CSE251: Electronic Devices and Circuits

Diodes - 1

Prepared By:

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Current-Voltage (I-V) Characteristics

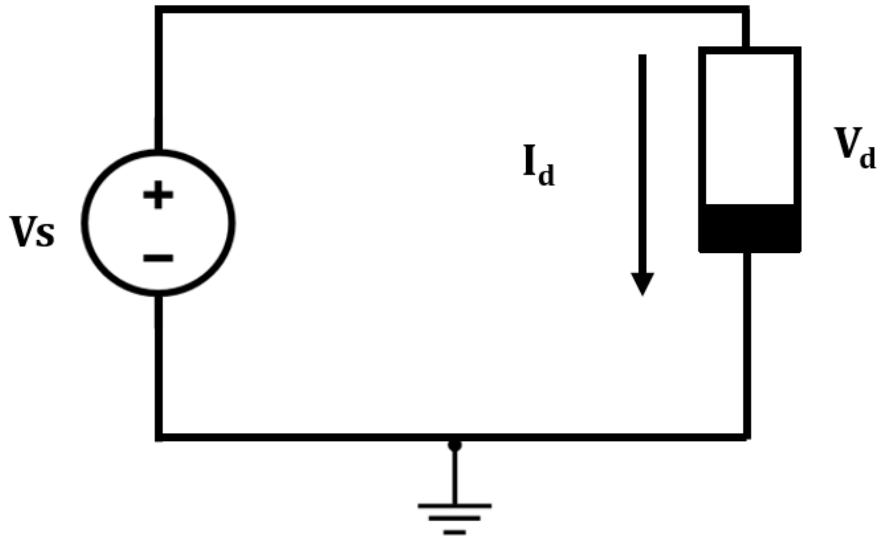
- I-V characteristic defines the relationship between the **current flow (through), I** and **voltage (across), V** an electronic device or element.

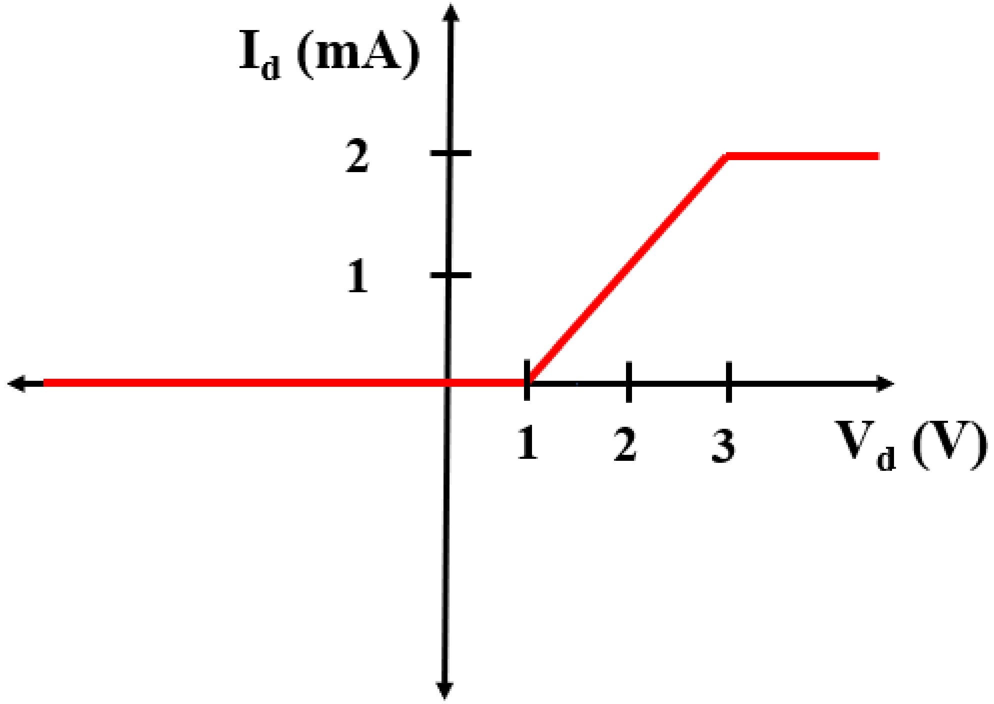
- A tool for understanding the operation of the circuit.

- The Current-Voltage (I-V) characteristics are found by evaluating the **response** of a device/element under different conditions. The behavior of a device depends on the **applied excitation** and can change if the excitation changes. For example, a device may act as an “open circuit” under certain input conditions and as “current source” in another. A diode acts as an open circuit below a specific threshold voltage and acts differently after that.

Current-Voltage (I-V) Characteristics

Example:

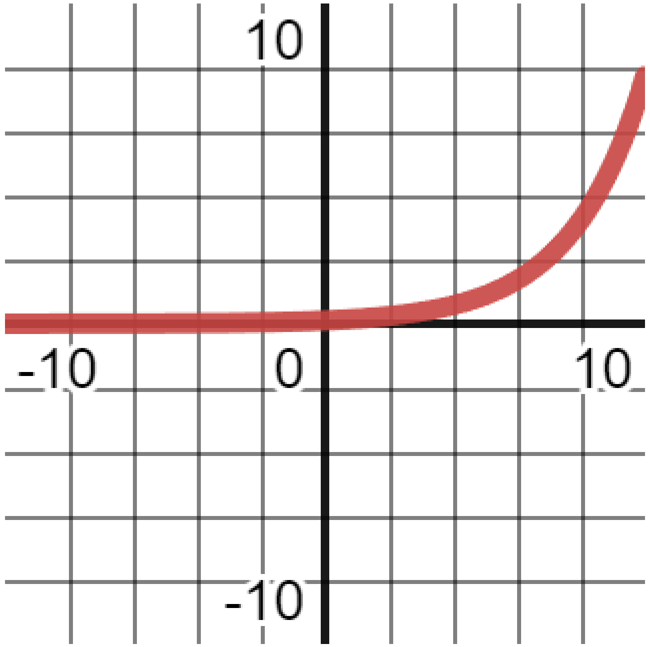




Current-Voltage (I-V) Characteristics

$$I = kV \qquad I = kV^2 \qquad I = \mathrm{A} \cdot \exp(\frac{V}{b})$$

$$y = mx \qquad y = ax^2 \qquad y = \mathrm{A} \cdot \exp(\frac{x}{b})$$



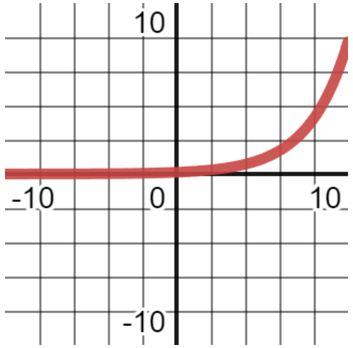
Type of (I-V) Characteristics

1. Linear Devices/Elements: The Current-Voltage relationship is linear i.e. the current through the element is a linear function of the applied voltage across it. The relationship can be characterized by:

$$I = kV$$

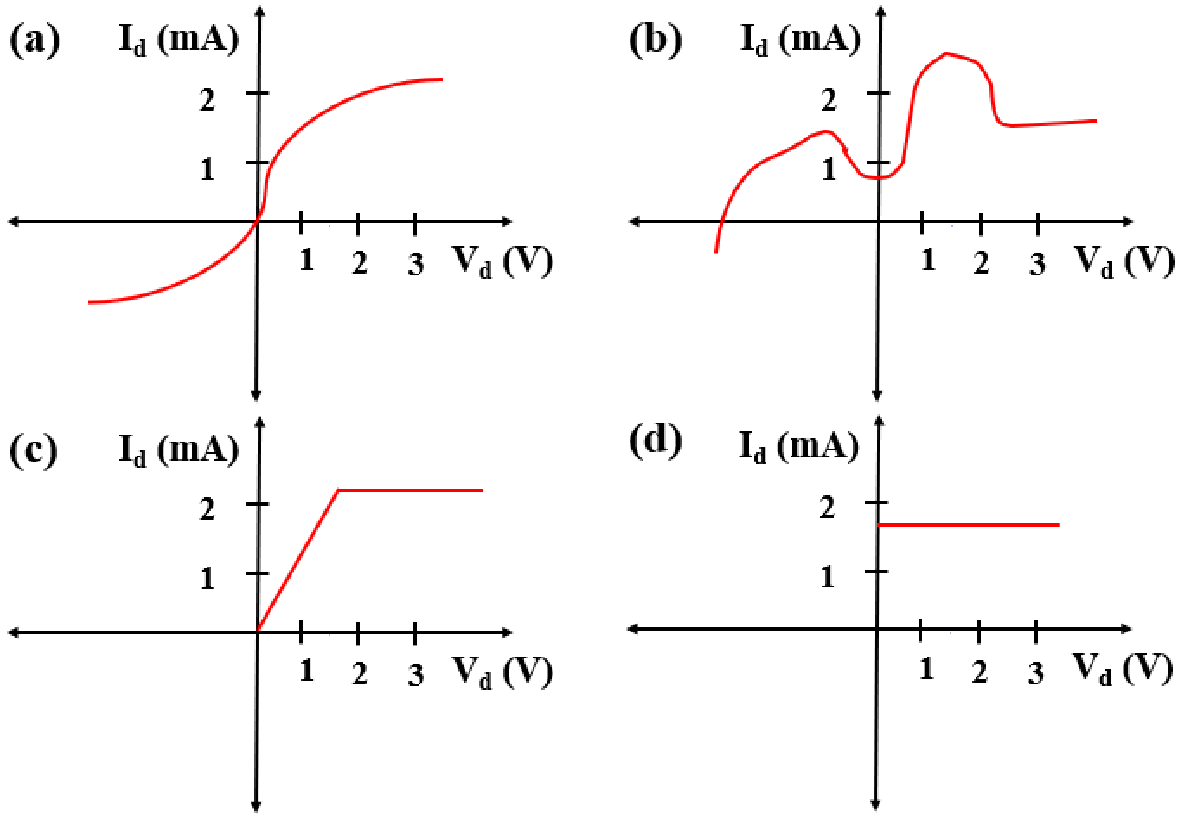
2. Non-Linear Devices/Elements: The Current-Voltage relationship is Non-linear i.e., the current through the element is a nonlinear function of the applied voltage across it.

$$I = k\sqrt{V}$$
$$I = kV^2$$
$$I = kV^3$$



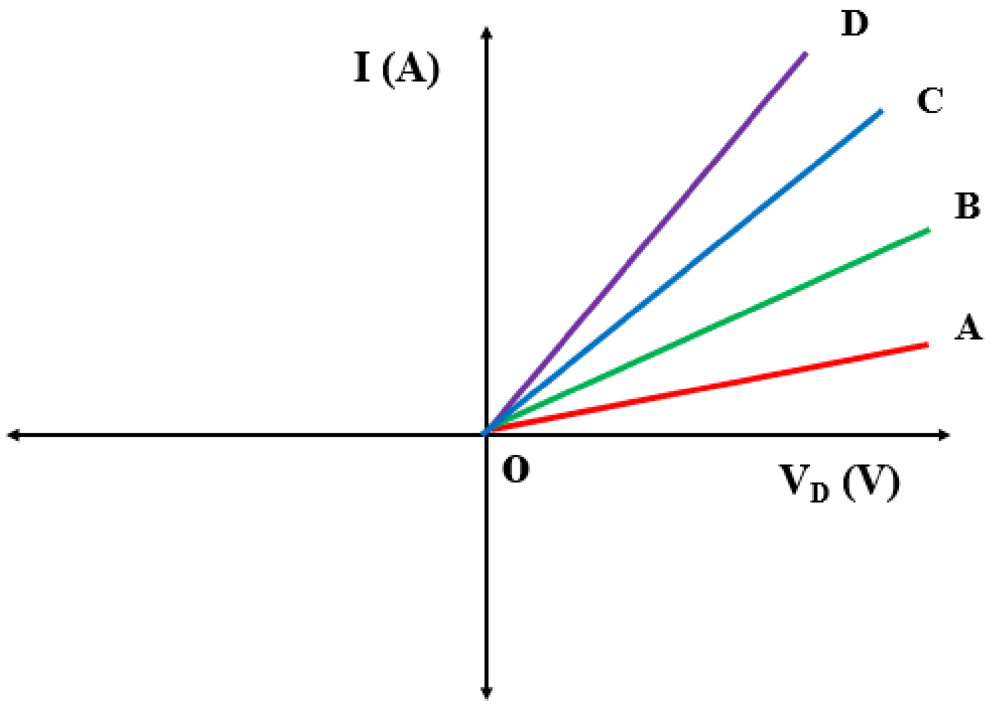
Type of (I-V) Characteristics

- Identify which of these I-V curves are Linear and which are Nonlinear



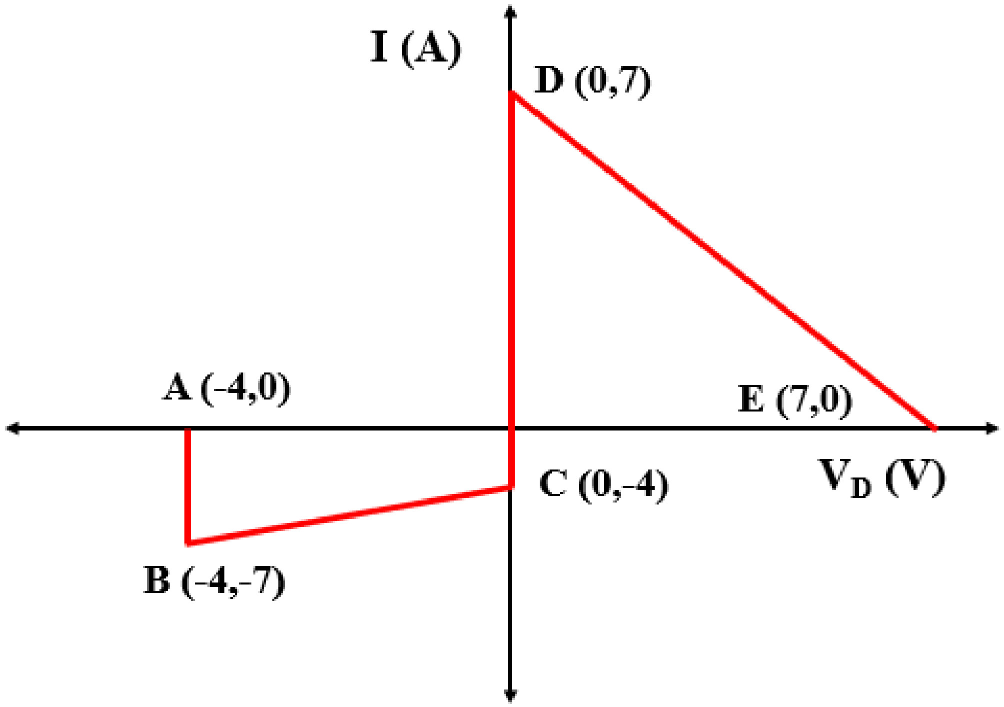
Linear Devices/Elements

- Write down the slopes of these following regions in ascending order (you do not need to calculate the slopes)



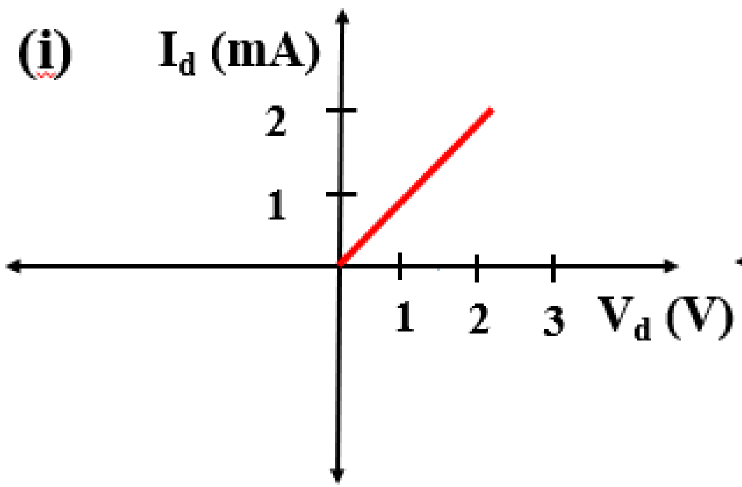
Linear Devices/Elements

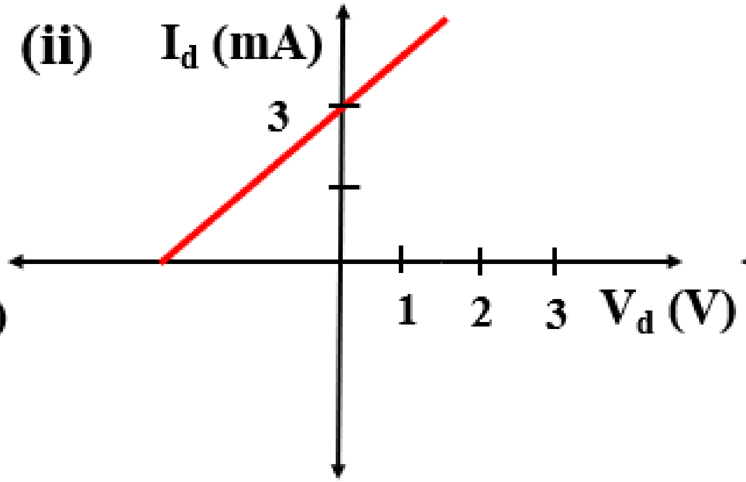
- Find out the slope of the following curves

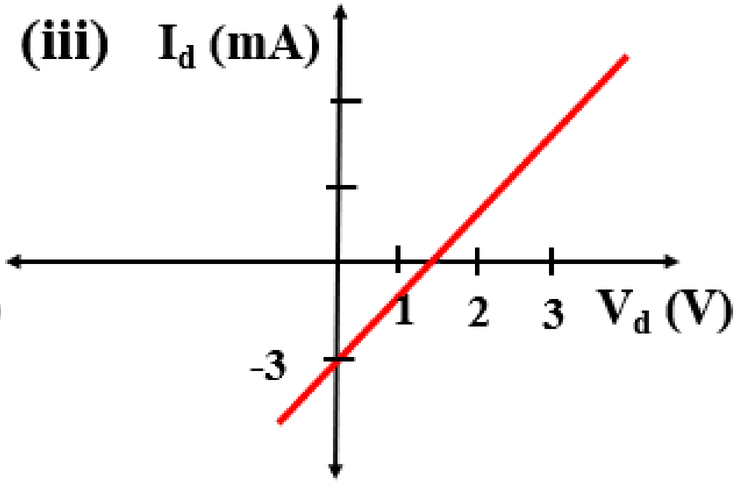


Linear Devices/Elements

- For the lines represented by $\boldsymbol{y = mx + c}$ what is the value of $\boldsymbol{c}$ in the following figures [Figure (i), (ii) and (iii)]

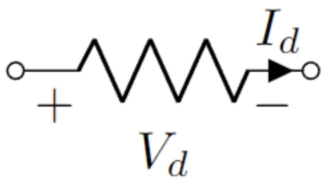


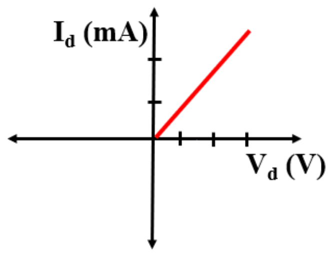




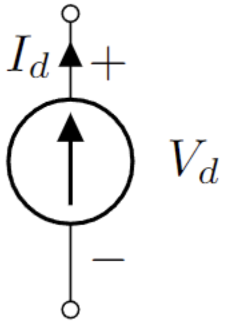
Linear Devices/Elements:

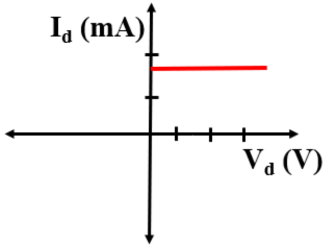
- Resistors



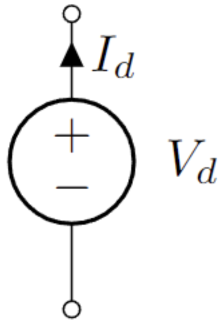


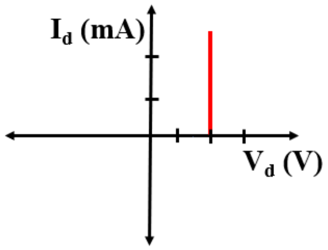
- Current Source





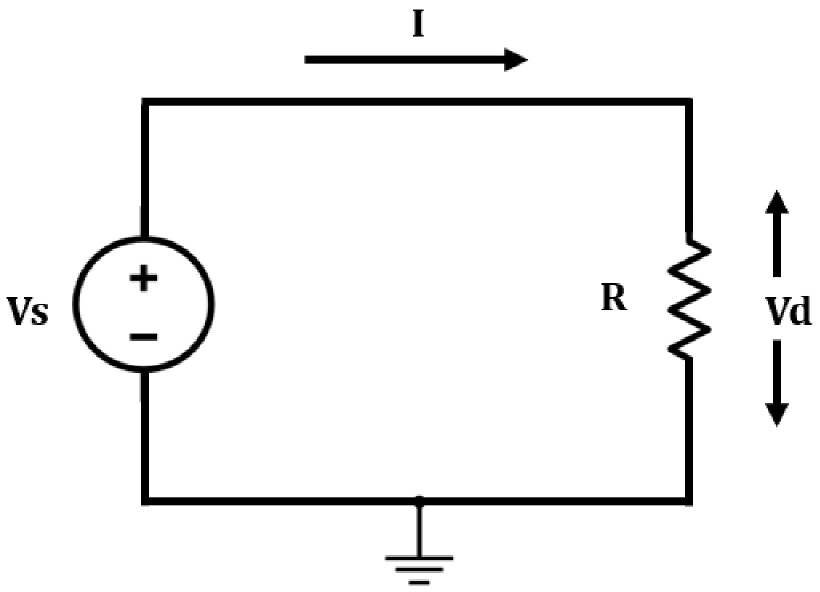
- Voltage Source





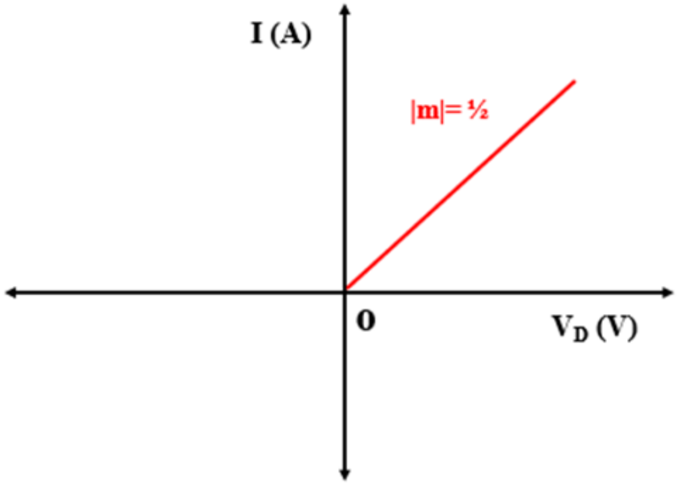
Resistor

- The relationship between current, $\boldsymbol{I}$ and voltage, $\boldsymbol{V_d}$ in a resistor of value '**R**' is defined by the "**<u>Ohm's law</u>**":



$$V_d = IR$$
$$\Rightarrow I = \frac{V_d}{R}$$
$$\Rightarrow I = \frac{1}{R} \cdot V + 0$$

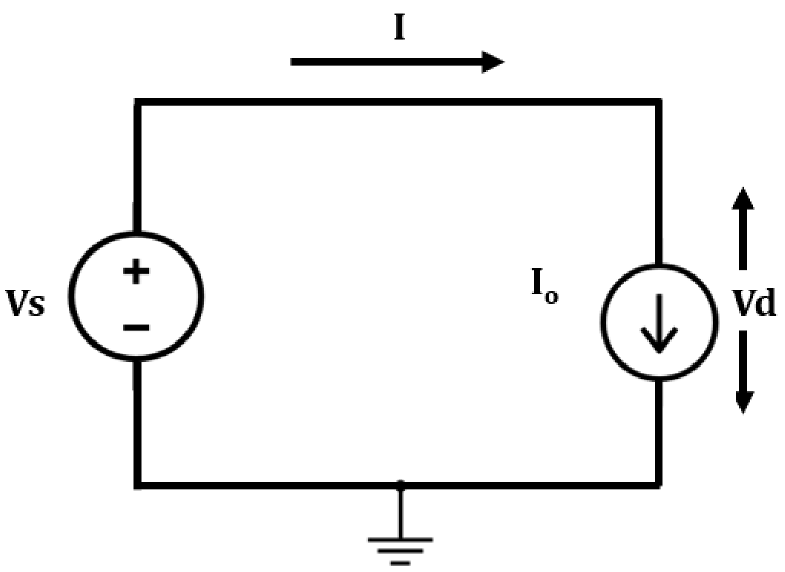
$$\boldsymbol{y = m \cdot x + c}$$



I-V curve of a 2Ω resistor

Current Source

- The value of current flow through a current source is **FIXED** and thus does not change with voltage. The equation is as follows



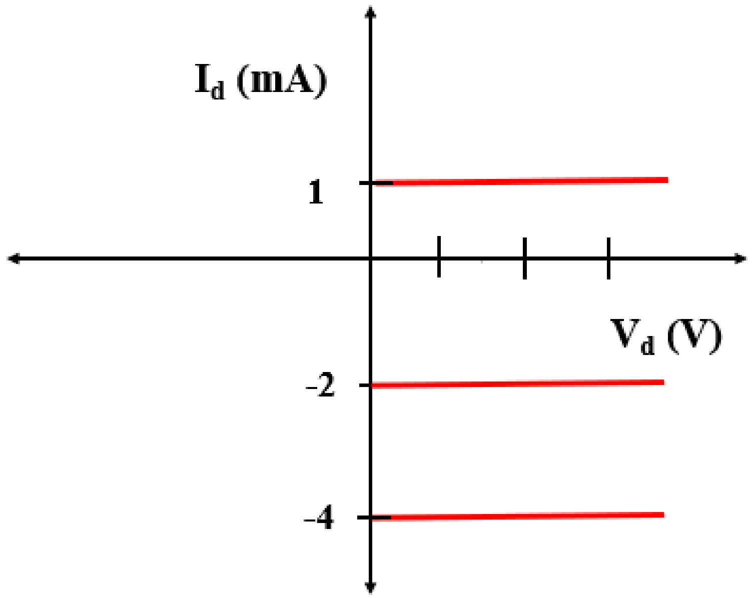
$$I = I_0$$

$$\boldsymbol{y = c}$$

$$I = 0 \cdot V_d + I_0$$

$$\boldsymbol{y = m \cdot x + c}$$

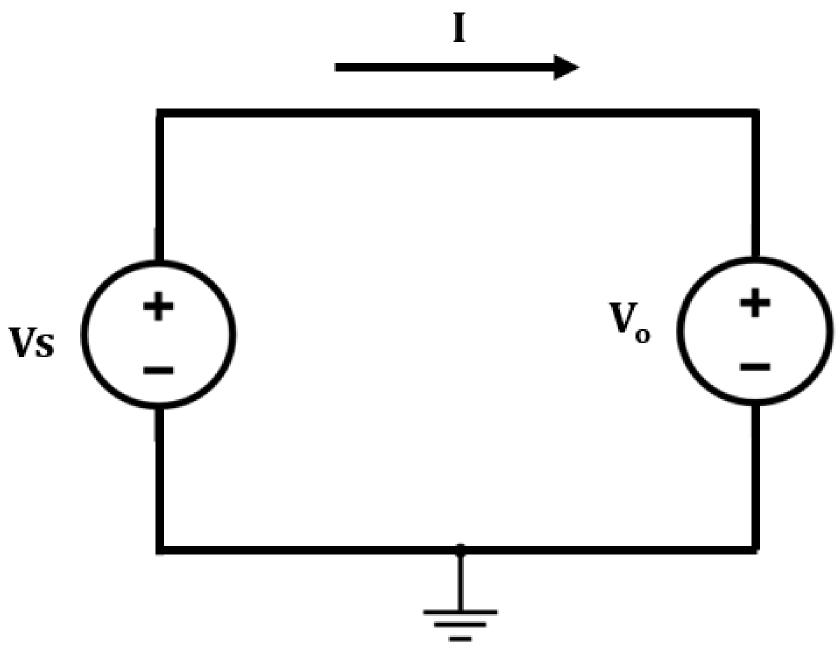
Slope: $\boldsymbol{m = 0}$



This curve intersects the y axis at $\boldsymbol{I = I_0}$.

Voltage Source

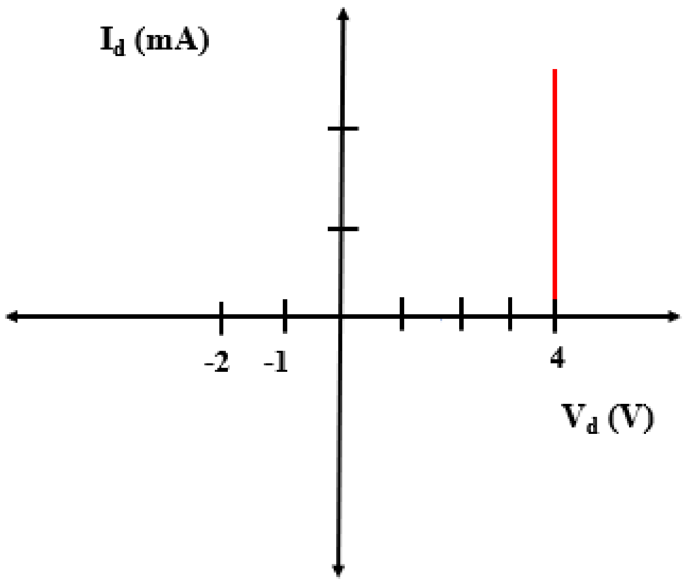
- The value of *voltage across a voltage source* is **FIXED** and thus does not change even if the current through the branch changes.



$$V = V_0$$

$$x = c$$

Slope: $m = \infty$

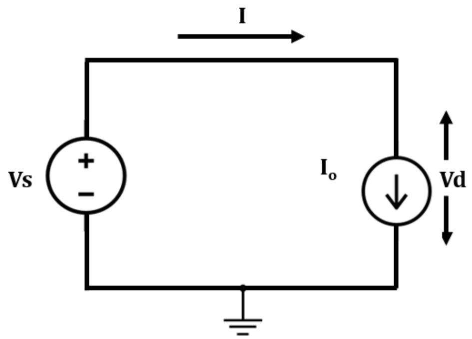


This curve intersects the x axis at $V_d = V_o$.

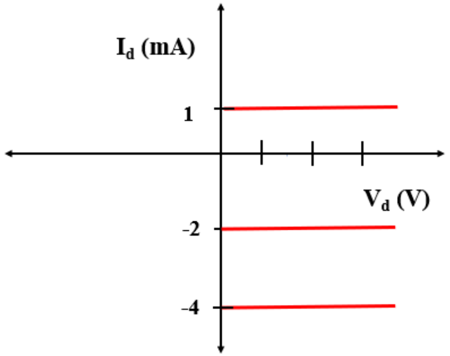
Electrical Sources

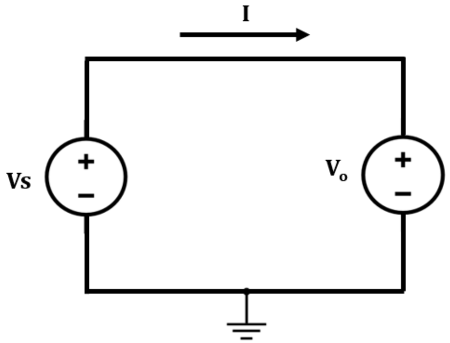
Ideally, internal resistance of a **CURRENT SOURCE** is **infinite (undefined)**

That of a **VOLTAGE SOURCE** is **zero**

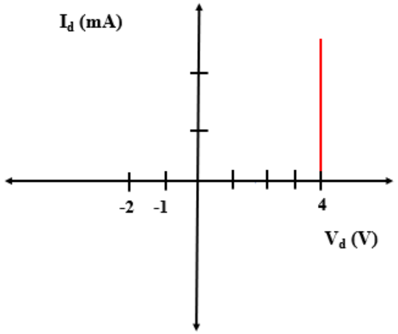


Resistance: ∞



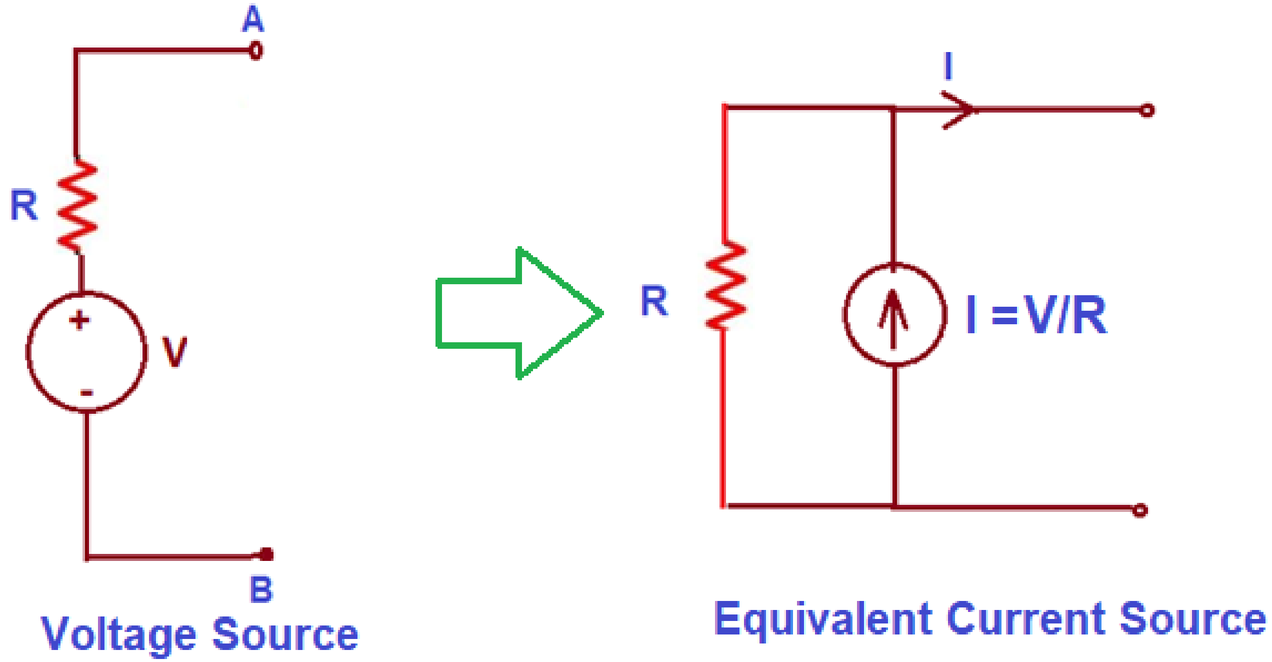


Resistance: 0

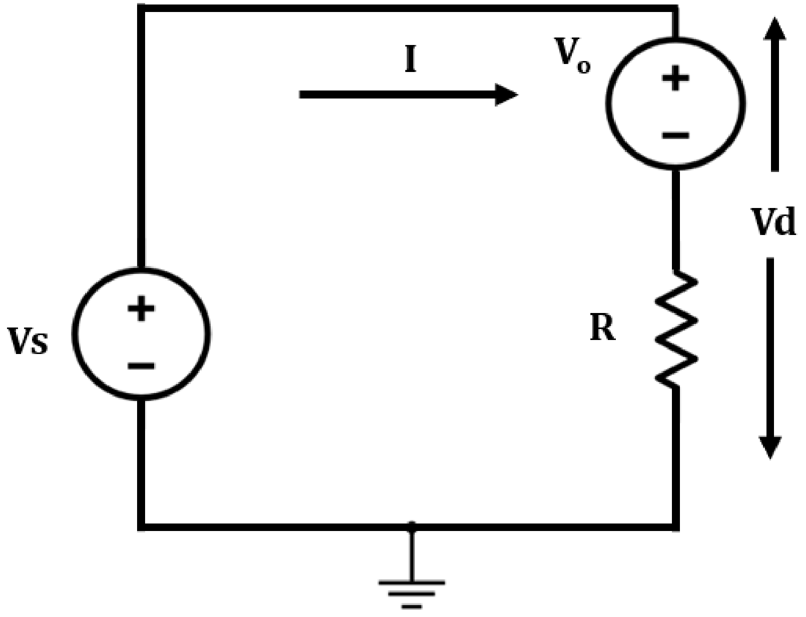


Hybrid/ Compound Linear Circuits

- Voltage Source in Series with a Resistor
- Current source in Parallel with a Resistor



Voltage Source in Series with a Resistor



$$V_d - V_o = IR$$

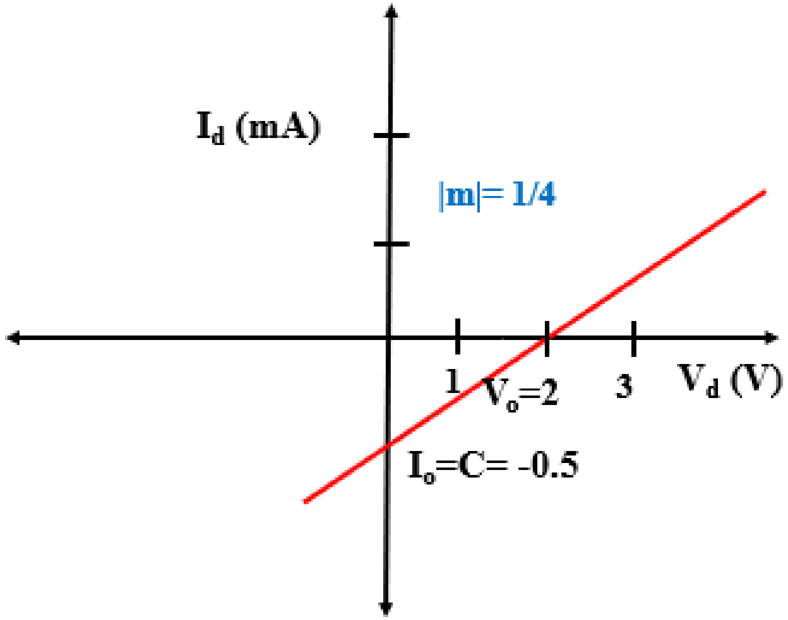
$$\Rightarrow I = \frac{V_d - V_o}{R}$$

$$\Rightarrow I = \frac{1}{R} \cdot V_d - \frac{Vo}{R}$$

$$\boldsymbol{y = mx + c}$$

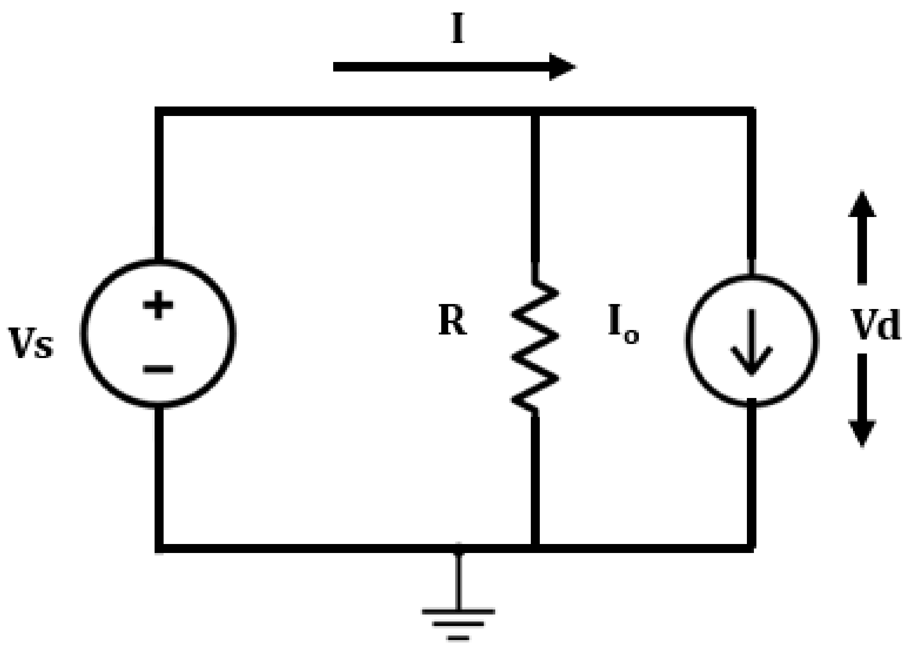
$$\boldsymbol{m = \frac{1}{R}}$$

$$\boldsymbol{c = -\frac{V_0}{R}}$$



I-V curve of a **4** $\boldsymbol{k\Omega}$ resistor in series with a **2 V** voltage source

Current source in Parallel with a Resistor



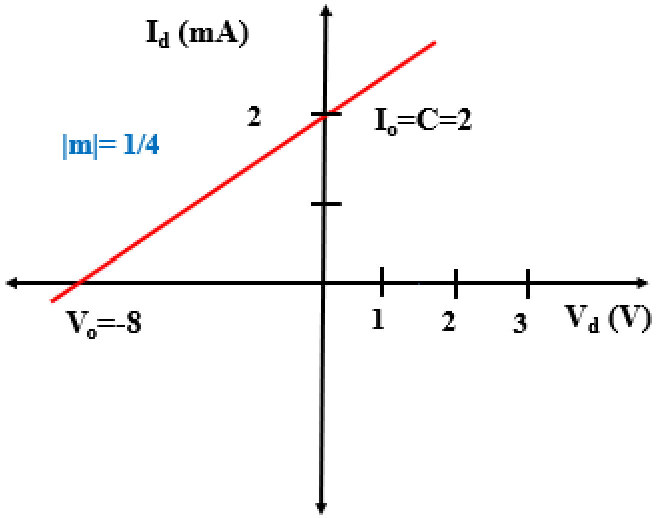
$$I = \frac{V_d}{R} + I_0$$

$$\Rightarrow I = \frac{1}{R} \cdot V_d + I_0$$

$$\boldsymbol{y = mx + c}$$

$$\boldsymbol{m = \frac{1}{R}}$$

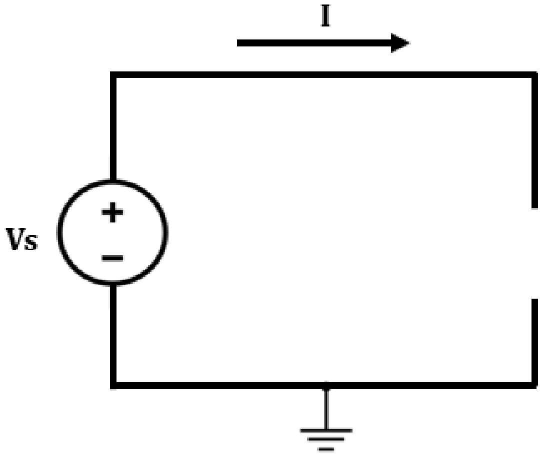
$$\boldsymbol{c = I_0}$$



The value of a resistor CAN NOT be Negative!

