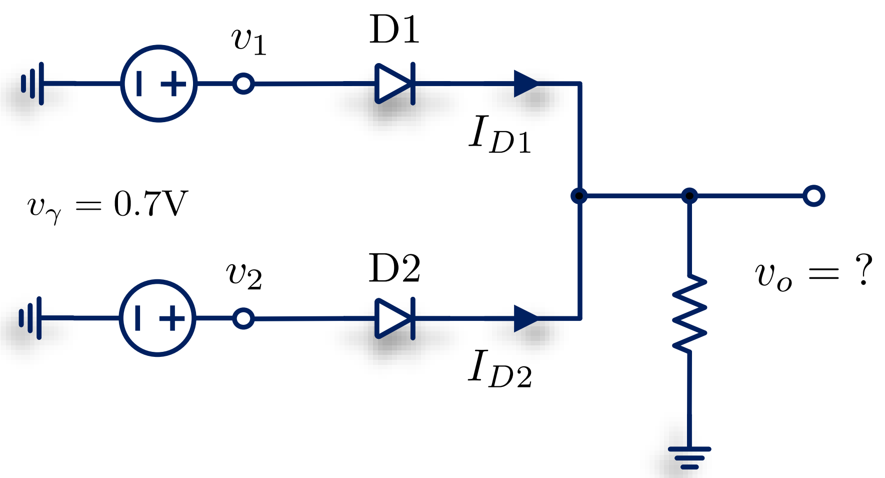


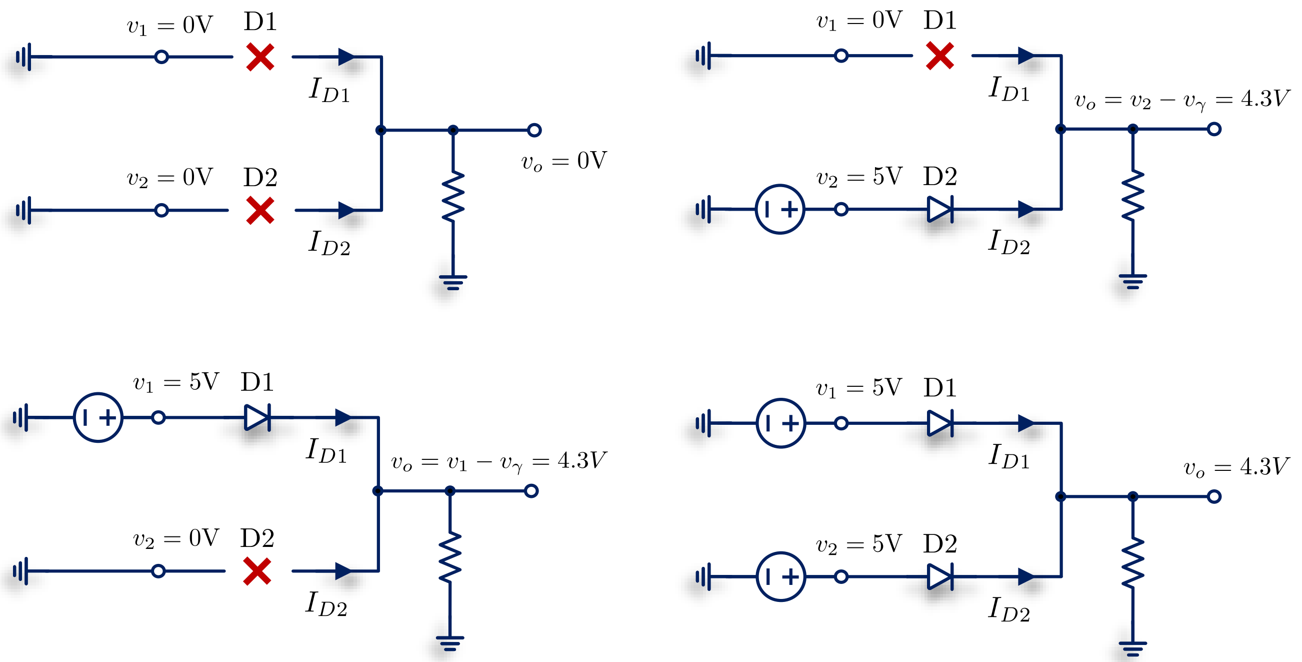
Two diode AND logic circuit response

V_1	V_2	V_O
0 V	0 V	0.7 V
0 V	5 V	0.7 V
5 V	0 V	0.7 V
5 V	5 V	5 V

OR Logic Diode Circuit

- Still assume both input voltage V_1 and V_2 have two voltage levels: 0V and 5V.
- **Four** Possible state depends on the combination of input voltage





