18-100 Introduction to Electrical and Computer Engineering

Lecture 04
Semiconductors, Diodes, and Light Emitting Diodes (LEDs)

Are you here?
Let us know and win prizes.

Course Syllabus

18-100: *Introduction to Electrical and Computer Engineering*

Spring 2025

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Office Location: HH A212
Email Address: mbudnik@andrew.cmu.edu
Office Hours: Monday, 2-4pm or by appointment

Schedule (Subject to Change)

Week	Date	Day	Lecture Topic
1	13-Jan	M	L01: Intro, Physics, EM, Leveling Students
	15-Jan	W	L02: Circuits Basics
2	20-Jan	M	Martin Luther King Celebration (No Lecture)
	22-Jan	W	L03: Equivalent Circuits
3	27-Jan	M	L04: Semiconductors, Diodes, LEDs
	29-Jan	W	L05: MOSFETs to Simple Gates
4	3-Feb	M	L06: Professional Identity, Professional Responsibility, and Ethics
	5-Feb	**W**	**Exam 1**
5	10-Feb	M	L07: Capacitors, RC Time Constants, RC Circuits
	12-Feb	W	L08: Inductors, RL Time Constants, 555
6	17-Feb	M	L09: Binary, Logic Gates, Boolean Logic
	19-Feb	W	L10: Latches, Registers, RAM, Flip-Flops
7	24-Feb	M	L11: Computers
	26-Feb	W	L12: Op Amps
	3-Mar	M	SPRING BREAK
	5-Mar	W	SPRING BREAK

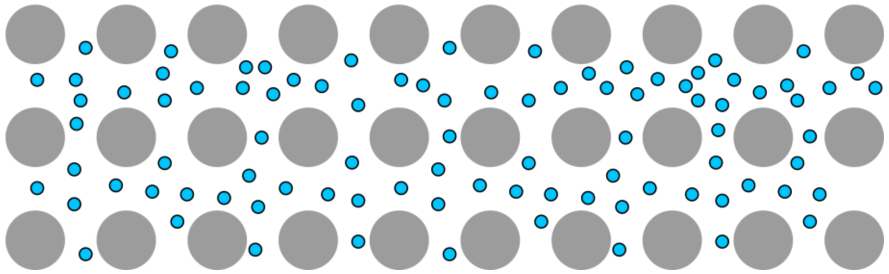
Objectives of this Lecture

- Semiconductors
- Diodes
- Light Emitting Diodes (LEDs)

Conductors vs. Insulators

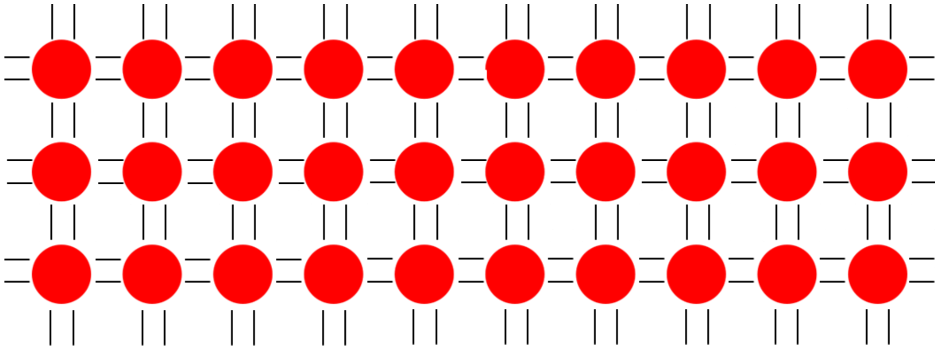
- Material **conductivity** is a material electrical property
- More free electrons, more current can flow