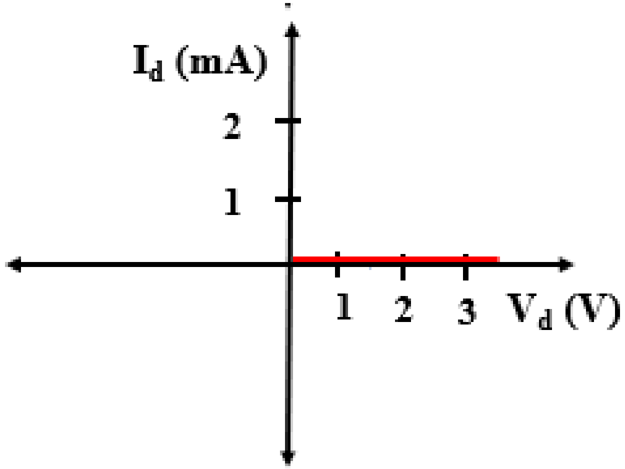
Degenerate Linear Elements

- Open Circuit

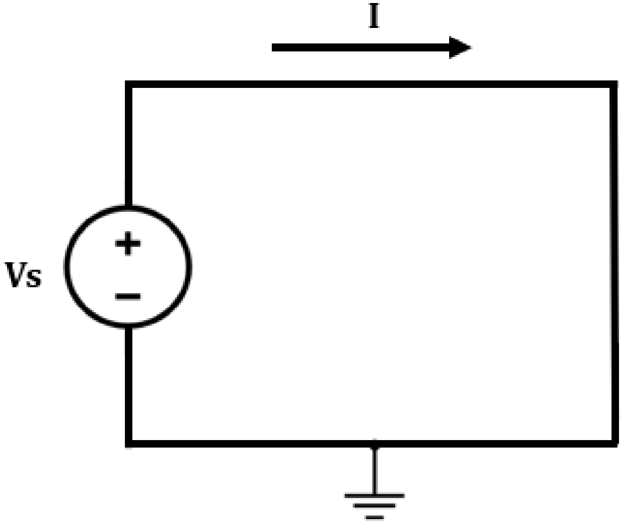


$$I_d = I_0 = 0$$

$$\boldsymbol{y = c = 0}$$

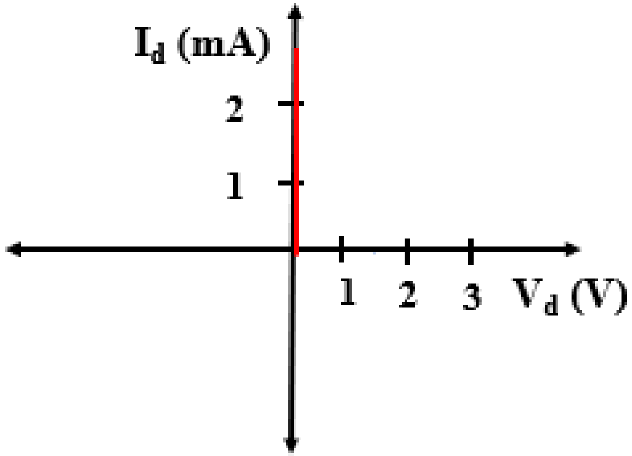


- Short Circuit



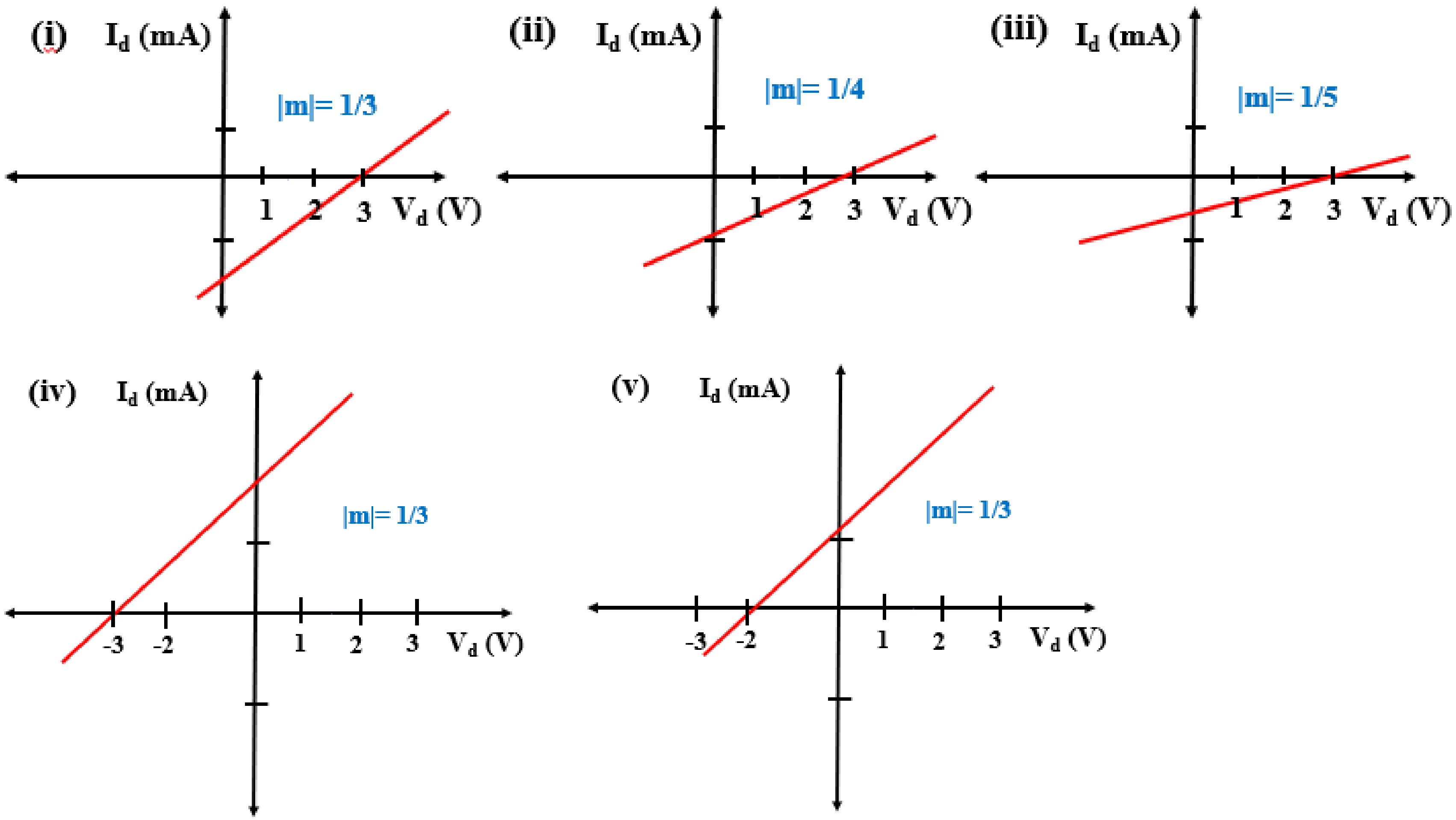
$$V = V_0 = 0$$

$$\boldsymbol{x = c = 0}$$



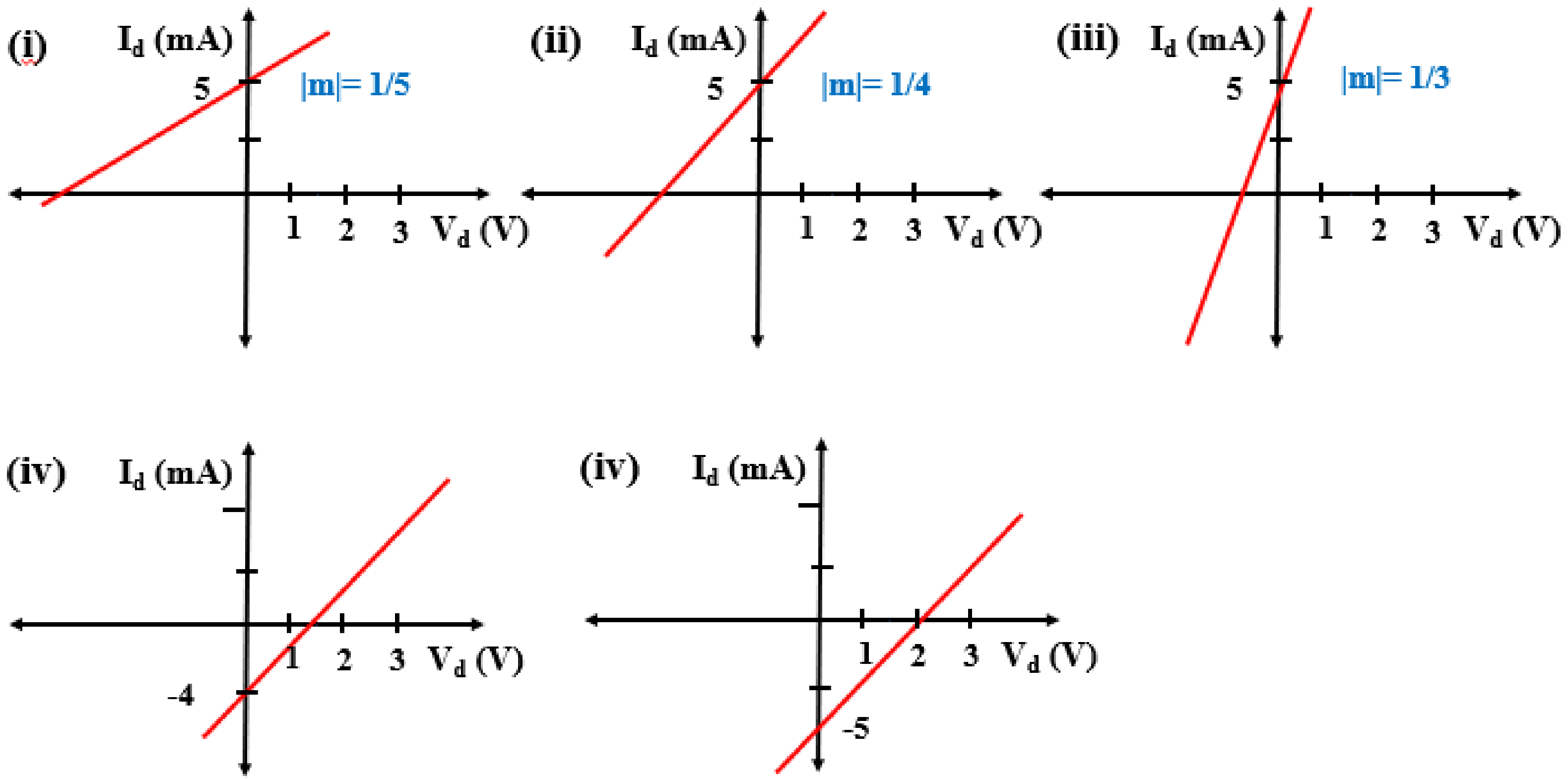
Voltage Source in Series with a Resistor

- Find the circuit



Current source in Parallel with a Resistor

Find the circuit

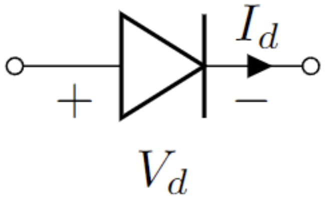


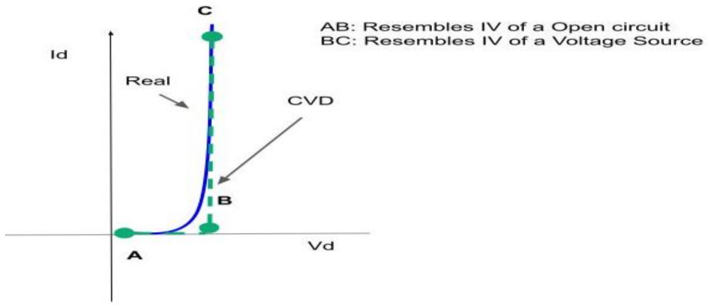
Practice Problems

1. A Voltage Source, $V_o = -10$ V in series with a resistor of $R = 3$ kΩ.
   i. Write down the equation representing this curve
   ii. Determine the unknown parameters
   iii. Label the I-V curve
2. A Current Source, $I_o = -5$ mA in parallel with a resistor of $R = 5$ kΩ.
   i. Write down the equation representing this curve
   ii. Determine the unknown parameters
   iii. Label the I-V curve
3. A Current Source, $I_o = 5$ mA in parallel with a resistor. The slope of the curve is, $m = -5\ k\Omega^{-1}$.
   i. Write down the equation representing this curve
   ii. Determine the unknown parameters
   iii. Label the I-V curve

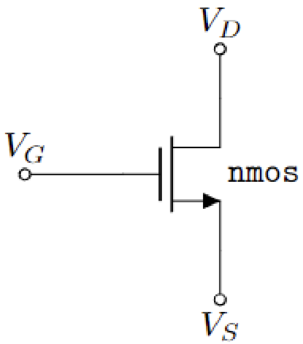
Non-Linear Devices/Elements

- Diode

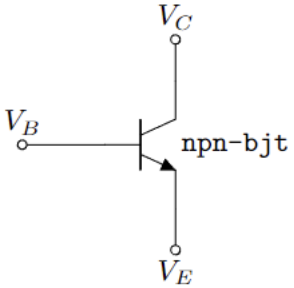


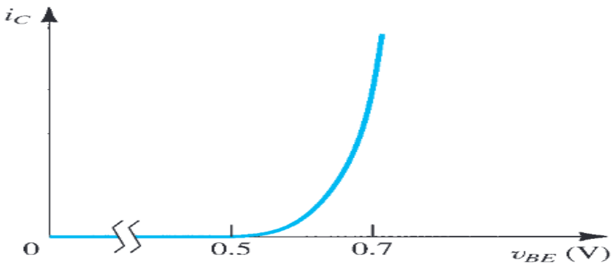


- MOSFET



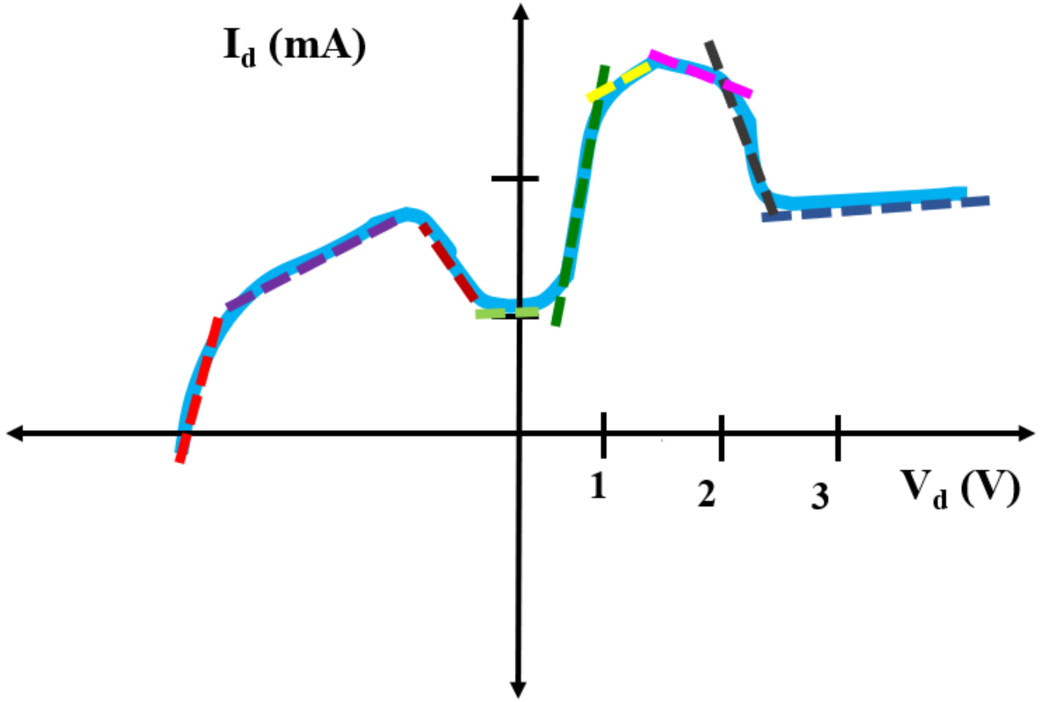
- BJT





Piecewise Linear Approximation for NL devices

- Simplifying non-linear IV characteristics by piecewise linear parts.
- Non-linear functions are usually approximated by a series of linear segments that follow the tangent of the non-linear segment as can be seen from the following figure.



