

Block C Unit 1 Outline

- 1) Semiconductor materials (eg. silicon)
 - » Intrinsic and extrinsic semiconductors
- 2) How a p-n junction works (basis of diodes)
- 3) Large signal models
 - » Ideal diode model
 - » Offset diode model
- 4) Finding the operating point
- 5) Application of diodes in rectification



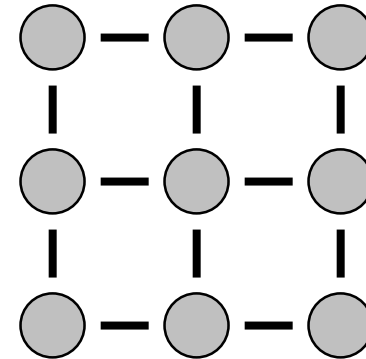
FIG. 1.2
*Intel® Core™ i7 Extreme Edition
Processor.*

Electrical Materials

Insulators

Electrons are bound to the nucleus and are therefore not free to move

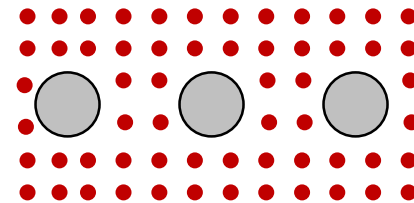
With no free electrons, conduction cannot occur



Conductors

Sea of free electrons not bound to the atoms

Ample availability of free electrons allows for electrical conduction



Semiconductors

Electrons are bound to the nucleus but vacancies are created due to thermal excitation

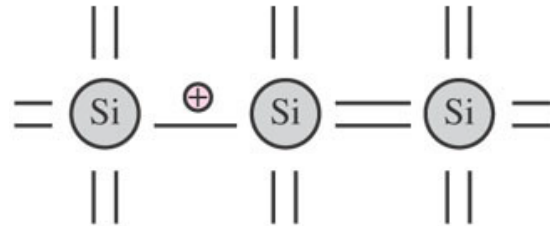
Electrical conduction occurs through positive (called holes) and negative (electrons) charge carriers

Electrons: mobile negative charge carriers

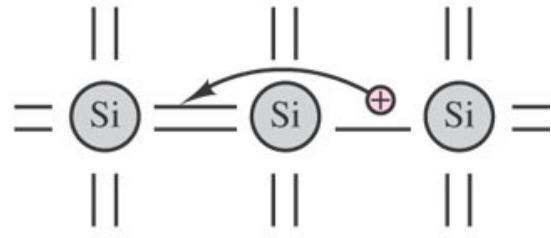
Holes: mobile positive charge carriers

Intrinsic semiconductors and conduction

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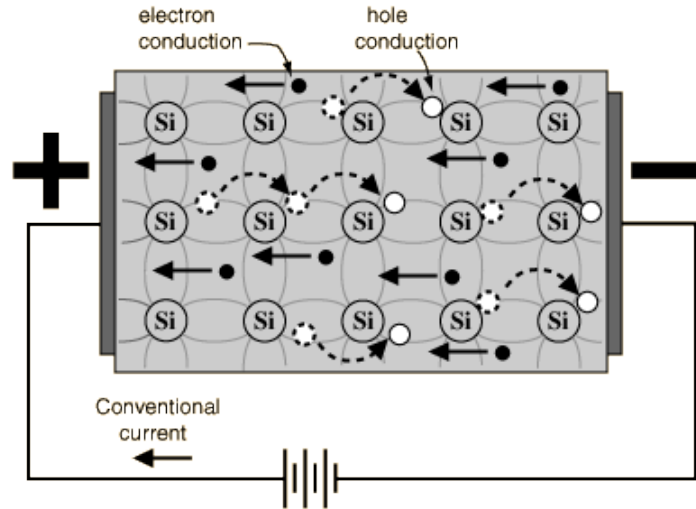
⊕ = Hole Electron jumps to fill hole



The net effect is a hole moving to the right

A vacancy (or hole) is created whenever a free electron leaves the structure.

This “hole” can move around the lattice if other electrons replace the free electron.



Each Si atom has 4 valence electrons and contributes 1 electron per bond
Each bond is formed by two electrons, 1 from each atom

Silicon (Si) is the dominant semiconductor material used in the electronics industry. In 1 m^3 of Si, there are $\sim 10^{28}$ atoms. Among these 10^{28} , there will be about 1.5×10^{16} **vacancies at room temperature**. This is known as the *intrinsic carrier concentration*: $n_i = 1.5 \times 10^{16} \text{ electrons/m}^3$. This corresponds to **1 free electron for every 10^{12} atoms**.

For intrinsic Si, no. of electrons = no. of holes

Extrinsic semiconductors

Intrinsic semiconductors:

$$n_{\text{electrons}} = n_{\text{holes}} \text{ (equal concentrations)}$$

Extrinsic semiconductors:

Greater concentration of one type of carrier over the other

N-type semiconductor

$$n_{\text{electrons}} \gg n_{\text{holes}}$$

(Mostly negative charge carriers)

P-type semiconductor

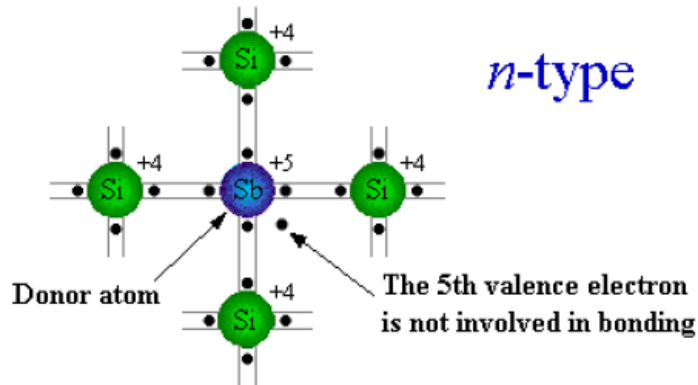
$$n_{\text{holes}} \gg n_{\text{electrons}}$$

(Mostly positive charge carriers)

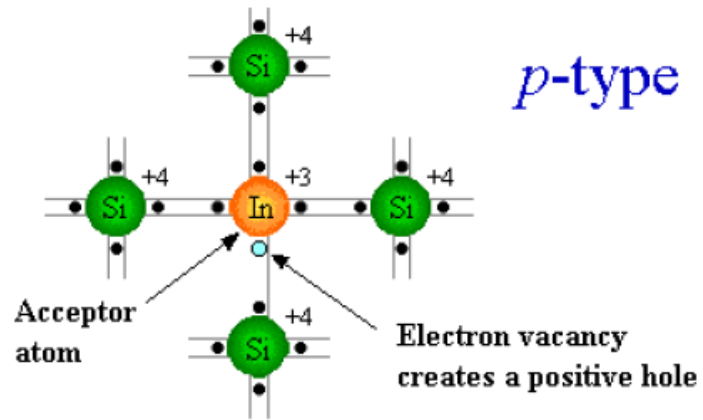
Doping to form extrinsic semiconductors

A semiconductor material that has been subjected to the doping process is called an extrinsic material. Both n-type and p-type materials are formed by adding a predetermined number of impurity atoms to a silicon base.

N-type extrinsic material



P-type extrinsic material



An **n-type** material is created by introducing impurity elements that have five valence electrons. In an n-type material, **electrons are the majority carriers**.

An **p-type** material is created by introducing impurity elements that have three valence electrons. In a p-type material, **holes are the majority carriers**.