Conductors have many free electrons



Gold, copper, aluminum, salt water…

Insulators have very few free electrons

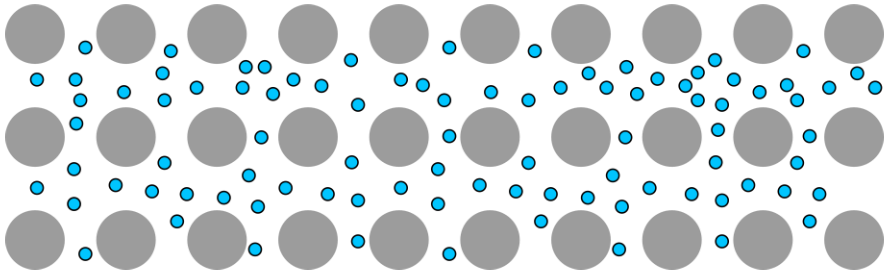


Rubber, glass, plastic, rust…

Conductors vs. Insulators vs. Semiconductors

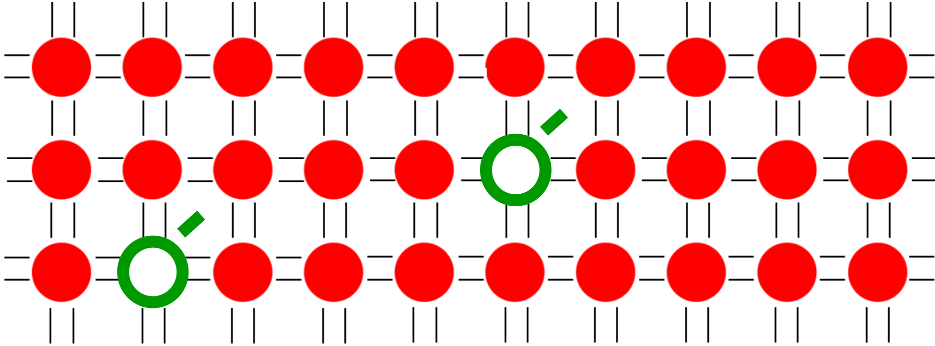
- Material **conductivity** is a material electrical property
- More free electrons, more current can flow

Conductors have many free electrons



Gold, copper, aluminum, salt water…

Semiconductors have a few free electrons



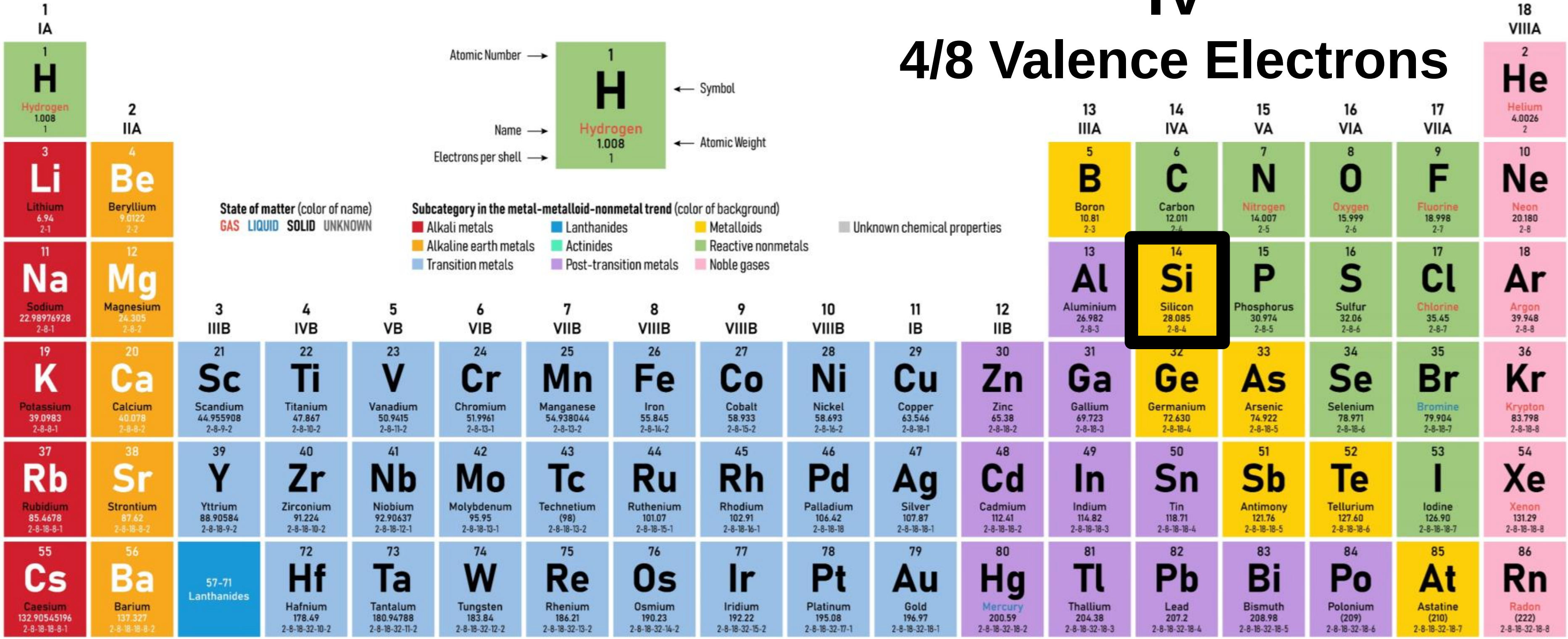
Silicon, germanium, gallium arsenide…

Start with a Block of Pure, Electrically Neutral Silicon (Or Another Semiconductor)