Semiconductor Devices

- Semiconductors are special class of materials (as opposed to conductors and insulators) that fall between conductors and insulators in terms of their electrical conductivity.
- By making simple material changes, such as doping, these materials can achieve remarkably precise control over electron flow.
- This ability to control electron flow makes semiconductors the optimal candidate for building non-linear electrical devices, where electron (current) flow is not always just proportional to the applied voltage.
- As these non-linear devices offer exceptional control over electron flow, the class of devices and circuits are branched under the umbrella term “Electronics”

Semiconductor Materials

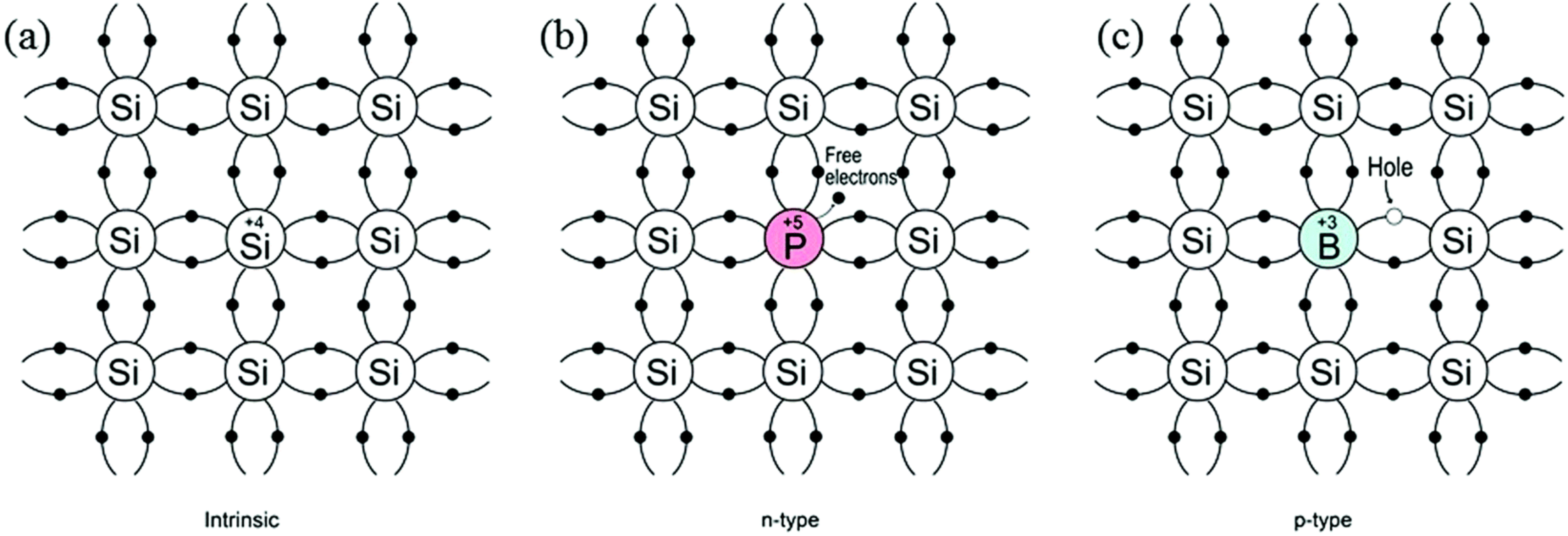
What is doping?

Doping is to deliberately inject atomic level “impurities” into a material (such as an “intrinsic” or **pure semiconductor** such as **Silicon**. These atoms are called dopants.

Usually, the concentration of the “dopant” atoms is much less than the actual concentration of the host material.

Since the atoms being injected are different from the actual material atom, they are considered impurities. A doped semiconductor is also known as “**Extrinsic**” semiconductor.

Semiconductor Materials

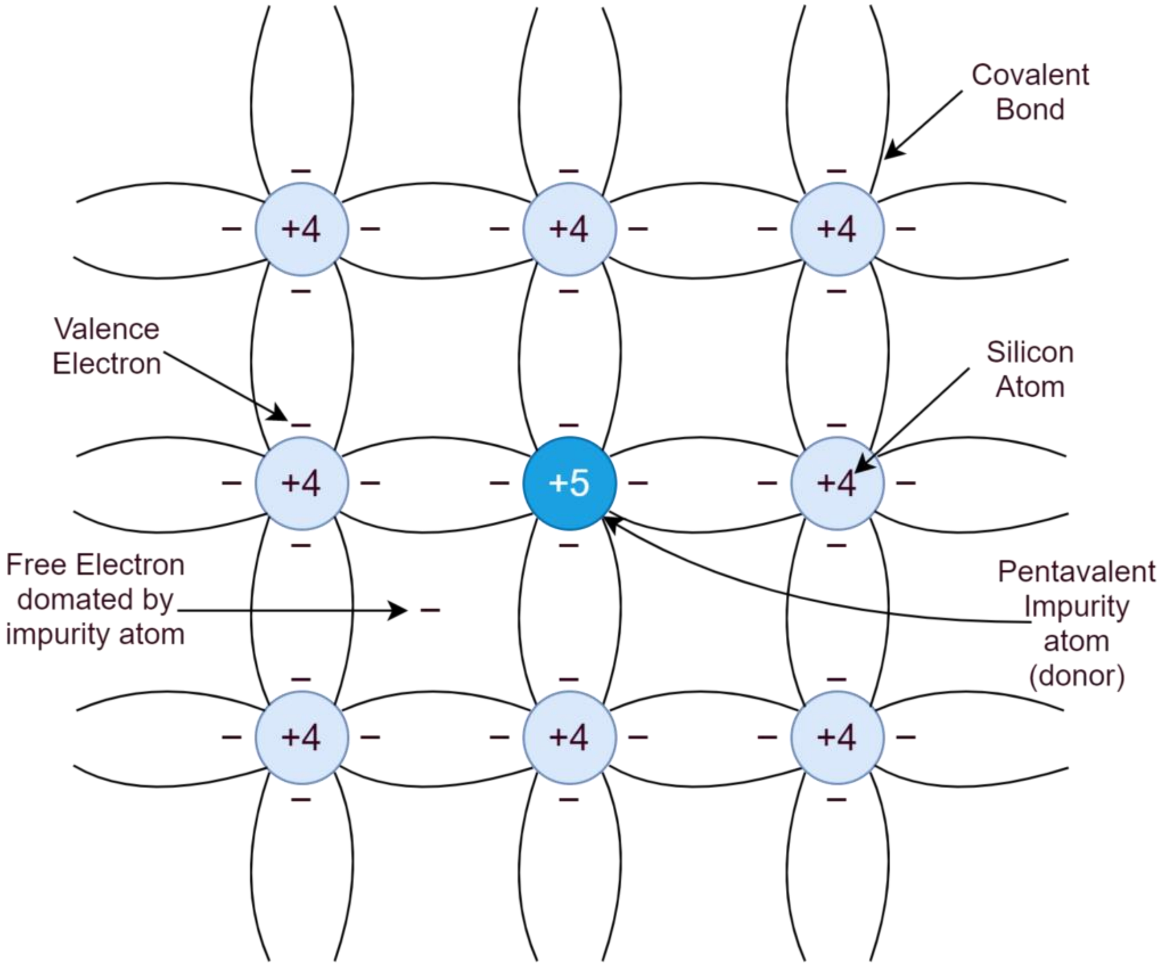


n-type doped → Si lattice is riddled with pentavalent atoms

p-type doped → Si lattice is riddled with trivalent atoms

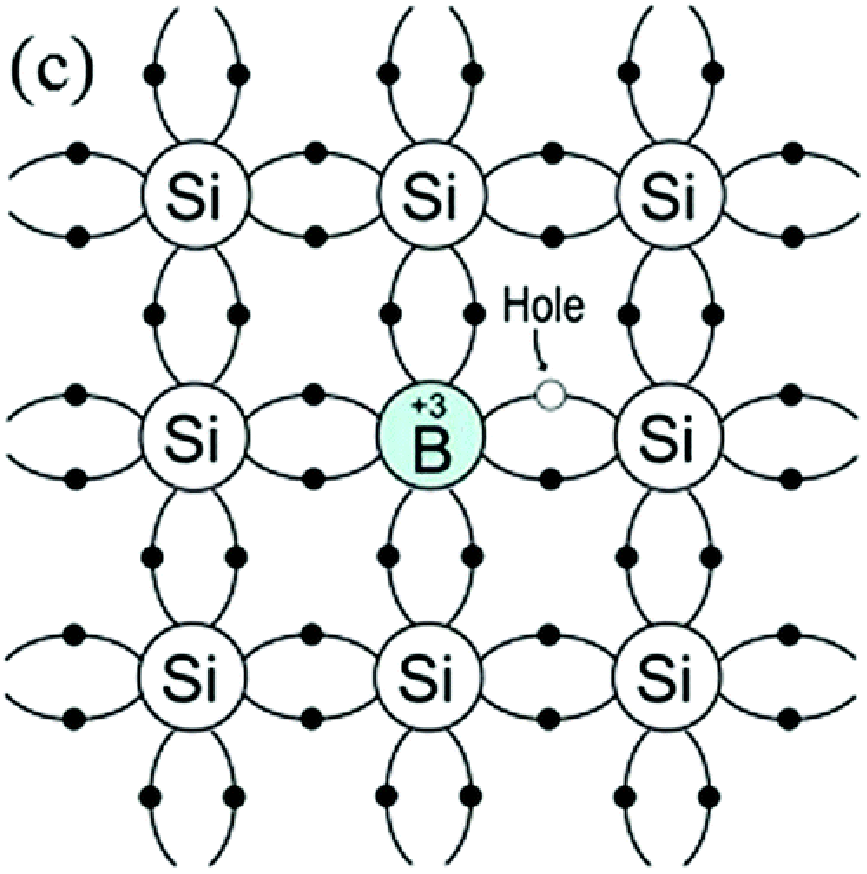
n-type doping

- n-type materials are doped with pentavalent atoms.
- Pentavalent atoms have one more electron than the surrounding tetravalent **Si** atoms.
- This lone extra electron acts as a mobile electron that can flow easily as it is not bonded to any atom.



p-type doping

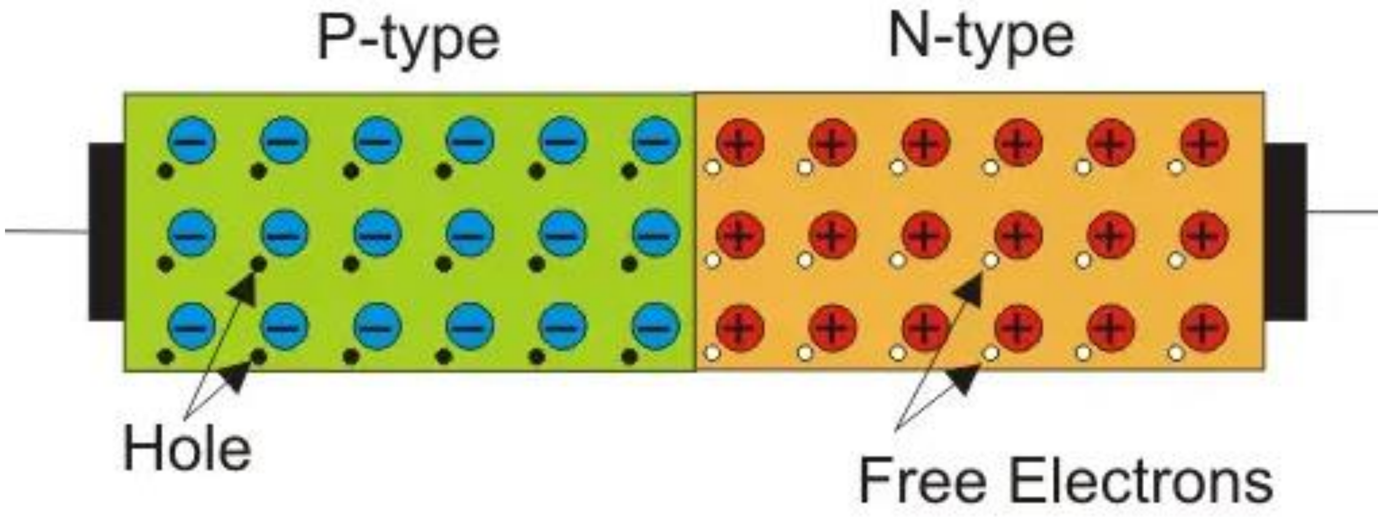
- p-type materials are doped with trivalent atoms.
- Trivalent atoms have one less electron than the surrounding tetravalent Si atoms.
- This absence of an electron (termed as a hole) acts as can flow easily from atom to atom across the material as it is not bonded to any atom. The flow of holes is opposite to the actual flow of electrons.



p-type

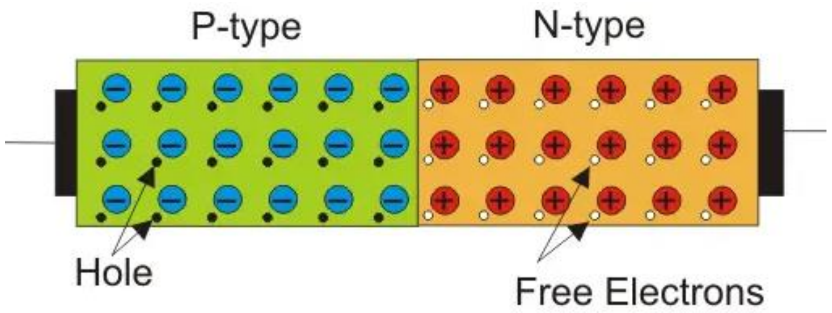
Semiconductor Devices

- Diode is the most basic semiconductor device.
- It is made by doping an intrinsic semiconductor (**Si**) half as **p-type** and the other half as **n-type**.



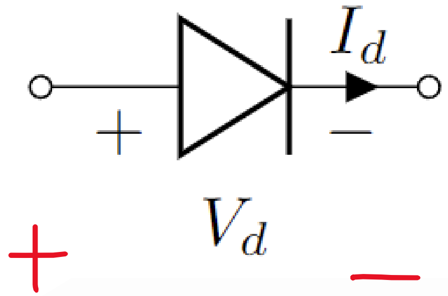
The **pn** junction diode: Physical characteristics

Internal Structure



Circuit Schematic

Anode



Cathode

Real device image

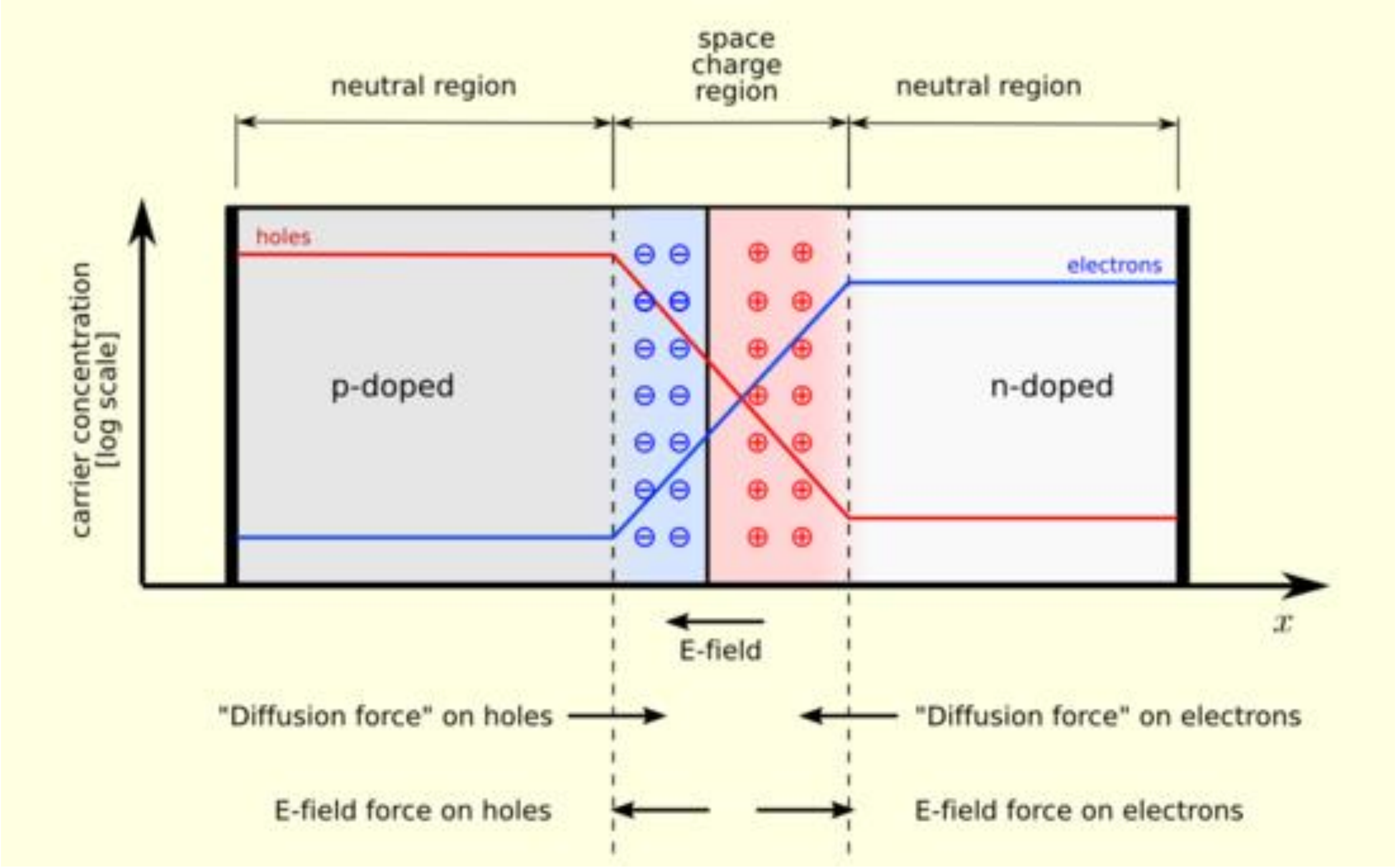
The **pn** junction diode: Physical characteristics

The depletion region:

This is the region in a **pn-**junction device sandwiched between the *n-doped* and *p-doped* regions.

In n-doped region, mobile electrons dominate charge flow. In p-type, holes dominate.

In a pn-junction depletion regions form naturally, as charge carriers (holes in p-type and electrons in n-type) near the pn junction boundary seep into each other.