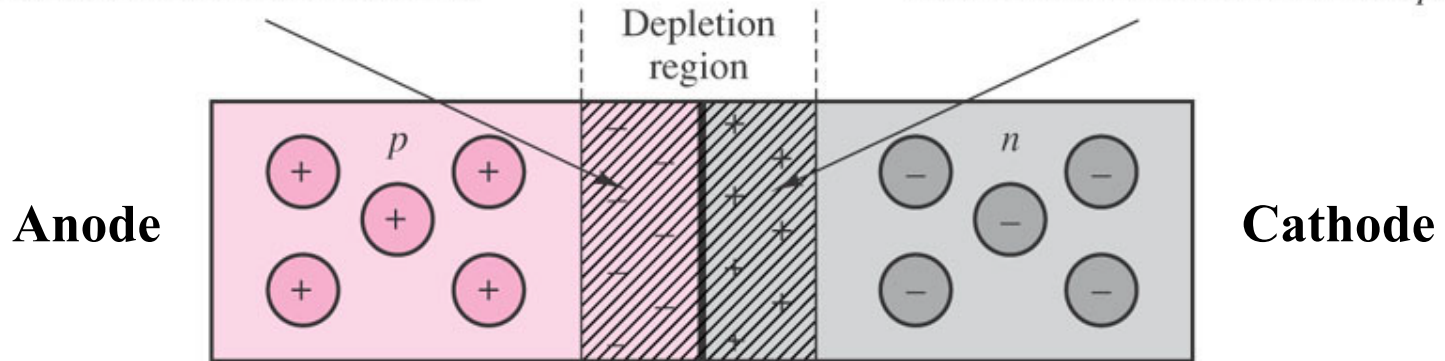
This process is called **DOPING**

p-n Junction

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The *p*-side depletion region is negatively charged because its holes have recombined with free electrons from the *n* side

The *n*-side depletion region is positively charged because its free electrons have recombined with holes from the *p* side

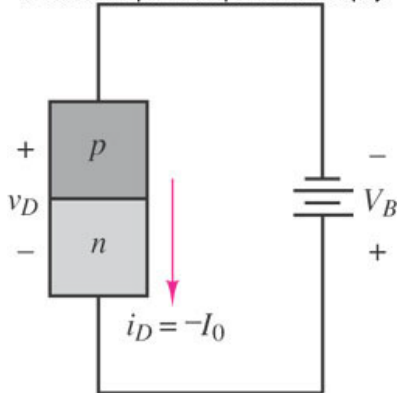


The pn junction forms the basis of the semiconductor diode.

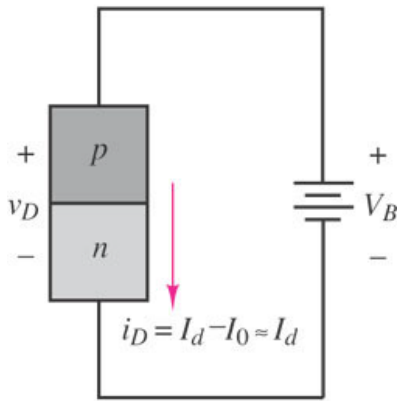
Within the depletion region, no free carriers exist since the holes and electrons at the interface between the *p*-type and *n*-type recombine.

Biasing and Conventions

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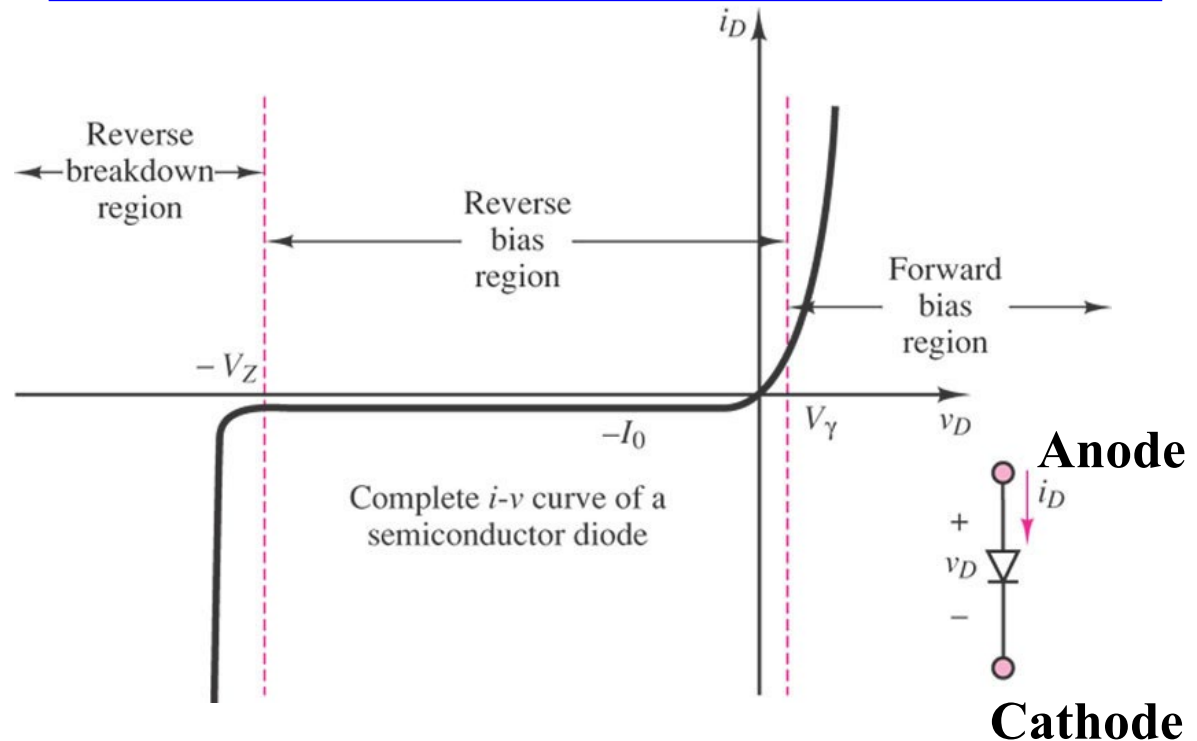


(a) Reverse-biased *pn* junction



(b) Forward-biased *pn* junction

Diode begins to conduct a significant amount of current: Voltage V_γ is typically around 0.7V

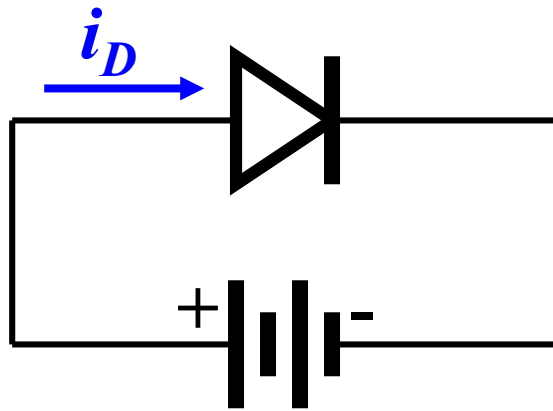
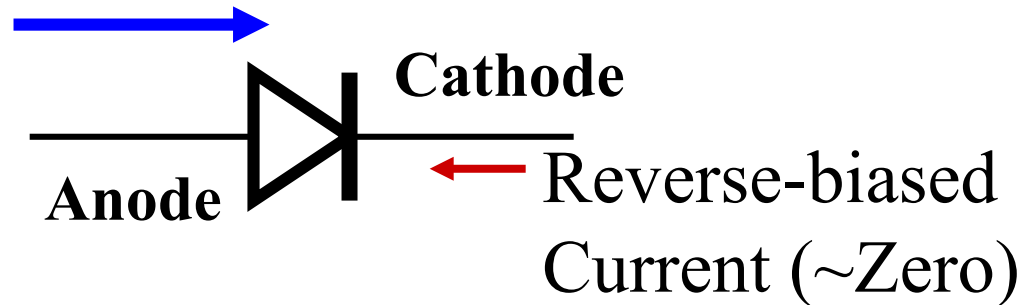


v_D : Voltage of **anode** relative to **cathode**

i_D : Current flowing from anode to cathode

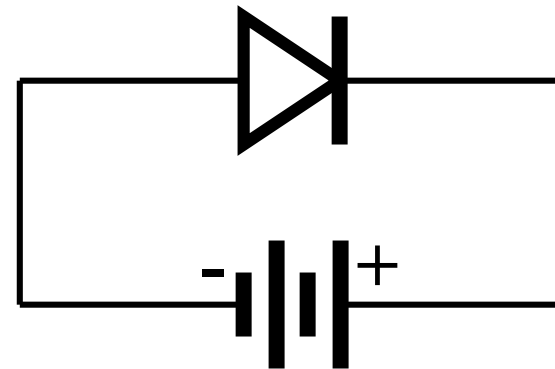
Diode Symbol and Operation

Forward-biased
Current (Large)