Two diode AND logic circuit response

V_1	V_2	V_O
0 V	0 V	0 V
0 V	5 V	4.3 V
5 V	0 V	4.3 V
5 V	5 V	4.3 V

Reinforce Your Learning 🤖

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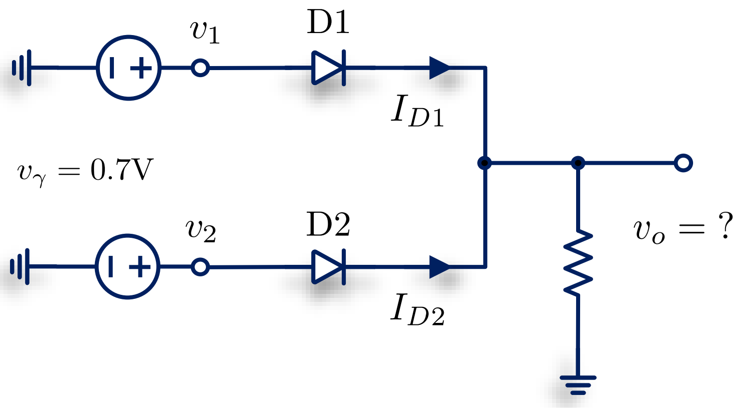
- Consider the OR logic circuit shown below. Assume the diode cut-in voltage is V_γ=0.7 .
- (a) Derive the value and equations of V_o versus V_I for 0 ≤ V_I ≤ 5V, if V_2=0V
- (b) repeat the part (a) if V_2 = 3V , if V_2=0V



LED Circuit

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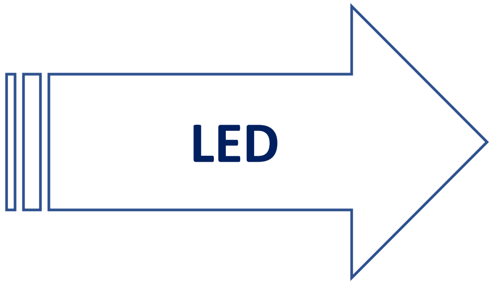
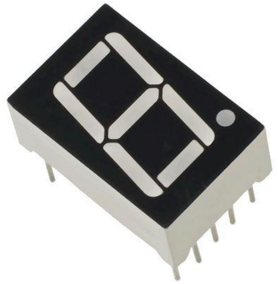
- A light-emitting diode (LED) is the inverse of a photodiode. A electrical current is converted into an optical signal

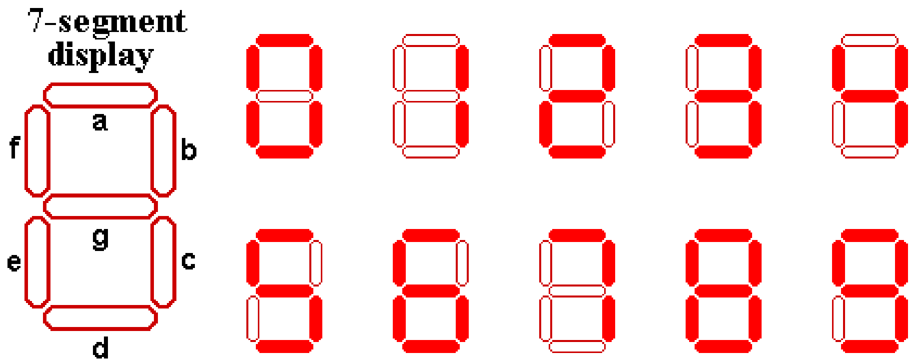
Electrical signal



Optical signal



- The most ordinary application of LED circuit is seven-segment display
  - Each segment is an LED (7 LEDs)
  - LED is normally controlled by IC logic gates



LED Circuit (Inside)

- The anodes of all LEDs are connected to a 5V source.
- The inputs are controlled by logic gates
- If V_I is "High" voltage, such as 5V
  - D1 is "OFF" and no light out
- If V_I is "LOW" voltage, such as 0V
  - D1 is "ON" and produces a light output
- How to display number of "7"?