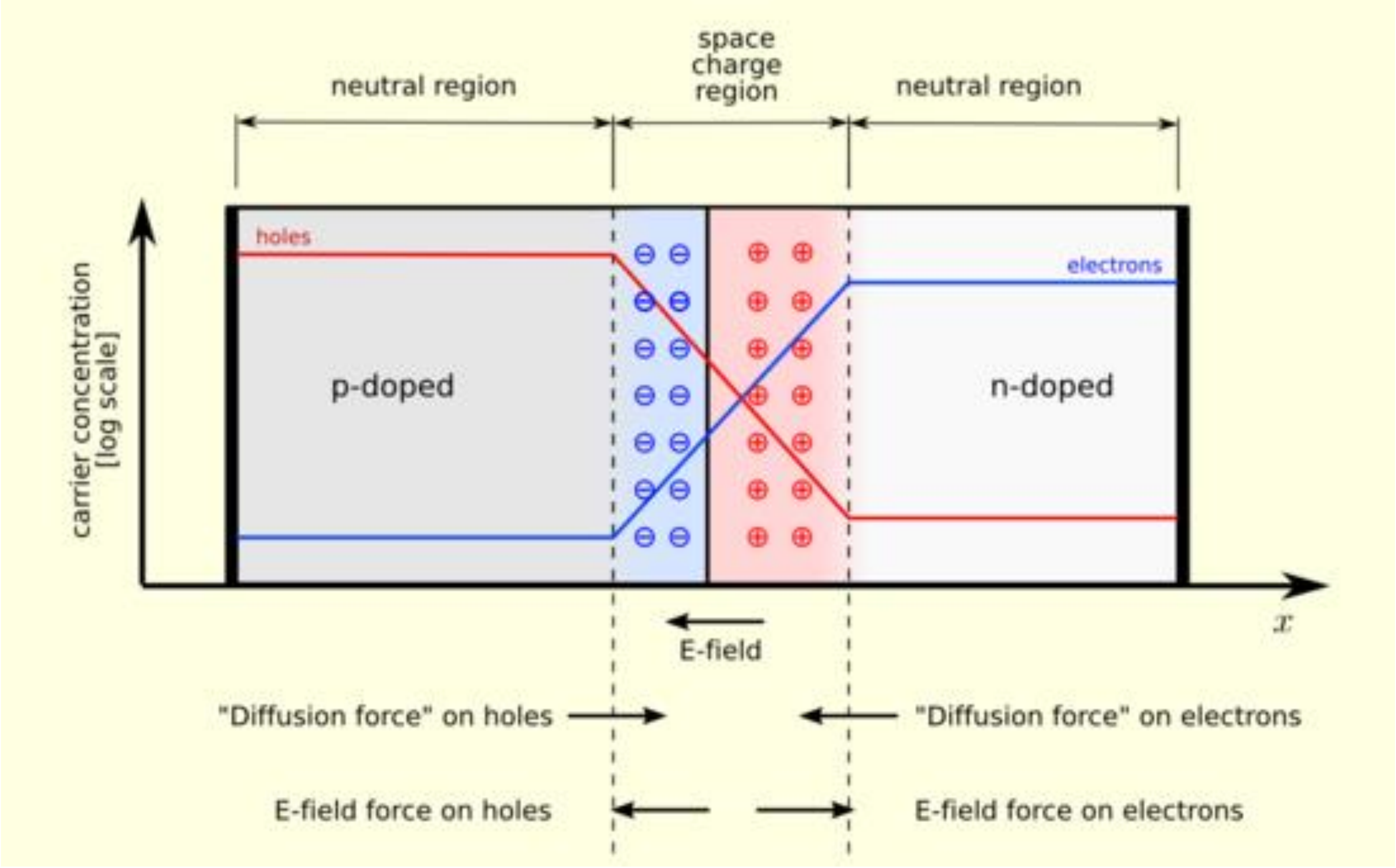
The **pn** junction diode: Physical characteristics

The depletion region:

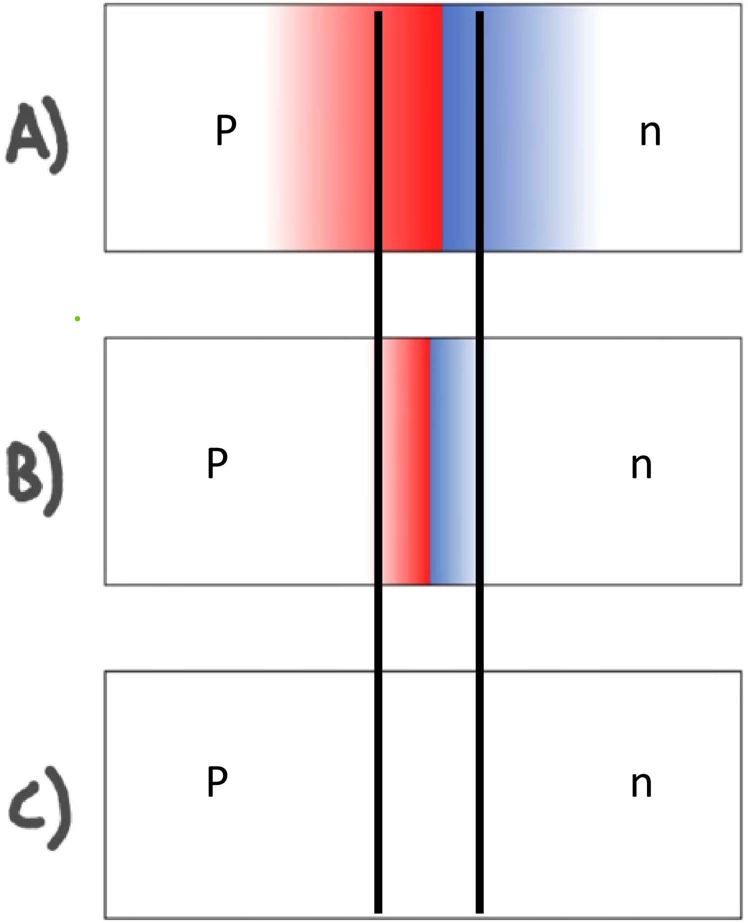
In a pn-junction depletion regions form naturally, as charge carriers (holes in p-type and electrons in n-type) near the pn junction boundary seep into each other.

Electrons from n-type region flow into p-type region while holes flow into n-type region from p-type region.

This mutual overflow into the opposite region, creates a space charge barrier, (like that in a capacitor).

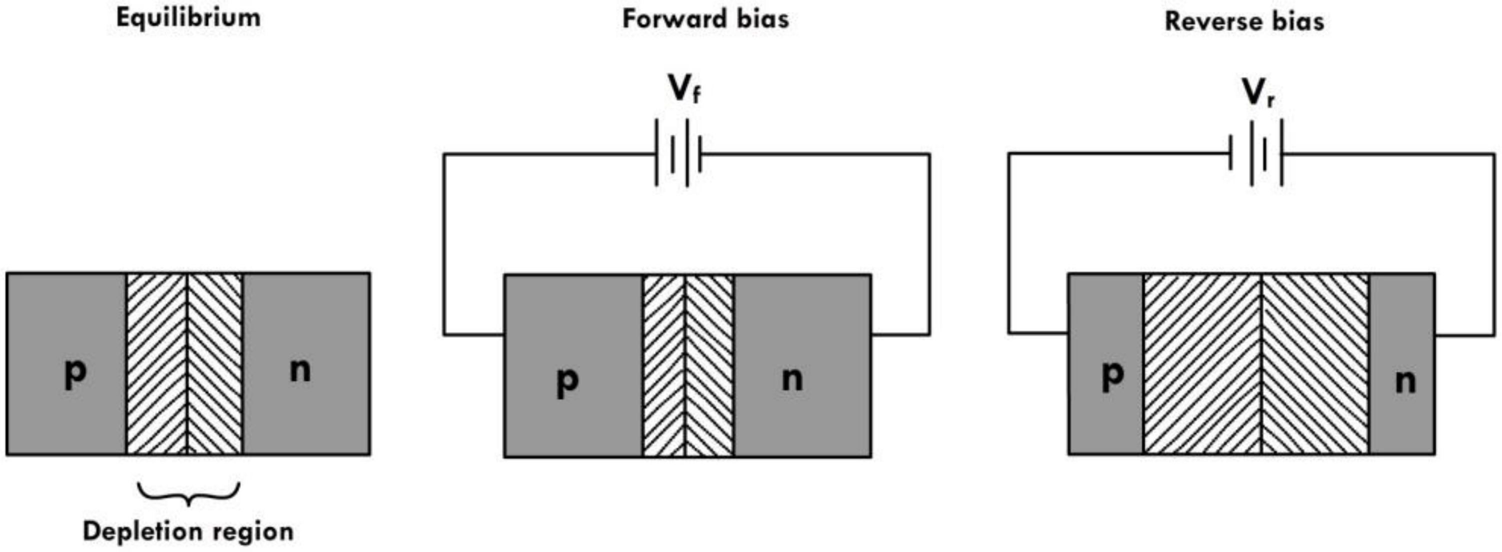


The **pn** junction diode: Modes of operation



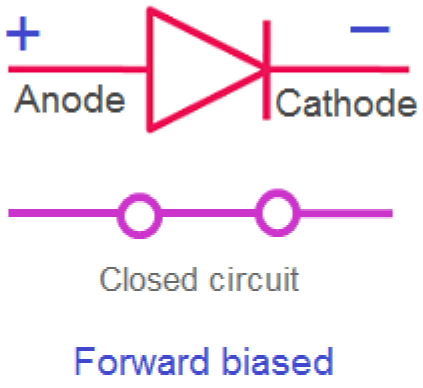
Depletion Region

A) Reverse Bias
B) No Bias
C) Forward Bias

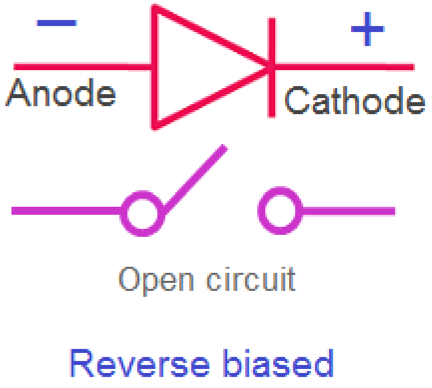


The **pn** junction diode: 2 Modes of operation

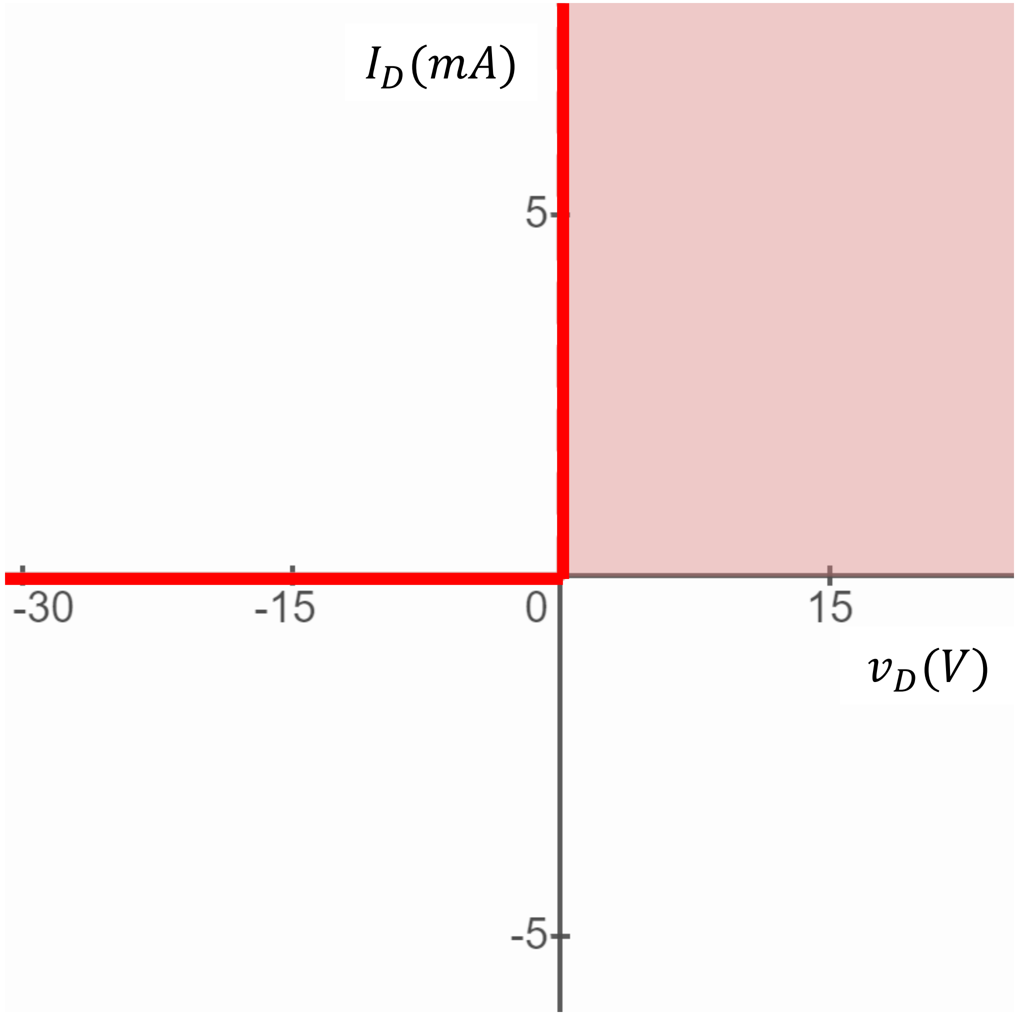
1. Forward Bias (FB):
   - Depletion Region is **constricted**.
   - ***Allow*** electrons to flow through the junction
   - Ideally acts as a **short circuit**



2. Reverse Bias (RB):
   - Depletion Region is **expanded**.
   - Bars / does not allow electron flow through the junction.
   - Ideally acts as an **open circuit**

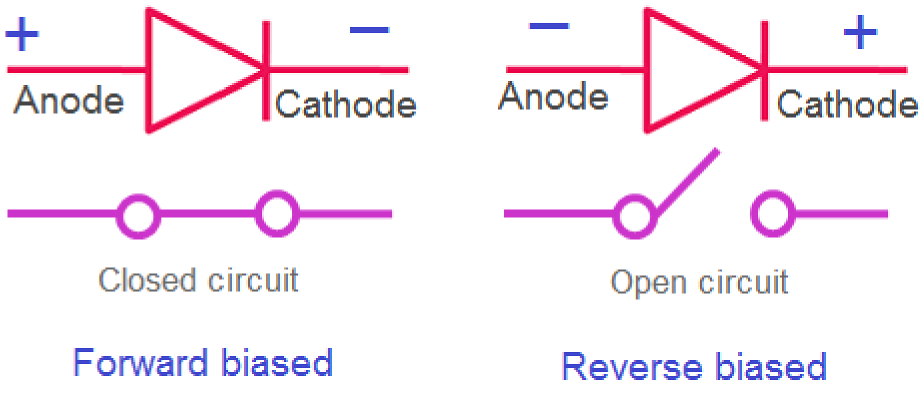


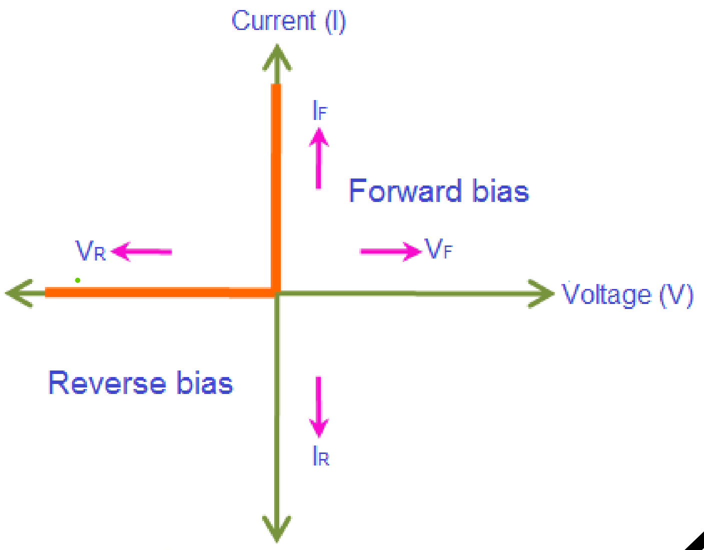
Piecewise Linear Models



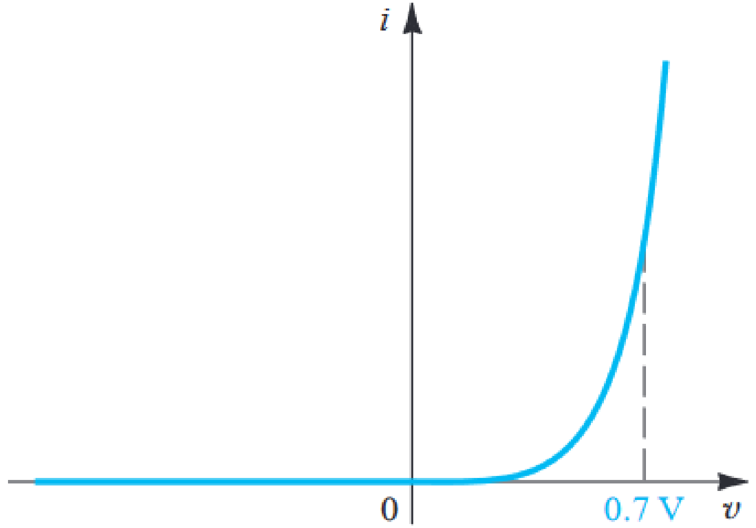
Diode Circuit Models

Ideal *Versus* Real Diode





Constant Voltage Drop
(CVD) Model



Ideal Model → **Real / Shockley** Model

Low Accuracy

Simple

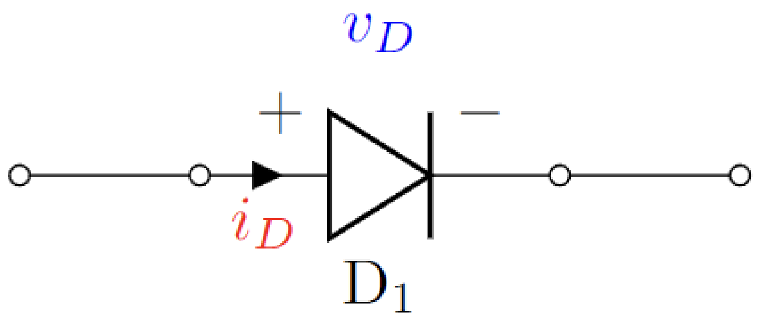
CVD with resistance
(CVD+R) Model

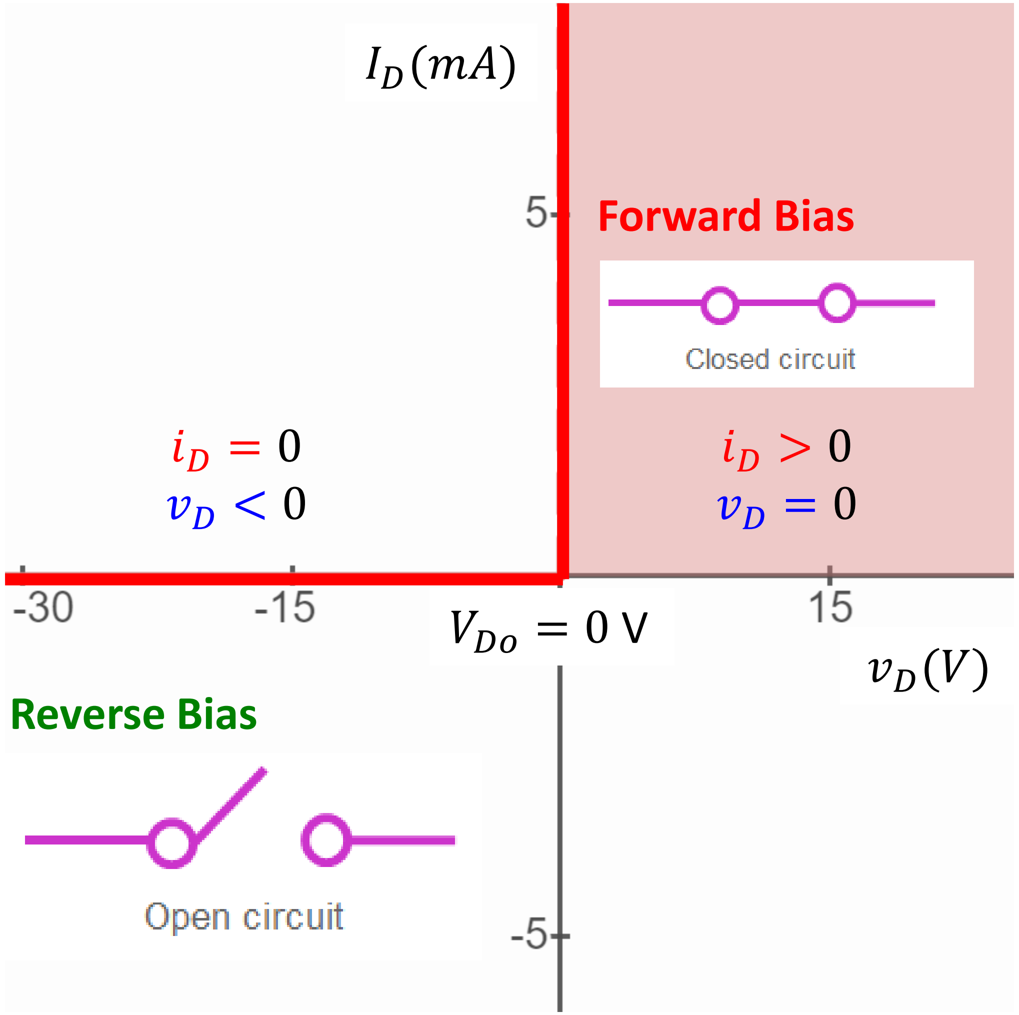
Increased Accuracy

More Complex

Diode Models

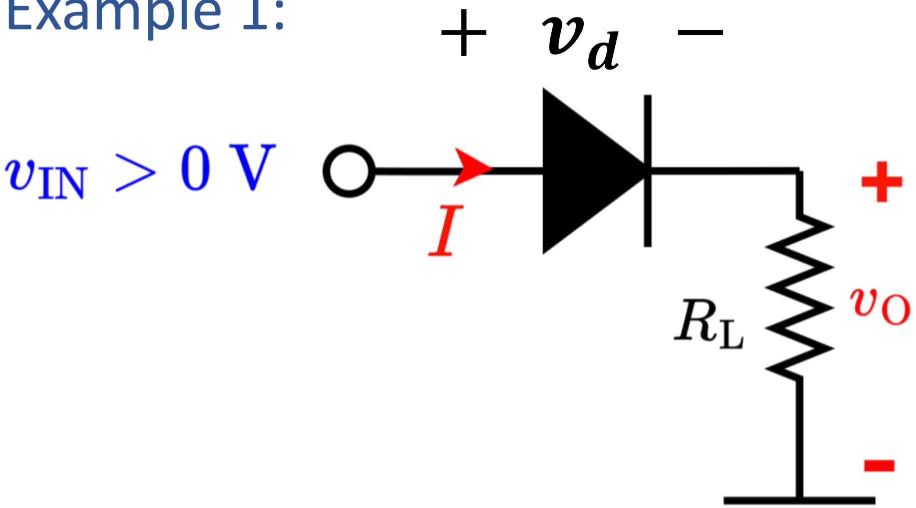
1. Ideal Diode Model:

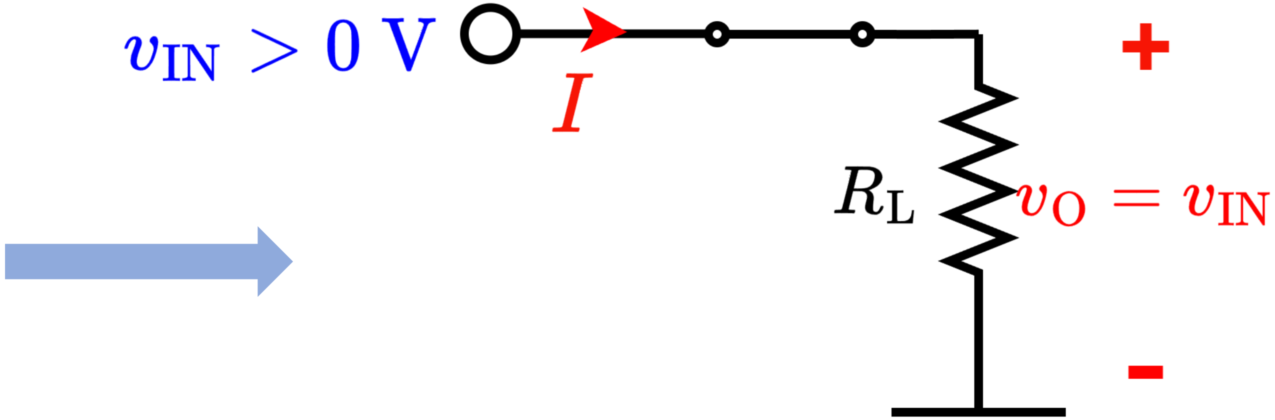




Example Problems (Ideal Diode)

Example 1:



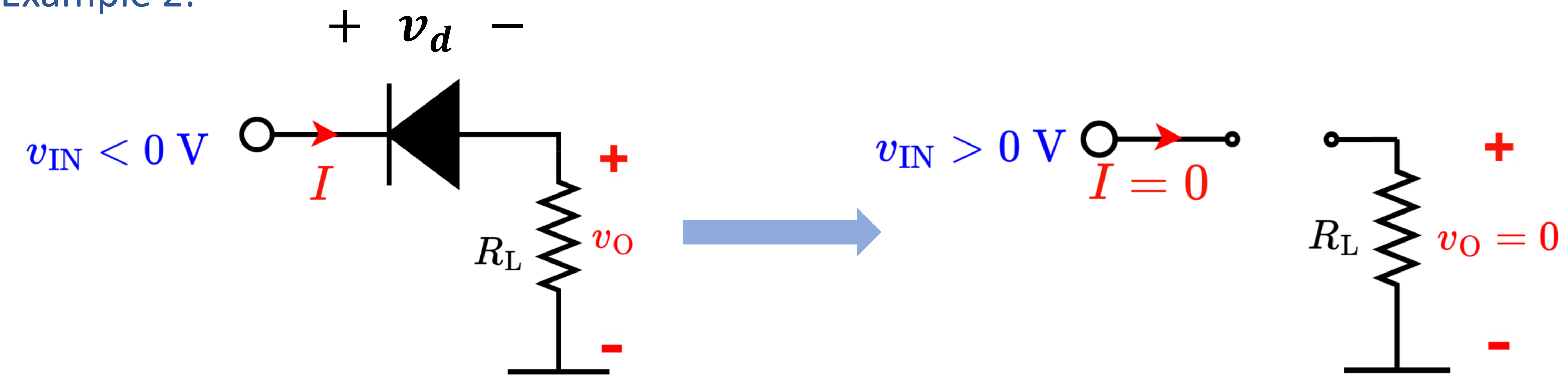


$$v_O = v_{IN} = 5 \text{ V}$$

$$I = \frac{v_O}{R_L} = \frac{5 \text{ V}}{2.5 \text{ k}\Omega} = 2 \text{ mA}$$

Example Problems (Ideal Diode)

Example 2:

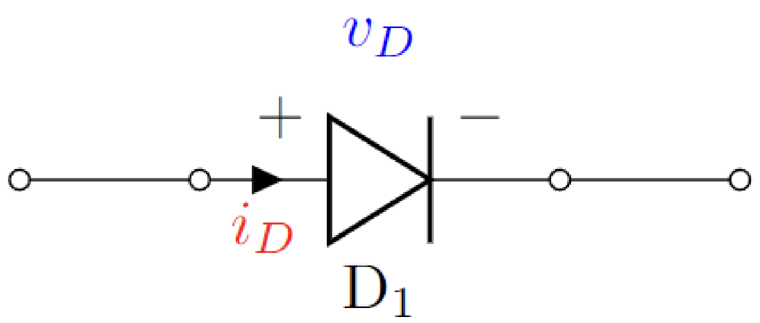


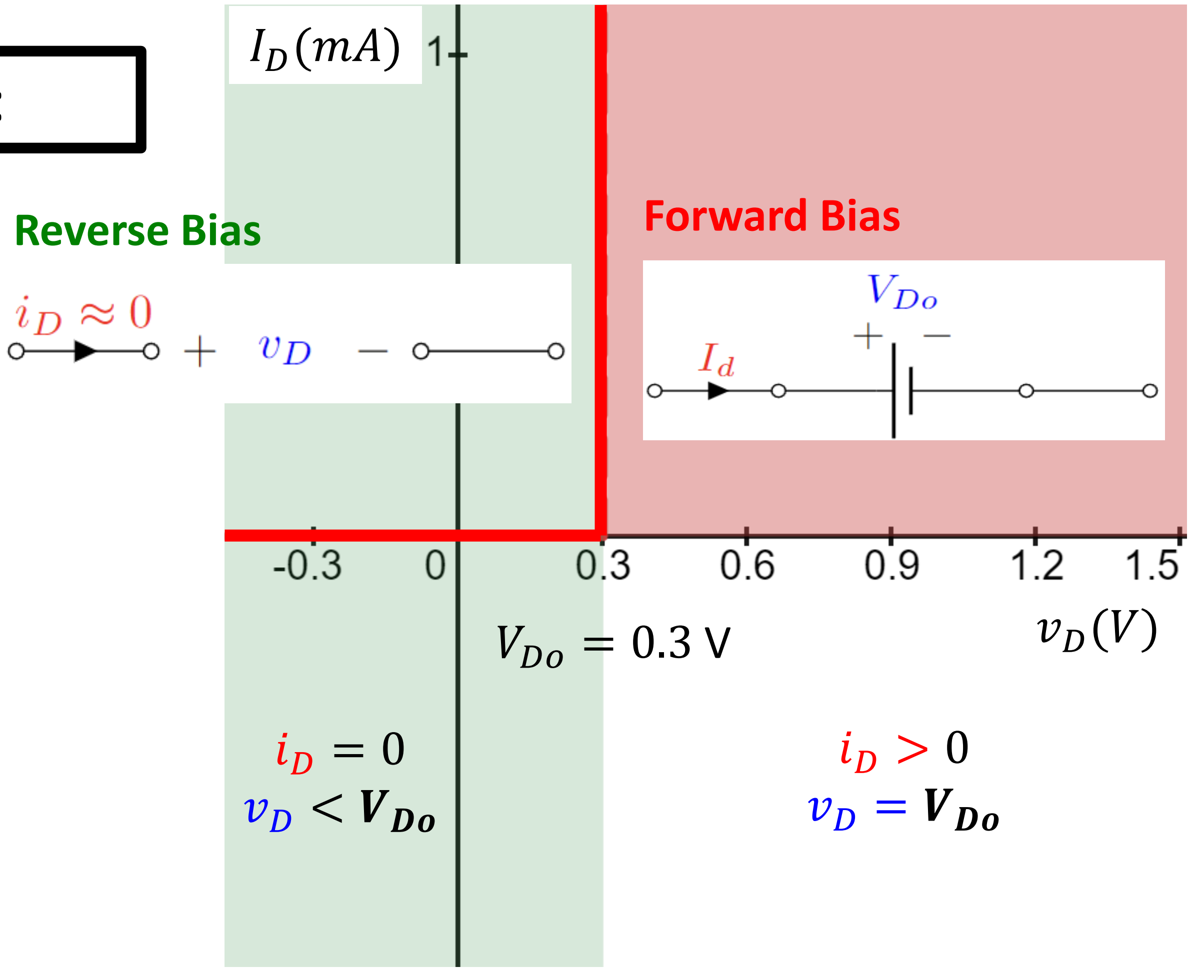
$$v_O = \cancel{v_{IN} = 5\text{ V}} = \mathbf{0\ V}$$

$$I = \cancel{\frac{v_O}{R_L}} = \mathbf{0\ mA}$$

Diode Models

2. Constant Voltage Drop (CVD) Model:



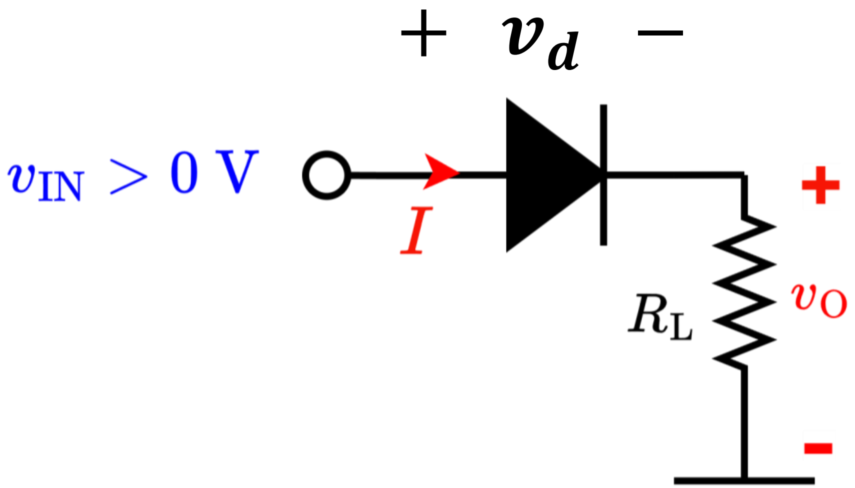


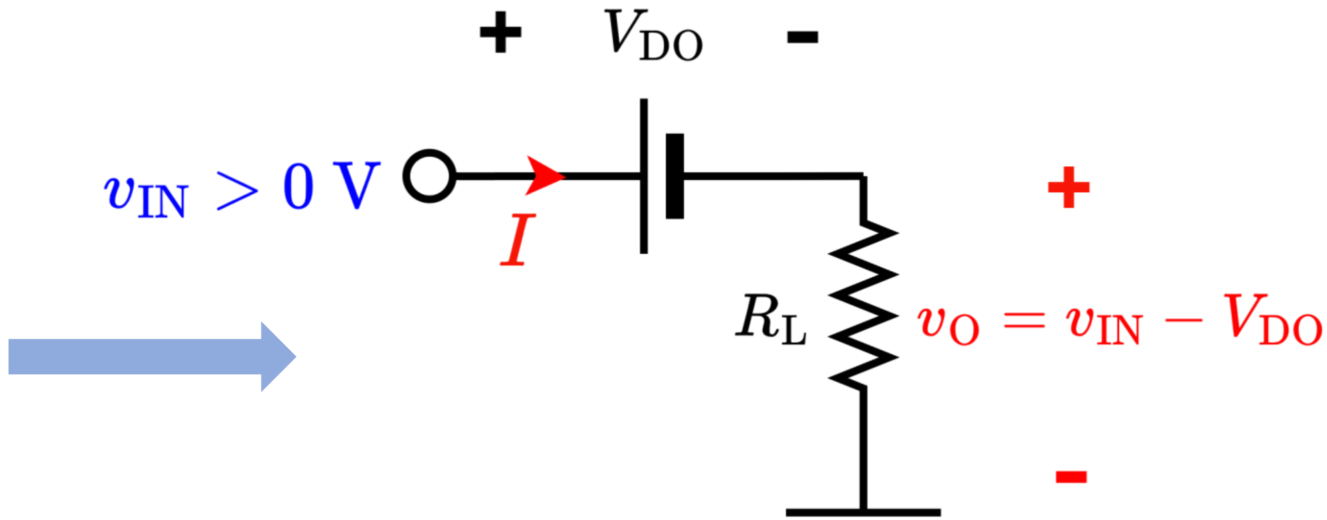
v_D: Total Voltage Across diode

V_{Do}: Diode Cut-off voltage (0.3 V here)

Example Problems (CVD Model)

Example 3:





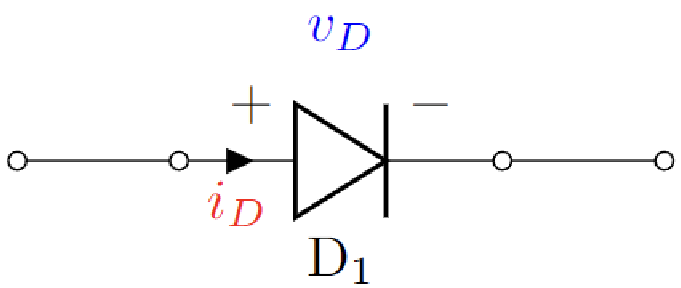
$$v_O = v_{IN} - V_{DO} = 5 - 0.7\ \mathrm{V}$$

Let, $V_{DO} = 0.7\ \mathrm{V}$

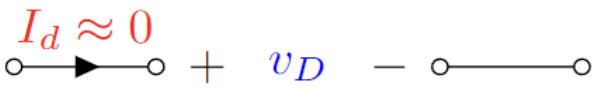
$$I = \frac{v_O}{R_L} = \frac{4.3\ \mathrm{V}}{2.5\ \mathrm{k\Omega}} = 1.72\ \mathrm{mA}$$

Diode Models

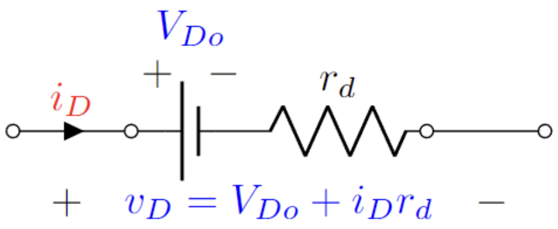
3. CVD+R Model:

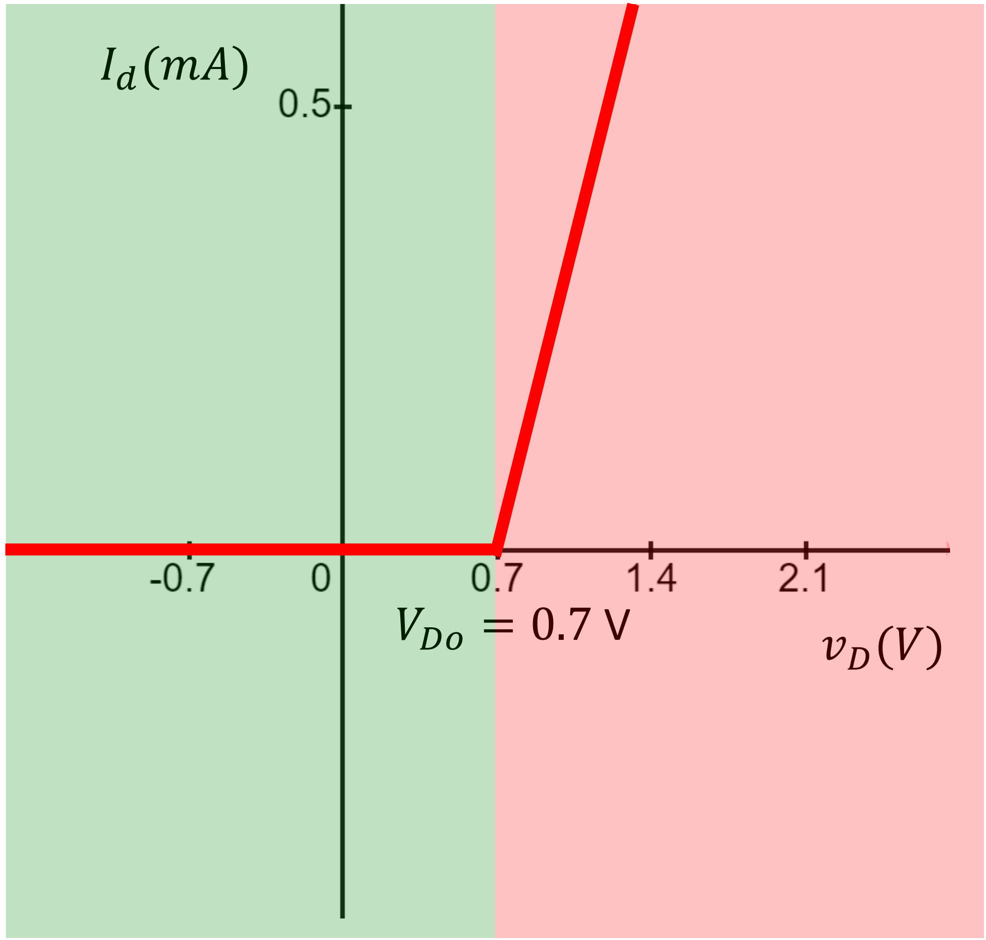


Reverse Bias



Forward Bias



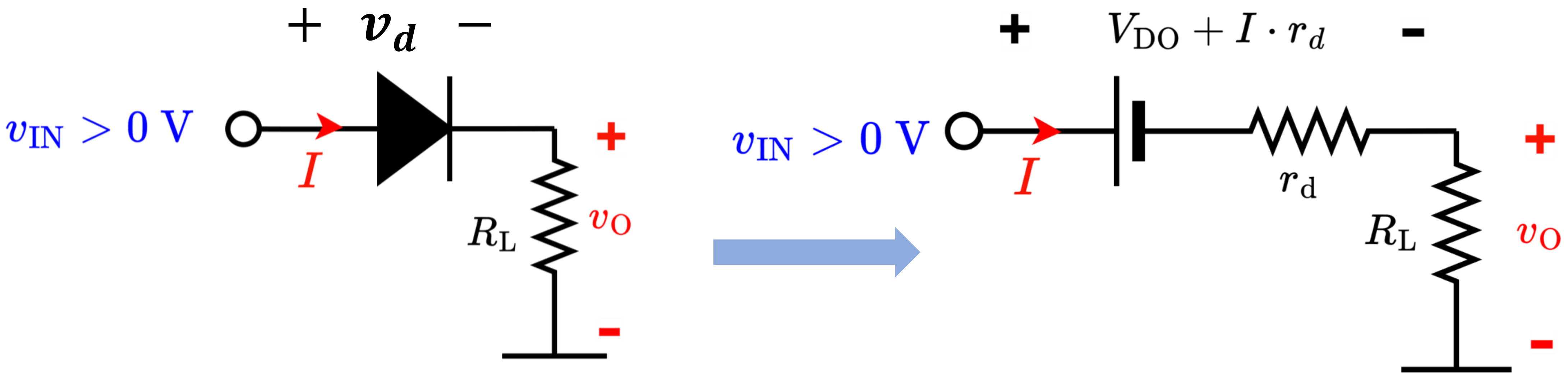


v_D: Total Voltage Across diode

V_{Do}: Diode Cut-off voltage (0.7 V)