Forward Biased:

Diode conducts

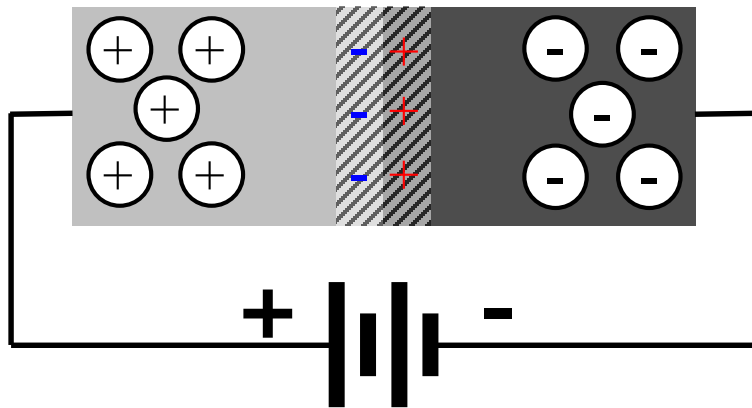
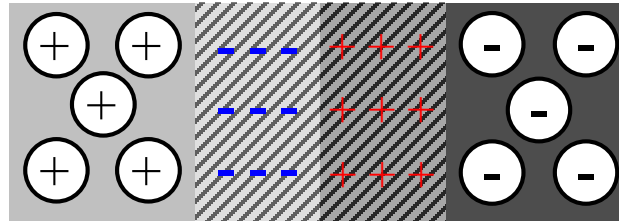


Reverse Biased:

Little or no current

PN diode depletion region

When no voltage is applied across the diode

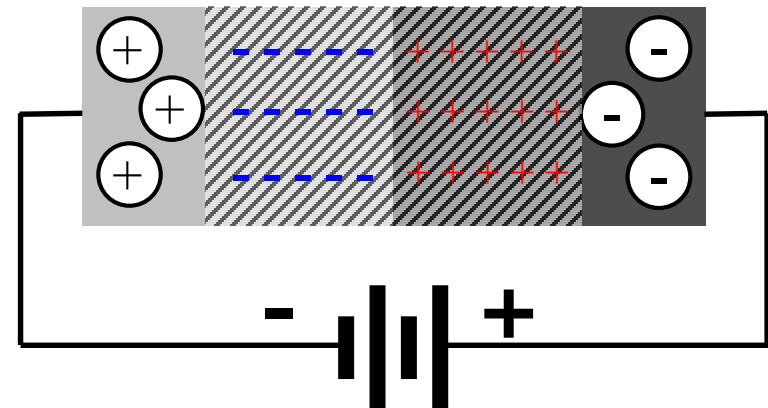


Forward biased:

Anode at higher voltage than cathode

Depletion width ↓, ↓ barrier for majority carriers to move across the depletion region

Large conduction current



Reverse biased:

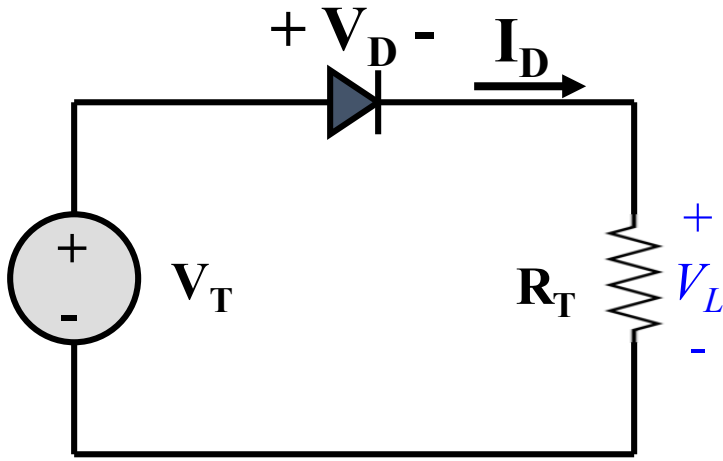
Anode at lower voltage than cathode

Depletion width ↑, ↑ barrier for majority carriers to move across the depletion region

Very small leakage current

Analyzing circuits with diodes by equations

Tedious: requires numerical methods



To find V_L where V_T and R_T are known,

First apply KVL around the loop:

$V_T = V_D + R_T I_D$, V_T and R_T are known

Then use the diode equation:

$I_D = I_0 [\exp(eV_D/kT) - 1]$, I_0 is known

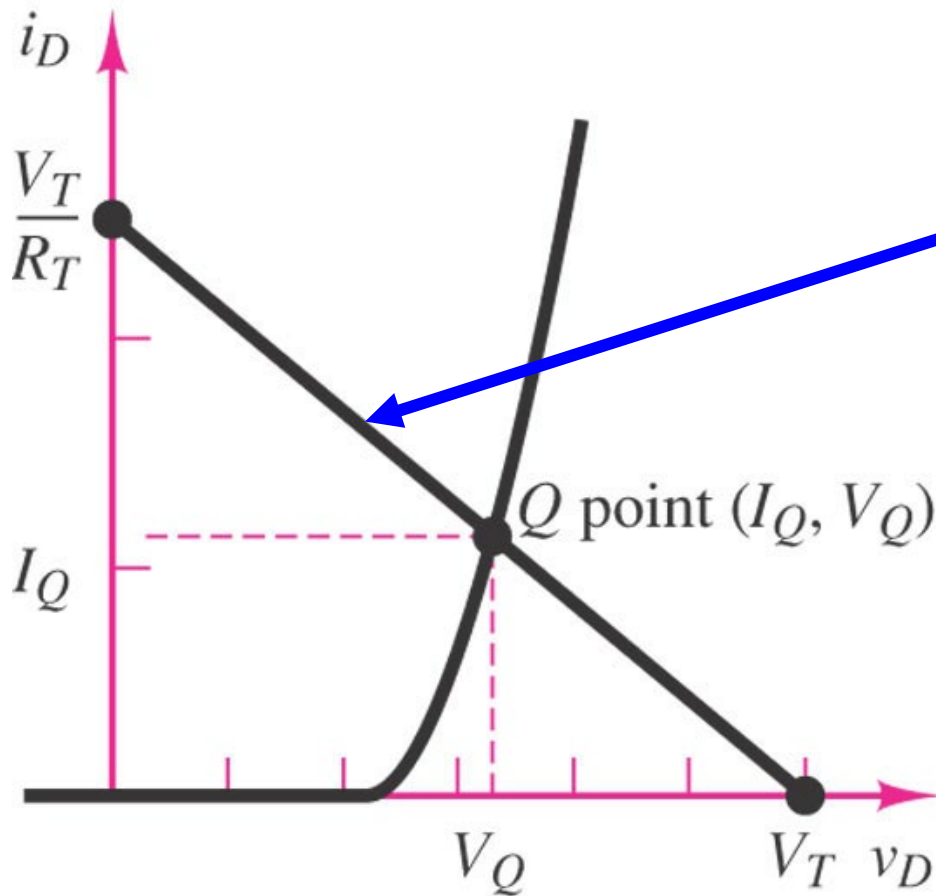
At $T = 300\text{K}$, $kT/e = 25\text{mV}$

We then need to solve these two simultaneous equations, which is not trivial. The other alternative is to use the graphical method to find the value of I_D and V_D (next slide)

Analyzing circuits with diodes by graphs

Plot of diode current vs diode voltage

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Equation from KVL

$$i_D = -\frac{1}{R_T} v_D + \frac{v_T}{R_T}$$

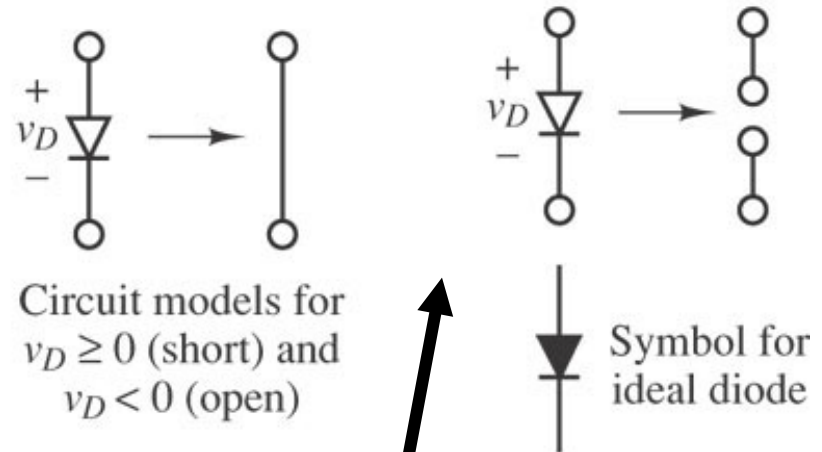
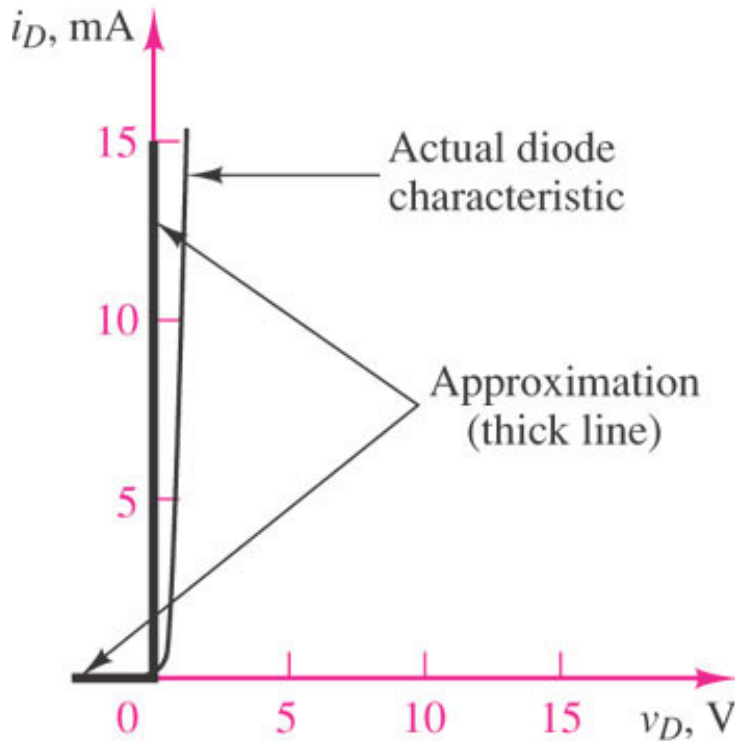
Operating point is where the load line & I-V curve of the diode **intersect**

Diode circuit large signal models

- 1) Large-signal models are a quick and fast alternative to analyze circuits with diodes
 - » Graphs (complicated with more components)
 - » Equations (write codes to solve)
- 2) Large signal models are **approximations**:
describing the device behavior for large changes in voltages & currents
- 3) Two types of large signal models for this course
(both based on a switch or ON/OFF concept):
 - » Ideal diode model
 - » Offset diode model

Ideal diode model

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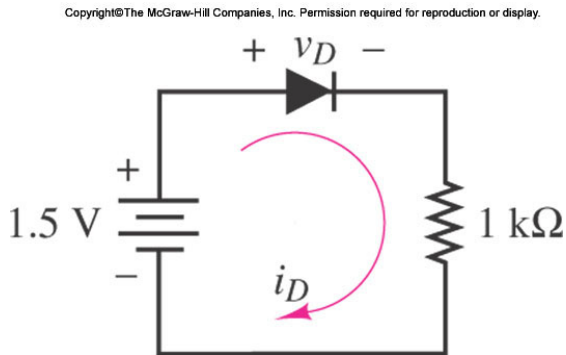
$v_D > 0$: Short circuit

$v_D < 0$: Open circuit

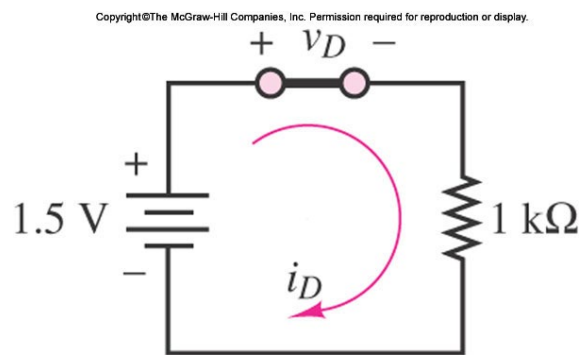
In other words, diode is treated like a switch here

Ideal diode model

CASE 1

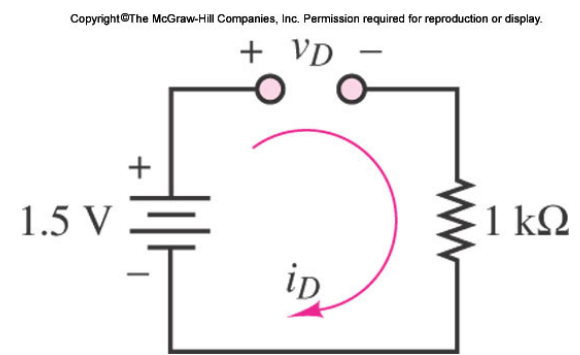


Circuit containing
ideal diode



Circuit assuming that the
ideal diode conducts

CASE 2



Circuit assuming that the
ideal diode does not conduct

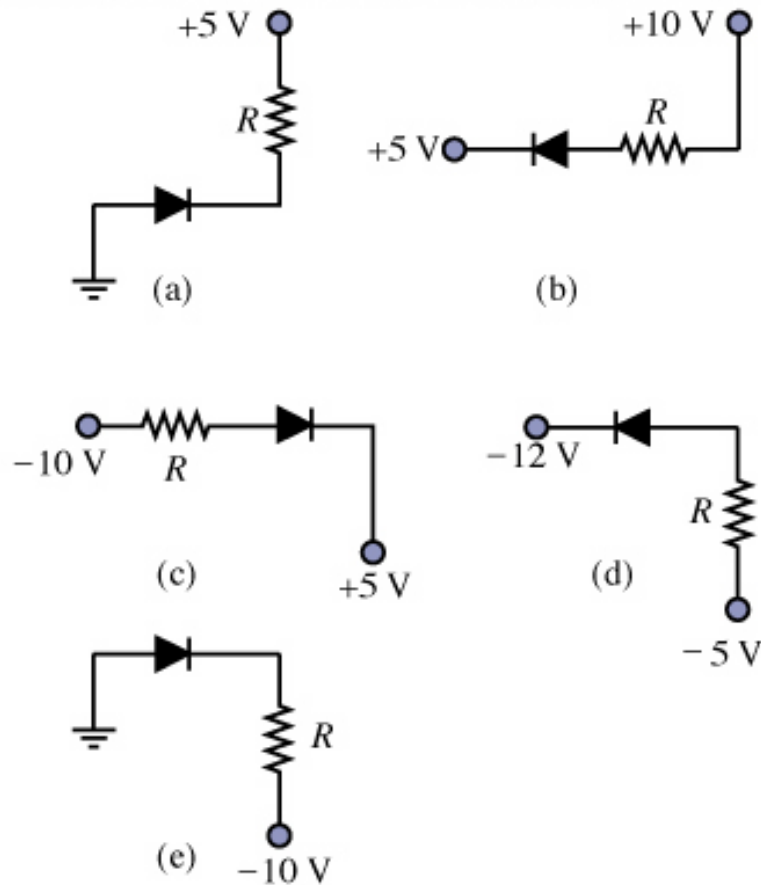
Case 1: Assuming the diode conducts and replacing it with a short circuit, we work out the direction of the current. We find that the diode current runs from the anode to the cathode. This is what we would expect if the diode was ON.