Example Problems (CVD Model)

Example 3:



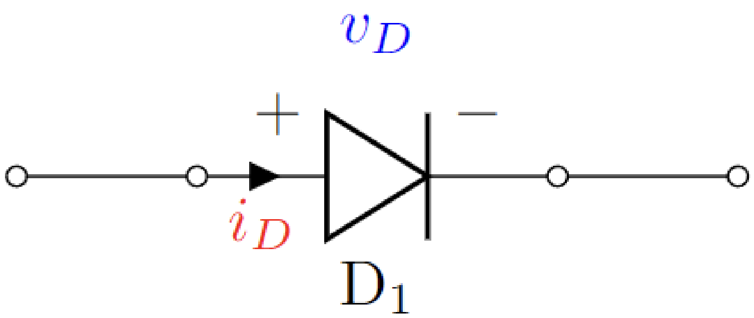
Let, $V_{DO} = 0.7$ V
$r_d = 50\ \Omega$

$$I = \frac{v_O - V_{DO}}{R_L + r_d} = \frac{4.3\ \text{V}}{2.5\ \text{k}\Omega + 0.05\ \text{k}\Omega} = 1.70\ \text{mA}$$

$$v_O = IR_L = \ 1.70 \times 2.5\ \text{V}$$

Diode Models

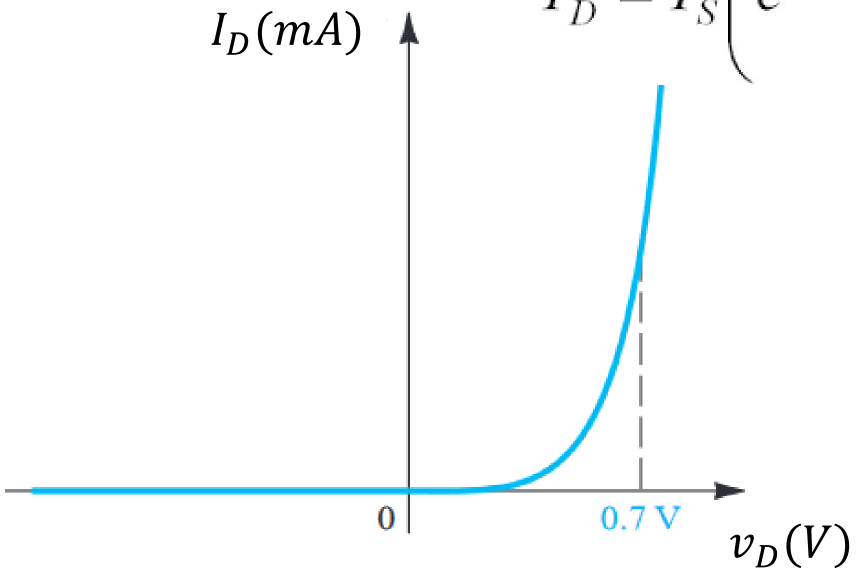
4. Shockley Diode Equation Model:



$$i_D = I_s\left[\exp\left(\frac{v_D}{nV_T}\right) - 1\right] \qquad V_T = \frac{kT}{q}$$

k = 1.38 × 10^{-23} J/K is Boltzmann's constant and q = 1.60 × 10^{-19} C is the magnitude of the electrical charge of an electron. At a temperature of 300 K, we have $V_T \simeq 26\,\mathrm{mV}$

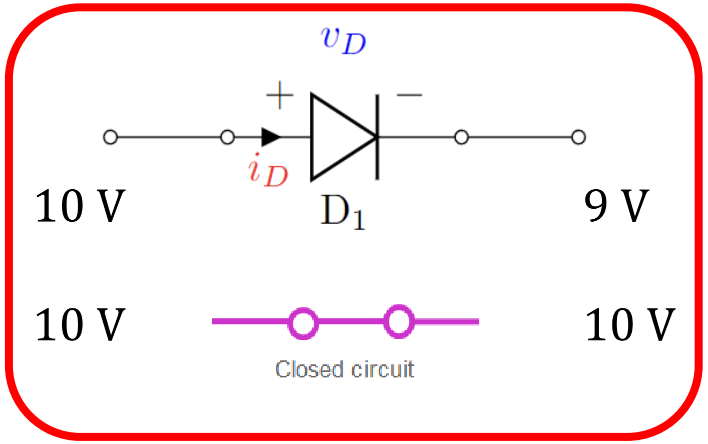
$$I_D = I_S\left(e^{\frac{qV_D}{nkT}} - 1\right)$$

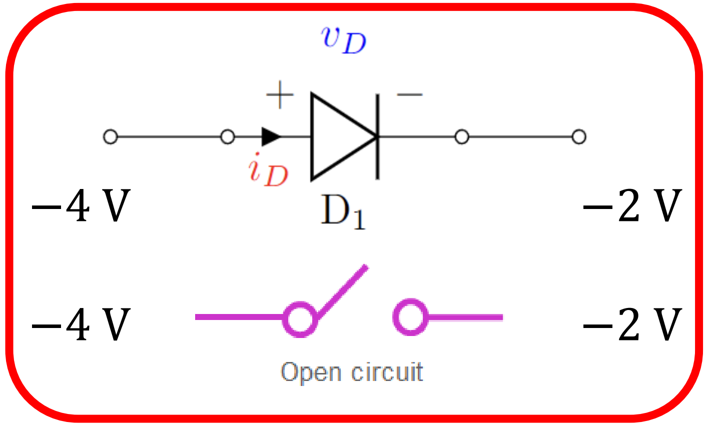


Where I_S is reverse saturation current

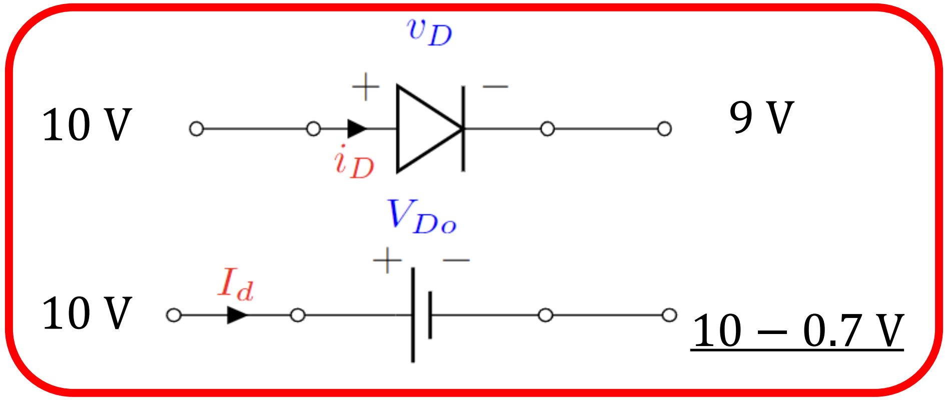
Diode Operation

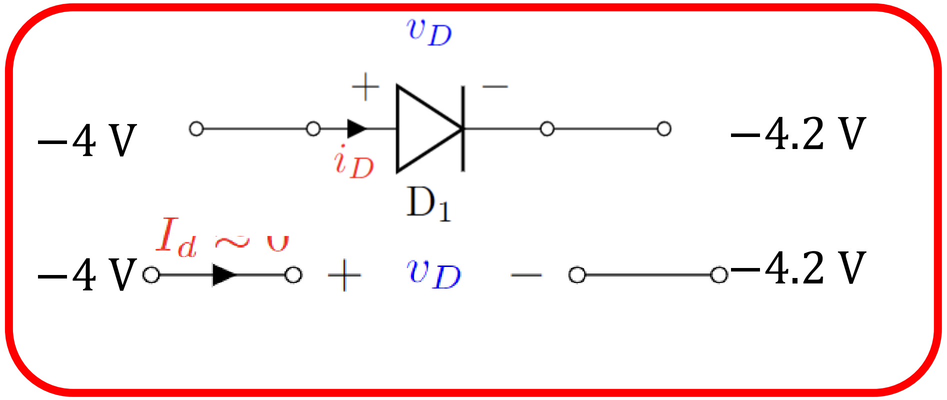
Ideal Diode





CVD Diode

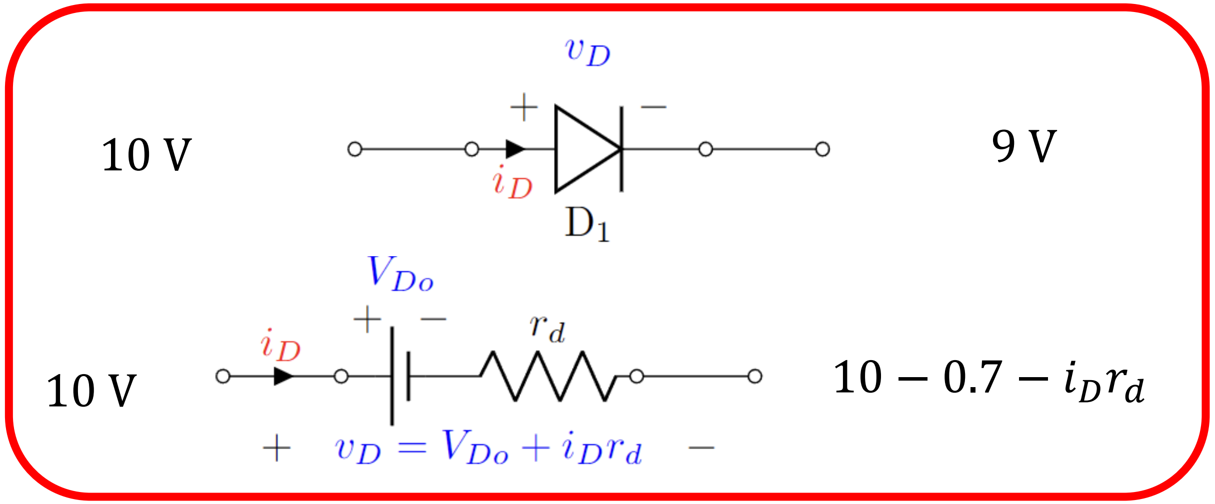


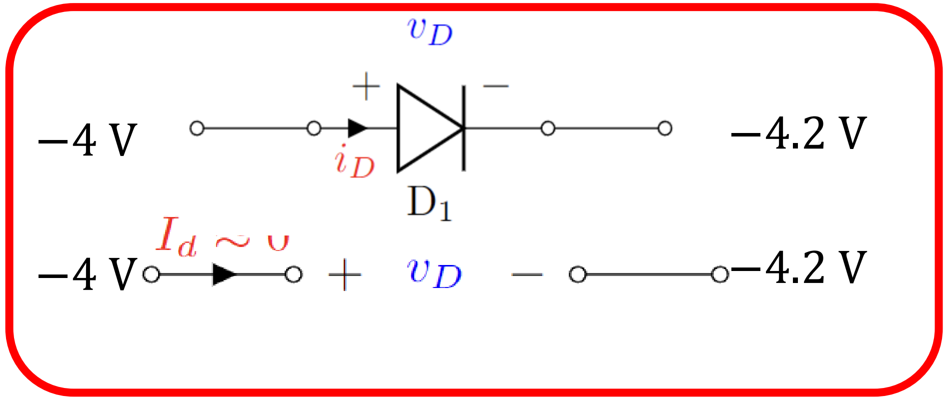


$$V_{Do} = 0.7\ \text{V}$$

Diode Operation

CVD+R Diode





$V_{Do} = 0.7$ V

Solving Circuits with diodes

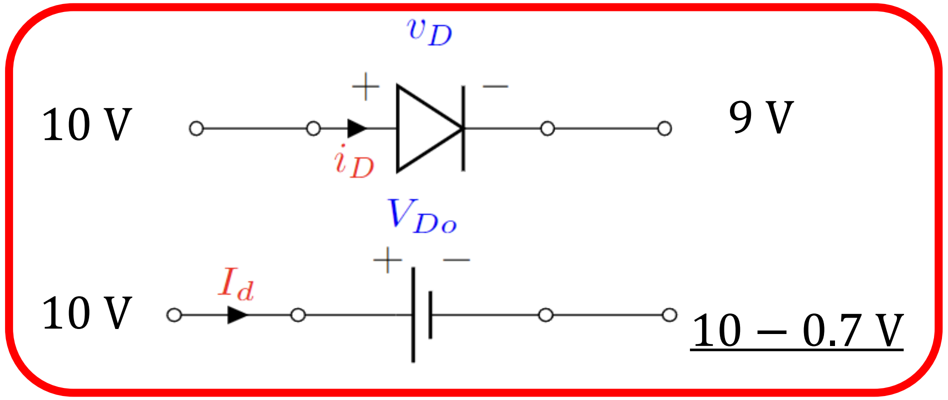
- Method of assumed states

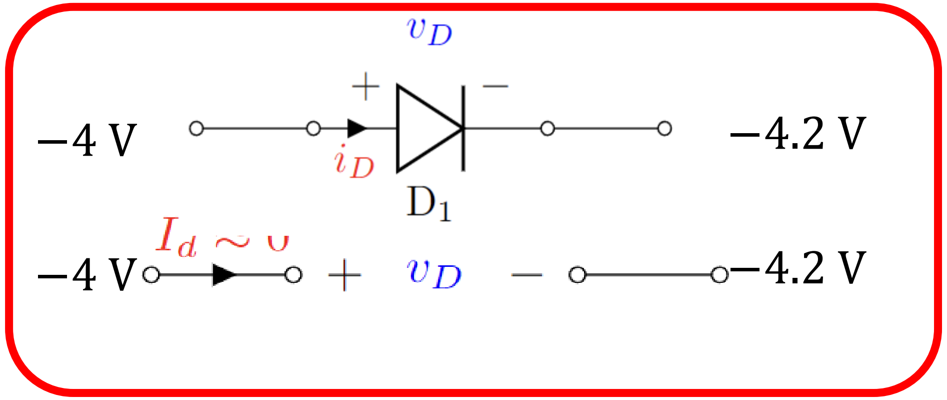
1. Assume a diode state – FB or RB
2. Replace FB/RB diode with circuit model
3. Solve circuit. Find current through diode and voltage across diodes

4. **Verify if current direction and voltage polarity matches with assumption (TRUE or FALSE).**
5. If assumption is false assume other state and repeat. Else, the result is finalized.

Verify Assumptions

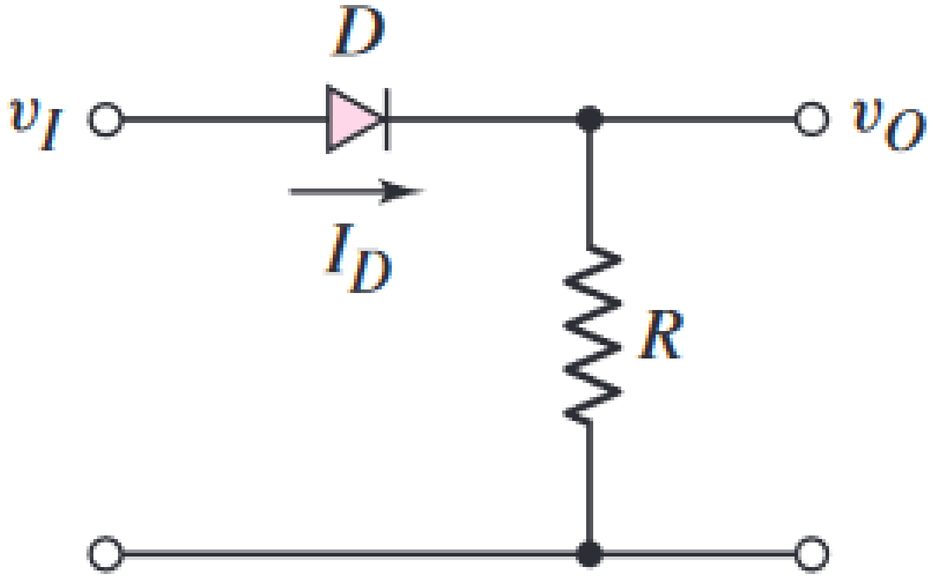
CVD Diode





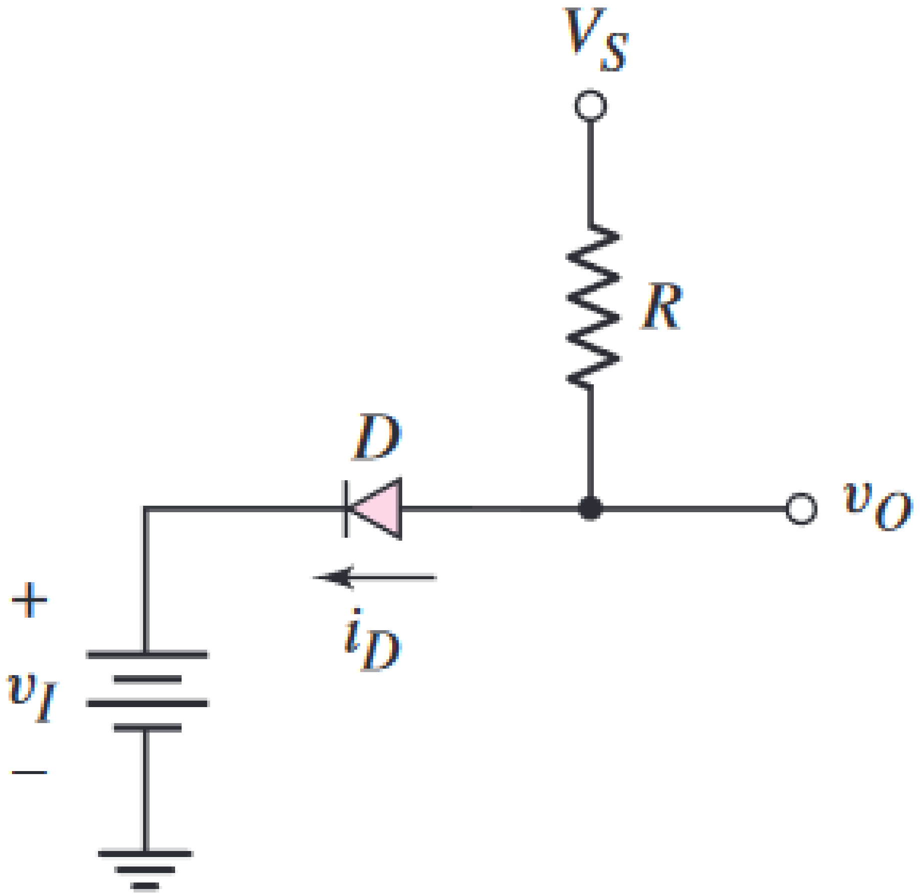
$V_{Do} = 0.7$ V

Solving Circuits with diodes



If $v_I = 5$ V and $V_{DO} = 0.7$ V, find $\boldsymbol{v_O}$

Solving Circuits with diodes

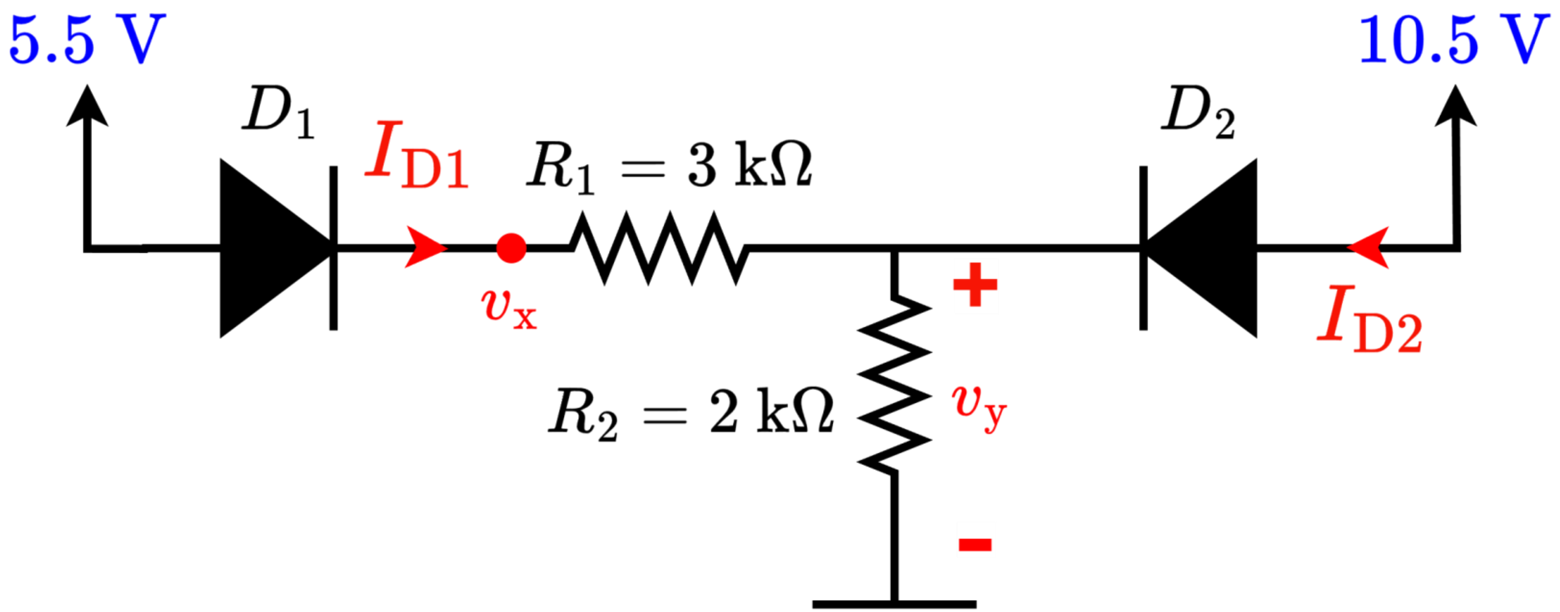


i) If $v_I = 5\text{ V}$, $V_S = 10\text{ V}$ and $V_{DO} = 0.7\text{ V}$, find $\boldsymbol{v_O}$

ii) If $v_I = 11\text{ V}$, $V_S = 10\text{ V}$ and $V_{DO} = 0.7\text{ V}$, find $\boldsymbol{v_O}$