Case 2: Assuming the diode blocks and replacing it with an open circuit, we work out the voltage drop across the diode. We find that the voltage of the anode is higher than the cathode. This is contrary to what we would expect if the diode was OFF.

Ideal diode example 1

(In-Class Assignment 8, Q4)

Determine which diodes are ON and which are OFF



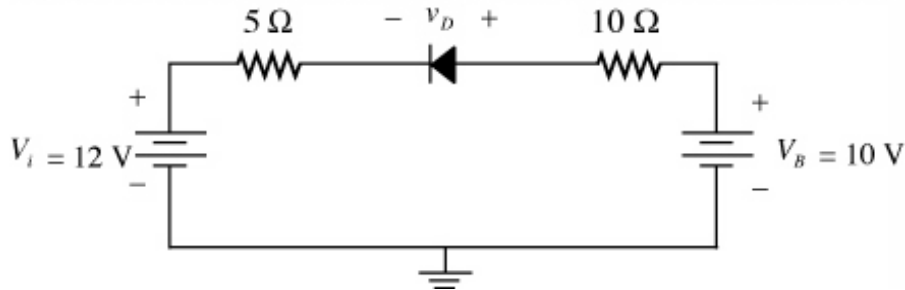
Ideal diode example 2

Problems 9.7 and 9.8

Determine whether the diode is conducting or not. Assume diode is ideal

Repeat for $V_i = 12\text{V}$ and $V_B = 15\text{V}$

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Case 1: Assume diode is ON: Replace with short circuit and find diode current direction
Diode confirmed as ON if diode flows from anode to cathode

Case 2: Assume diode is OFF: Replace with open circuit and find voltage drop across diode
Diode confirmed as OFF if voltage drop from anode to cathode is negative

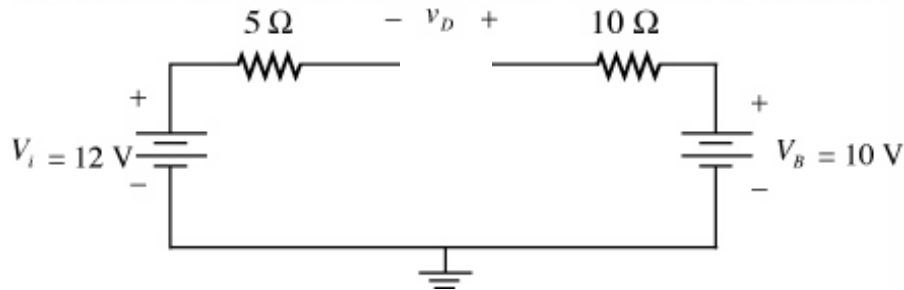
Ideal diode example 2 solution

Case 1: Assume diode is ON → Replace diode with short circuit

Diode current (I_D) = $(10-12)/(5+10) = -2/15$ A

→ Contrary to our assumption that the diode is ON

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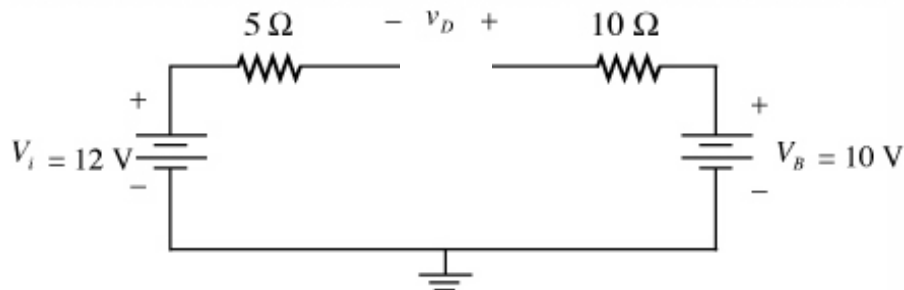


Case 2: Assume diode is OFF → Replace diode with open circuit

Diode voltage drop (V_D) = $10-12 = -2$ V

→ Confirms our assumption that the diode is OFF

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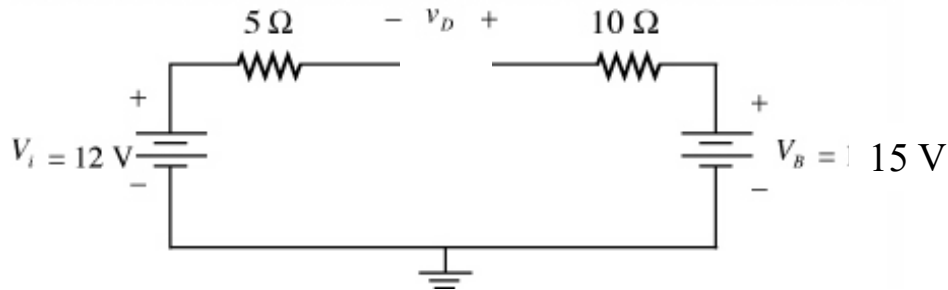
Ideal diode example 2 solution

Case 1: Assume diode is ON → Replace diode with short circuit

Diode current (I_D) = $(15-12)/(5+10) = 0.2$ A

→ Confirms our assumption that the diode is ON

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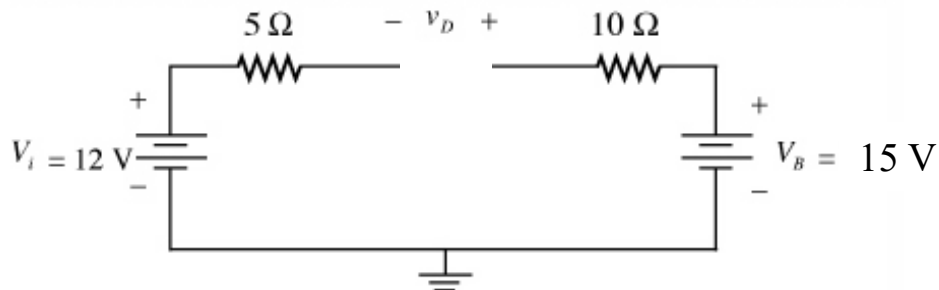


Case 2: Assume diode is OFF → Replace diode with open circuit

Diode voltage drop (V_D) = $15-12 = 3$ V

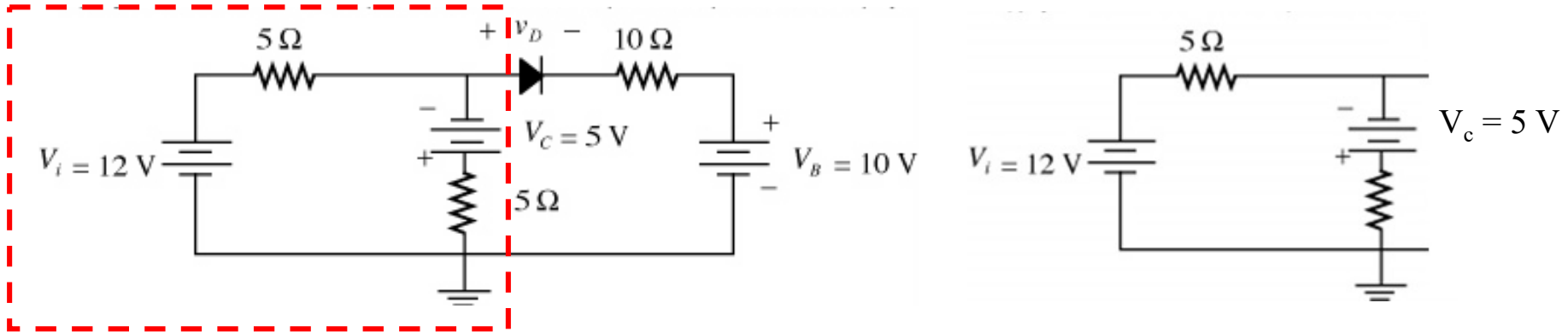
→ Contrary to our assumption that the diode is OFF

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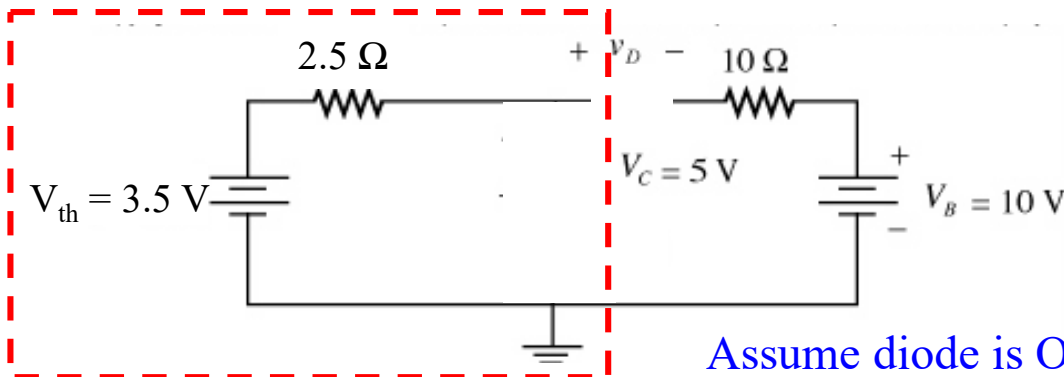


Ideal diode model example 3

Determine the state of the diode assuming it is ideal.



Transform marked out section of circuit to Thevenin



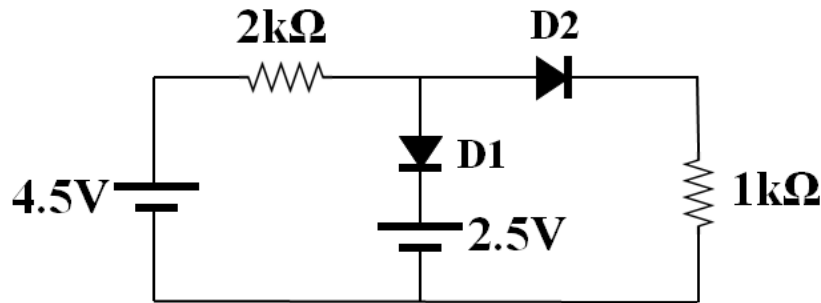
Assume diode is OFF $\rightarrow$ Replace diode with open circuit

Diode voltage drop (V_D) = $3.5 - 10 = -6.5\text{ V}$

$\rightarrow$ Confirms diode is OFF

Ideal diode example 4

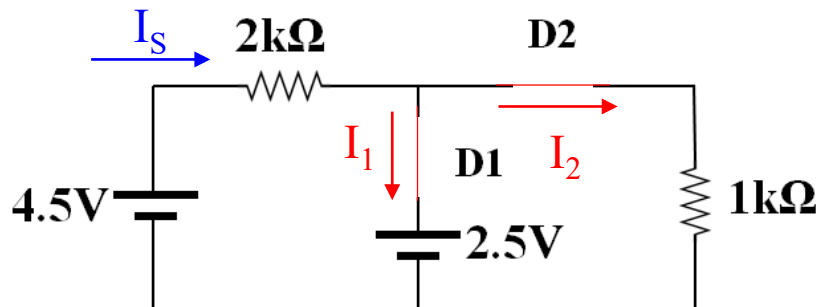
- (i) Determine the state of all the diodes (D1 and D2).
- (ii) For the diodes that are OFF, find the reverse bias voltages. For the diodes that are ON, find the forward bias currents.



4 possible combinations of the state of the two diodes. **Only 1** of the 4 combinations is correct.

Attempt 1: Try D1 ON and D2 ON

⇒ Replace D1 and D2 with short circuit and determine direction of diode current



$$I_2 = 2.5/1k = 2.5 \text{ mA}$$

$$I_S = (4.5-2.5)/2k = 1 \text{ mA}$$

$$I_1 + I_2 = I_S \rightarrow I_1 = -1.5 \text{ mA}$$

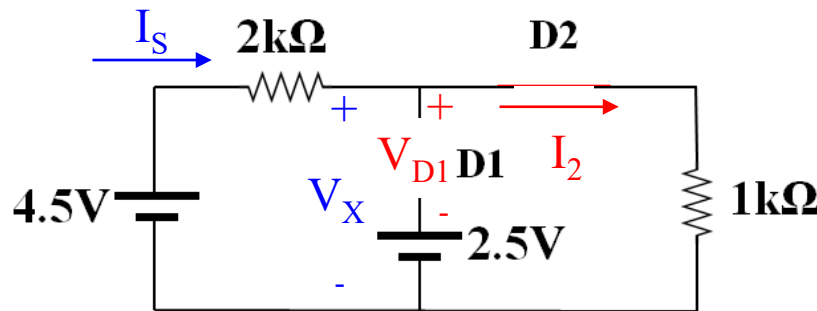
Ideal diode example 4 solution

Since Attempt 1 was a failure, we try another combination

Attempt 2: D1 OFF and D2 ON

⇒ Replace D1 with open circuit (then find V_{D1})

⇒ Replace D2 with short circuit (then find I_2)



I_S now equals I_2

$$I_2 = 4.5 / (2k + 1k) = 1.5 \text{ mA}$$

(Confirmed as same direction expected of forward bias)

Next: Check the value of V_{D1}

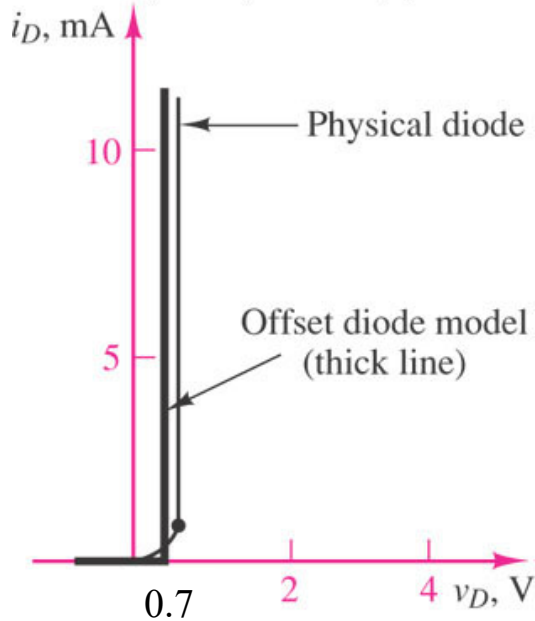
$$V_X = 1.5 \text{ V}$$

$$V_{D1} = 1.5 - 2.5 = -1 \text{ V}$$

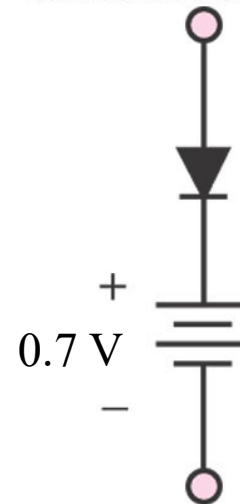
(Confirmed as reverse bias)