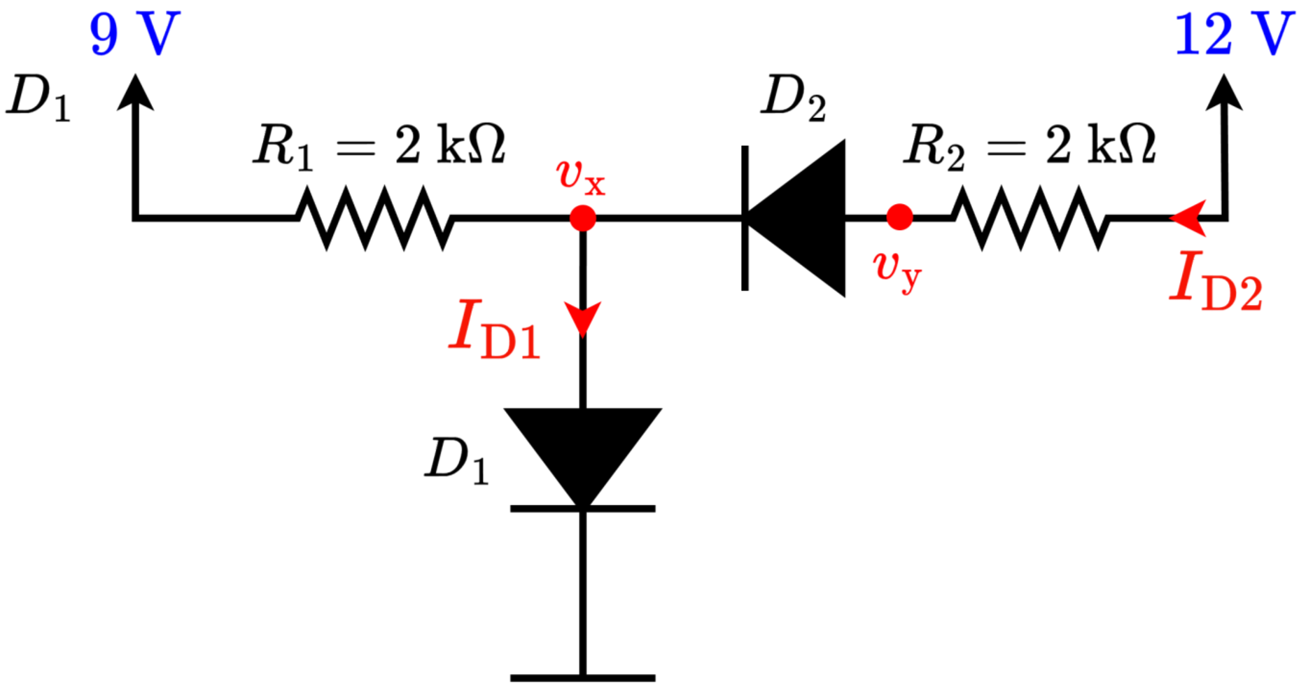
iii) If $v_I = 0\text{ V}$, $V_S = 10\text{ V}$ and $V_{DO} = 0.7\text{ V}$, find $\boldsymbol{v_O}$

Solving Circuits with diodes



Analyze the circuit to find I_{D1}, I_{D2}, v_x and v_y. Consider $\boldsymbol{V_{DO} = 0.5\ \mathrm{V}}$.
[Validate Assumptions]

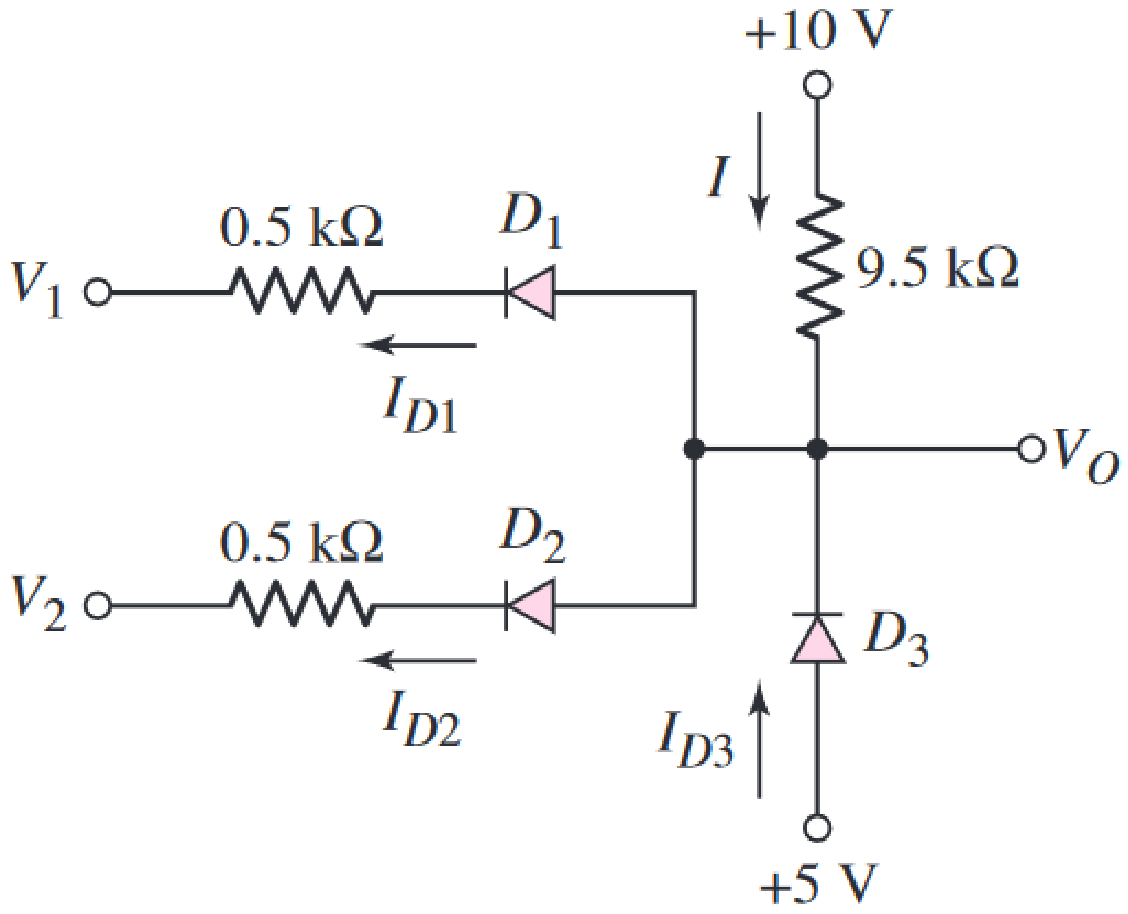
Solving Circuits with diodes



Analyze the circuit to find I_{D1}, I_{D2}, v_x and v_y. Consider $\boldsymbol{V_{DO} = 1\ \mathrm{V}}$.
[Validate Assumptions]

Are the diodes consuming power or delivering power?

Solving Circuits with diodes



Analyze the circuit to find I_{D1}, I_{D2}, I_{D3} and I for the following cases: Consider $\boldsymbol{V_{DO} = 0.6\ \mathrm{V}}$. **[Validate Assumptions]**

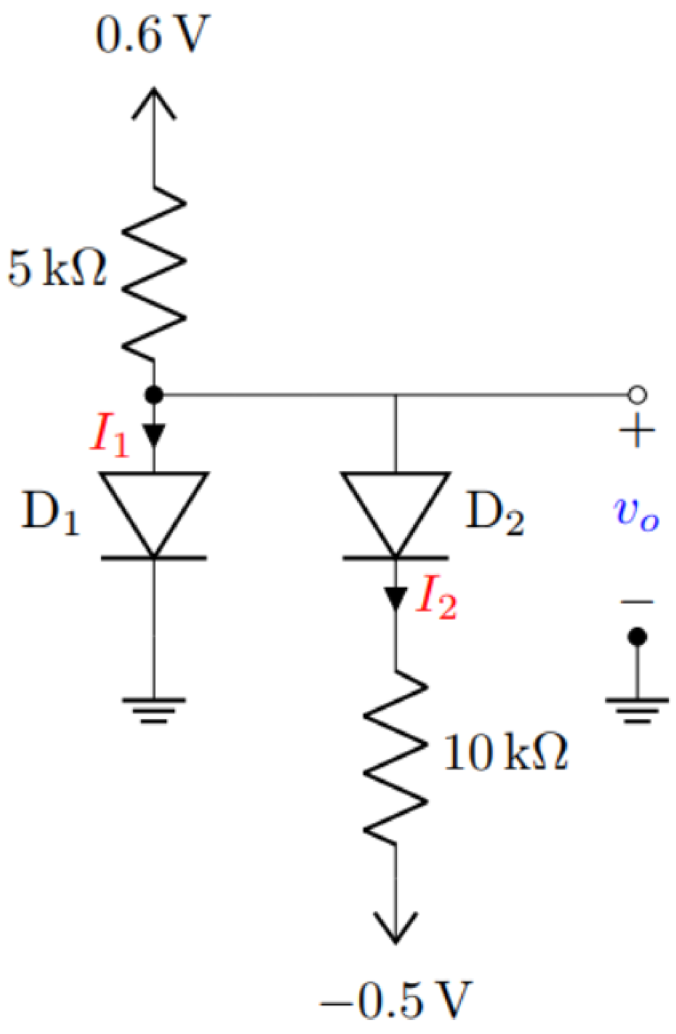
$$\boldsymbol{V_1 = V_2 = 0\ \mathrm{V}}$$

$$\boldsymbol{V_1 = V_2 = 5\ \mathrm{V}}$$

$$\boldsymbol{V_1 = 5\ \mathrm{V}, \qquad V_2 = 0\ \mathrm{V}}$$

$$\boldsymbol{V_1 = 0\ \mathrm{V}, \qquad V_2 = 2\ \mathrm{V}}$$

Solving Circuits with diodes



Analyze the circuit to find I_1, I_2, and $\boldsymbol{v_O}$ for

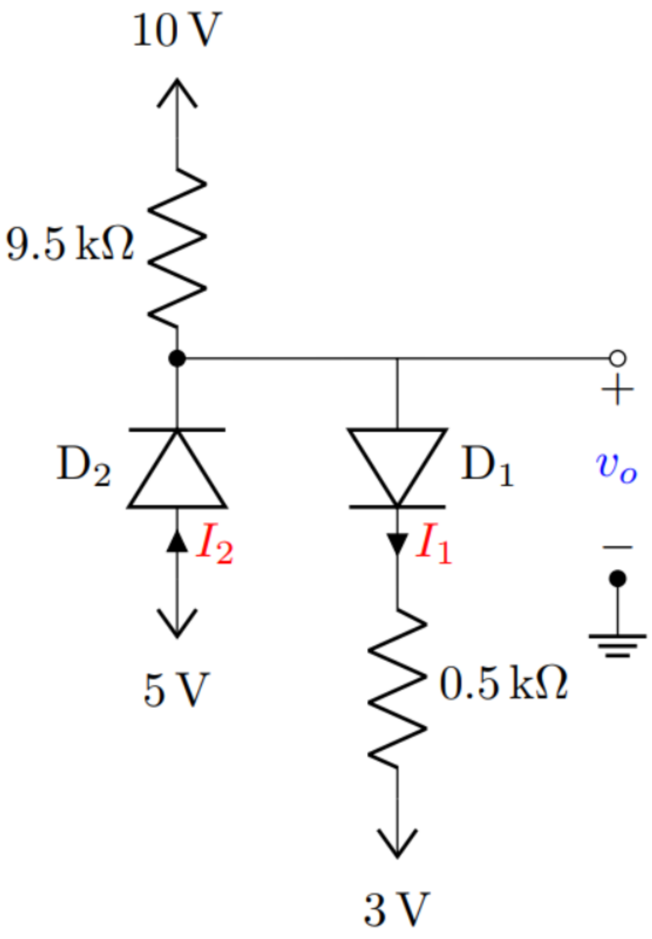
i. Assuming all diodes as ideal

ii. Consider $\boldsymbol{V_{D1} = 0.5\ \mathrm{V}}$ and $\boldsymbol{V_{D2} = 0.7\ \mathrm{V}}$**. (CVD model)**

iii. Consider $\boldsymbol{V_{DO} = 0.6\ \mathrm{V}}$ and $\boldsymbol{r_d = 50\ \Omega}$**. (CVD+R model)**

[Validate Assumptions]

Solving Circuits with diodes



Analyze the circuit to find I_1, I_2, and $\boldsymbol{v_O}$ for

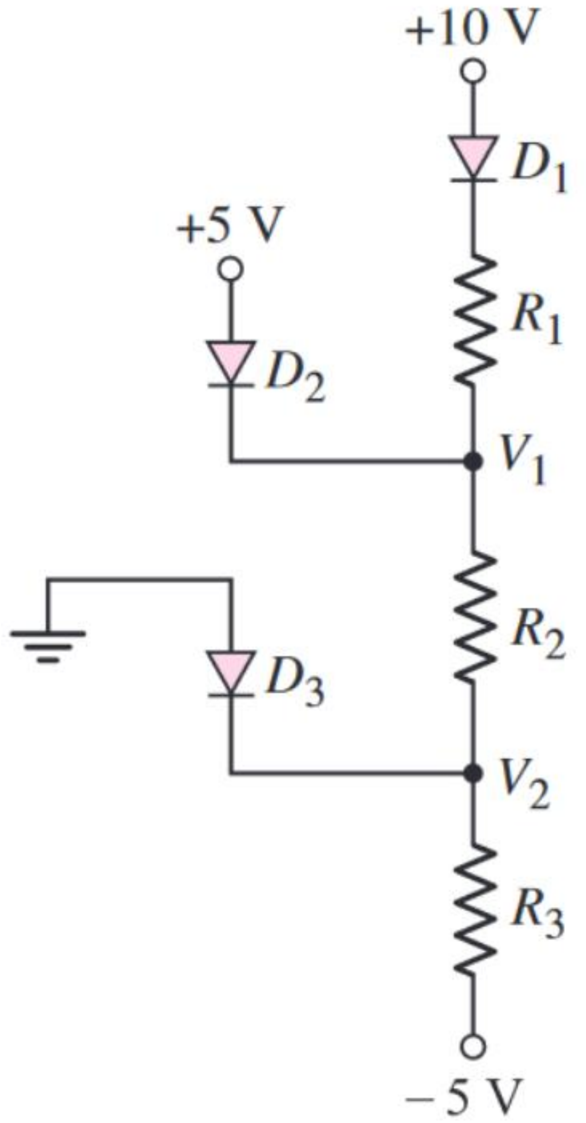
i. Assuming all diodes as ideal

ii. Consider $\boldsymbol{V_{DO} = 0.6\ \mathrm{V}}$. **(CVD model)**

iii. Consider $\boldsymbol{V_{DO} = 0.6\ \mathrm{V}}$ and $\boldsymbol{r_d = 50\ \Omega}$. **(CVD+R model)**

[Validate Assumptions]

Solving Circuits with diodes



a. Determine $\boldsymbol{R_1, R_2}$ and $\boldsymbol{R_3}$ such that

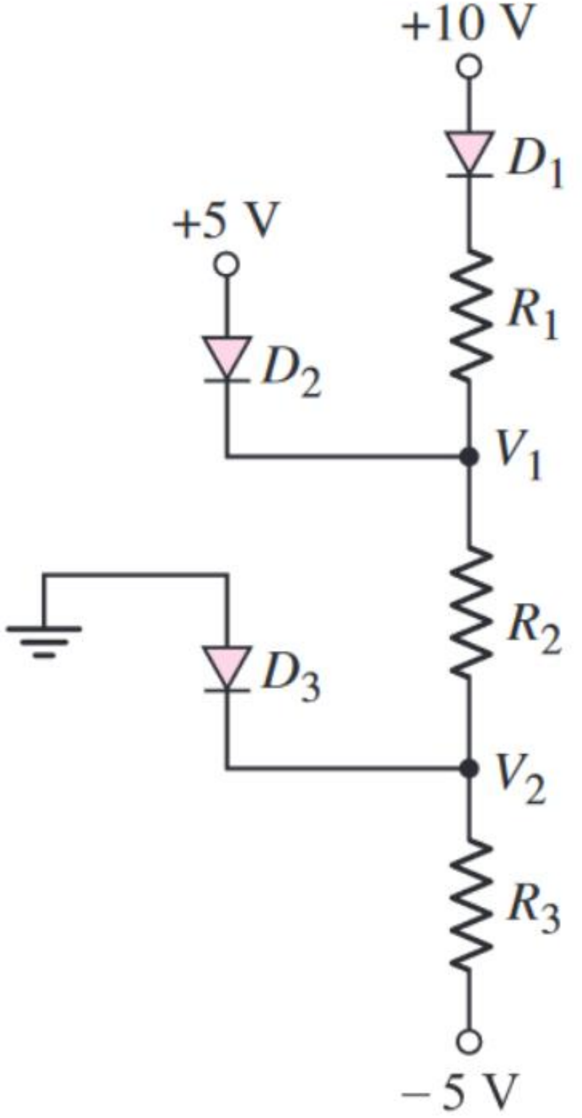
$$I_{D1} = 0.2 \text{ mA},$$
$$I_{D2} = 0.3 \text{ mA}$$
$$I_{D3} = 0.5 \text{ mA}$$

b. Find $\boldsymbol{V_1, V_2}$ and each diode current for

$$R_1 = 10 \text{ k}\Omega$$
$$R_2 = 4 \text{ k}\Omega$$
$$R_3 = 2.2 \text{ k}\Omega$$

Consider $\boldsymbol{V_{DO} = 0.6}$ **V. [Validate Assumptions]**

Solving Circuits with diodes



a. Find $\boldsymbol{V_1, V_2}$ and each diode current for

$$R_1 = 3\ \mathrm{k\Omega}$$
$$R_2 = 6\ \mathrm{k\Omega}$$
$$R_3 = 2.5\ \mathrm{k\Omega}$$

b. Find $\boldsymbol{V_1, V_2}$ and each diode current for

$$R_1 = 6\ \mathrm{k\Omega}$$
$$R_2 = 3\ \mathrm{k\Omega}$$
$$R_3 = 6\ \mathrm{k\Omega}$$

Consider $\boldsymbol{V_{DO} = 0.6\ \mathrm{V}}$. **[Validate Assumptions]**