Offset diode model

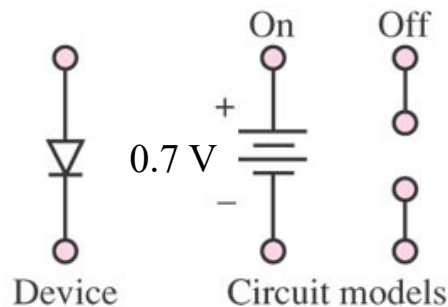
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V_γ is typically used to denote the offset voltage



$$v_D \geq 0.7 \text{ V}$$

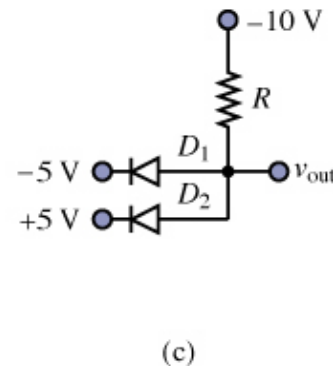
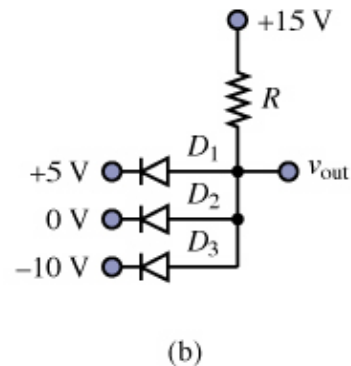
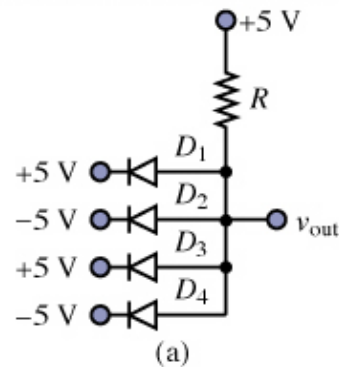
Diode $\rightarrow$ 0.7 V battery

$$v_D < 0.7 \text{ V}$$

Diode $\rightarrow$ open circuit

Offset model example 1

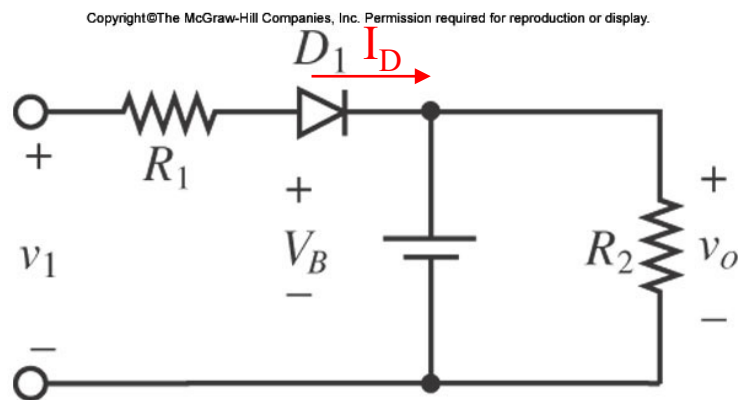
Determine V_{out} in each of the following cases and the associated states of the diodes. Assuming a 0.7 V drop across each forward-biased diode.



Offset model example 2

Determine the state of the diode assuming it has a turn on voltage (V_γ) of 0.7 V and given that $V_1 = 5\text{ V}$, $V_B = 2\text{ V}$, $R_1 = 1\text{ k}\Omega$, $R_2 = 500\text{ }\Omega$.

What is the lowest value of V_1 for the diode to turn on?



Work with assumption that diode is ON:

→ Find the direction and value of I_D

→ $V_1 = I_D \cdot R_1 + V_\gamma + V_B$

→ $I_D = (5 - 2.7) / 1\text{ k} = 2.3\text{ mA}$

→ Confirms that diode is ON

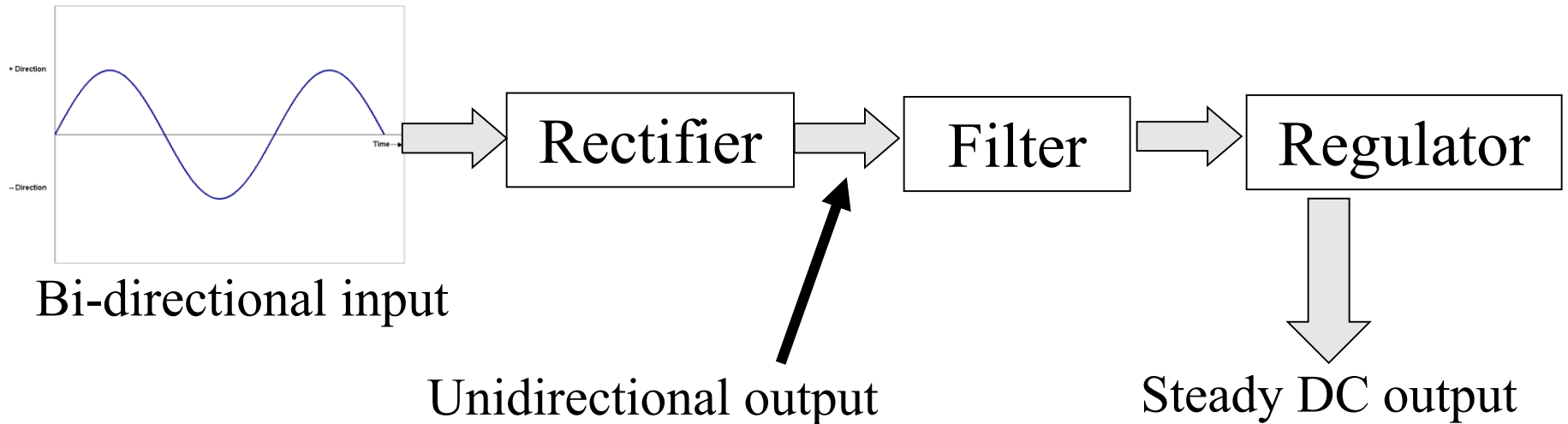
Lowest value of V_1 for diode to be on:

$$I_D = (V_1 - V_\gamma - V_B) / R_1 = (V_1 - 2.7) / 1\text{ k}$$

For I_D to be positive → $V_1 > 2.7\text{ V}$

Application of diodes: Rectifiers

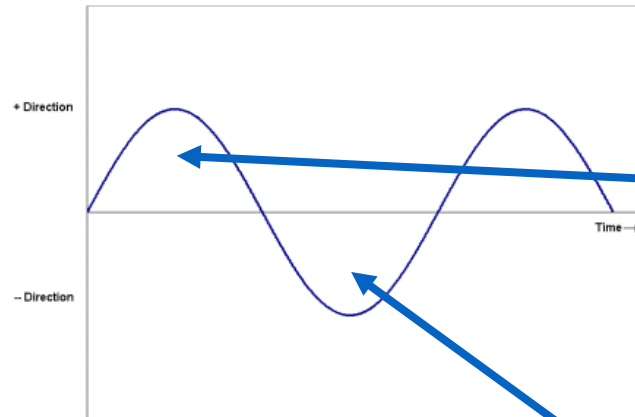
One common application of diodes is rectification. In rectification, an AC sinusoidal source is converted to a unidirectional output which is further filtered and regulated to give a steady DC output.



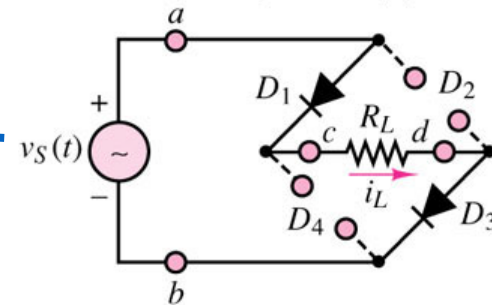
Next we apply the large signal models to analyze a rectifier

Full-Wave Rectifier

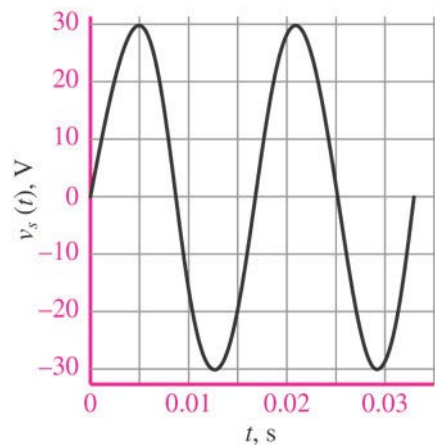
Comprises 2 sets of diode pairs
Each pair conducts in turn on each half-cycle



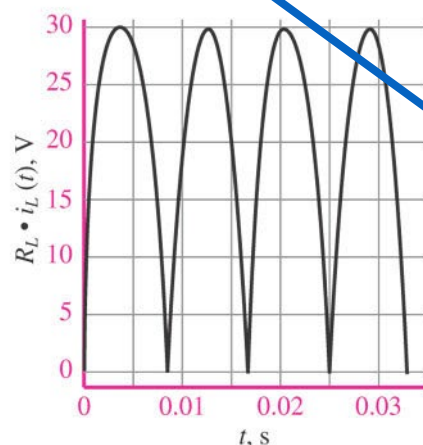
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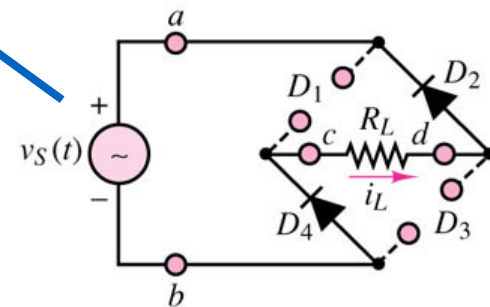
During the positive half-cycle of $v_s(t)$, D_1 and D_3 are forward-biased and $i_L = v_s(t)/R_L$ (ideal diodes).



(a)



(b)



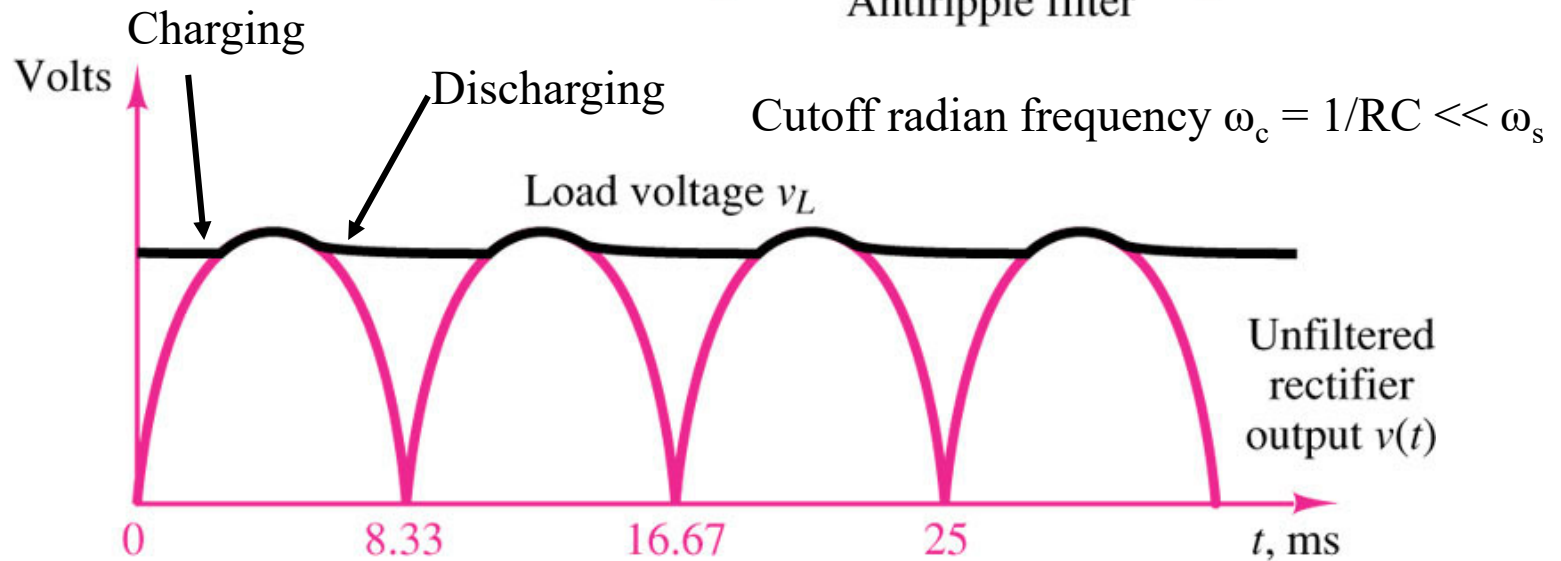
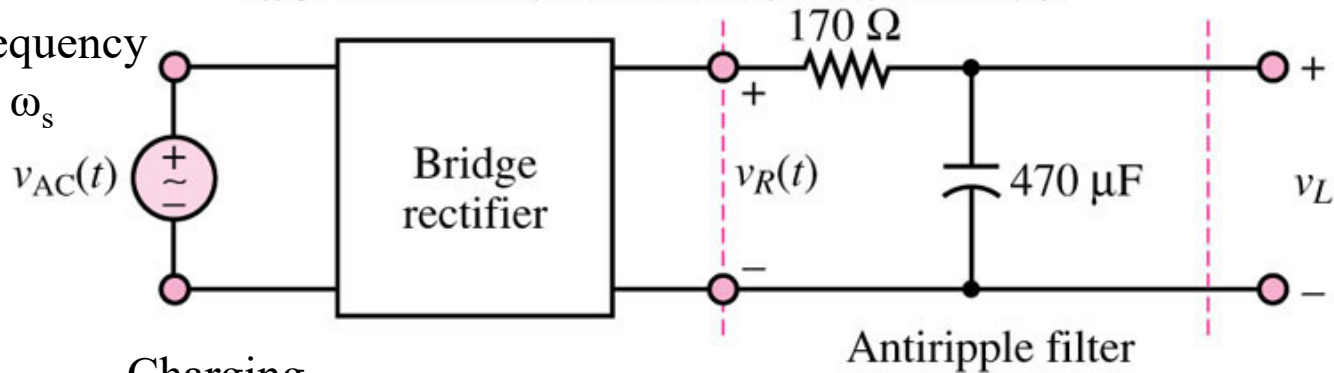
During the negative half-cycle of $v_s(t)$, D_2 and D_4 are forward-biased and $i_L = -v_s(t)/R_L$ (ideal diodes).

Ripple filter

Anti-ripple filter is used to smoothen out the rectifier output

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Radian frequency
of source: ω_s



Summary

- 1) Free carriers are required for conduction
- 2) Positively and negatively charged free carriers can be engineered in semiconductors
- 3) Diode is a nonlinear device that we can model as an approximation as either conducting or blocking using large signal models
- 4) Large signal diode models an approximation
 - » Ideal: Diode conducts with 0V offset across diode
 - » Offset: Conduction results in a small offset voltage
- 5) Rectifiers are one application of diodes