Column

IV

4/8 Valence Electrons



Start with a Block of Pure, Electrically Neutral Silicon:

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Start with a Block of Pure, Electrically Neutral Silicon: Strong Covalent Bonds Make It an Insulator

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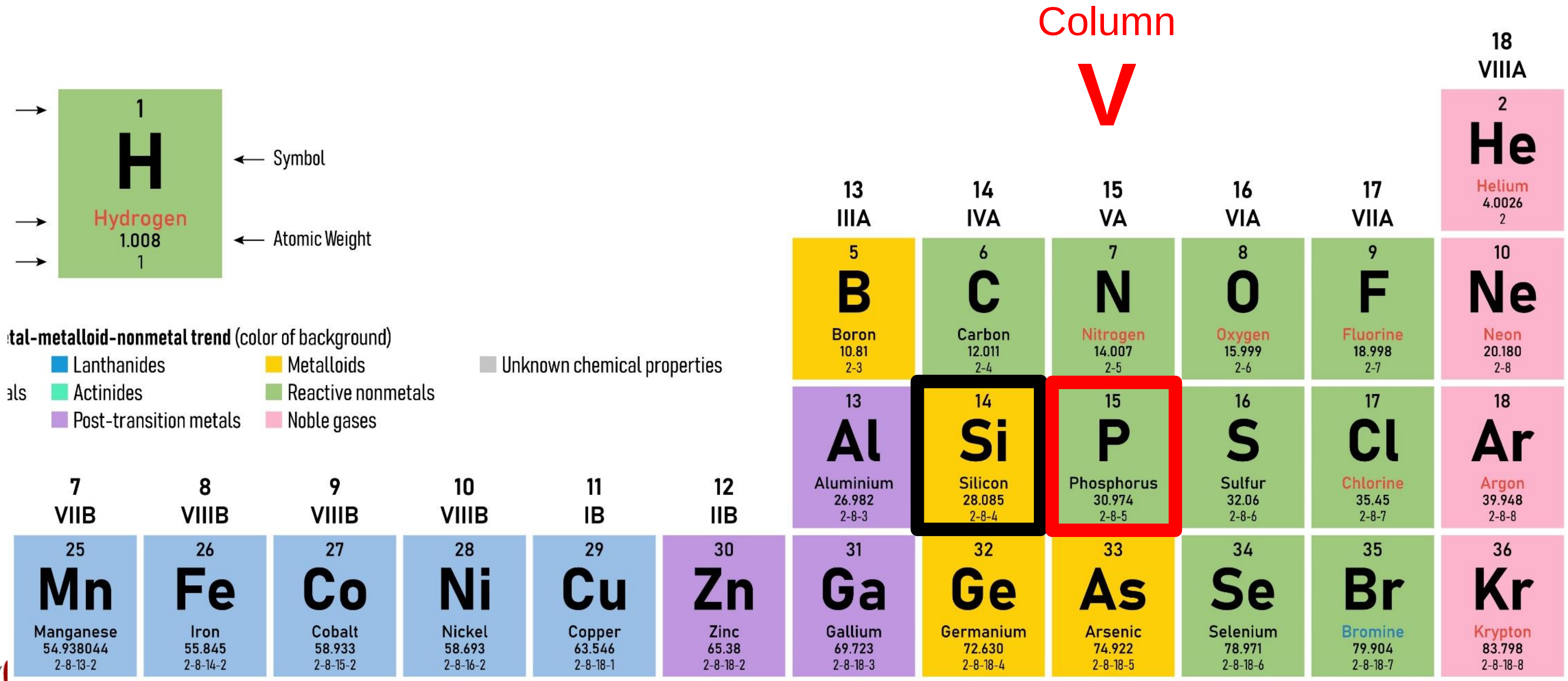
Phosphorus Has One Extra Valence Electron (5/8)



Phosphorus Has One Extra Valence Electron

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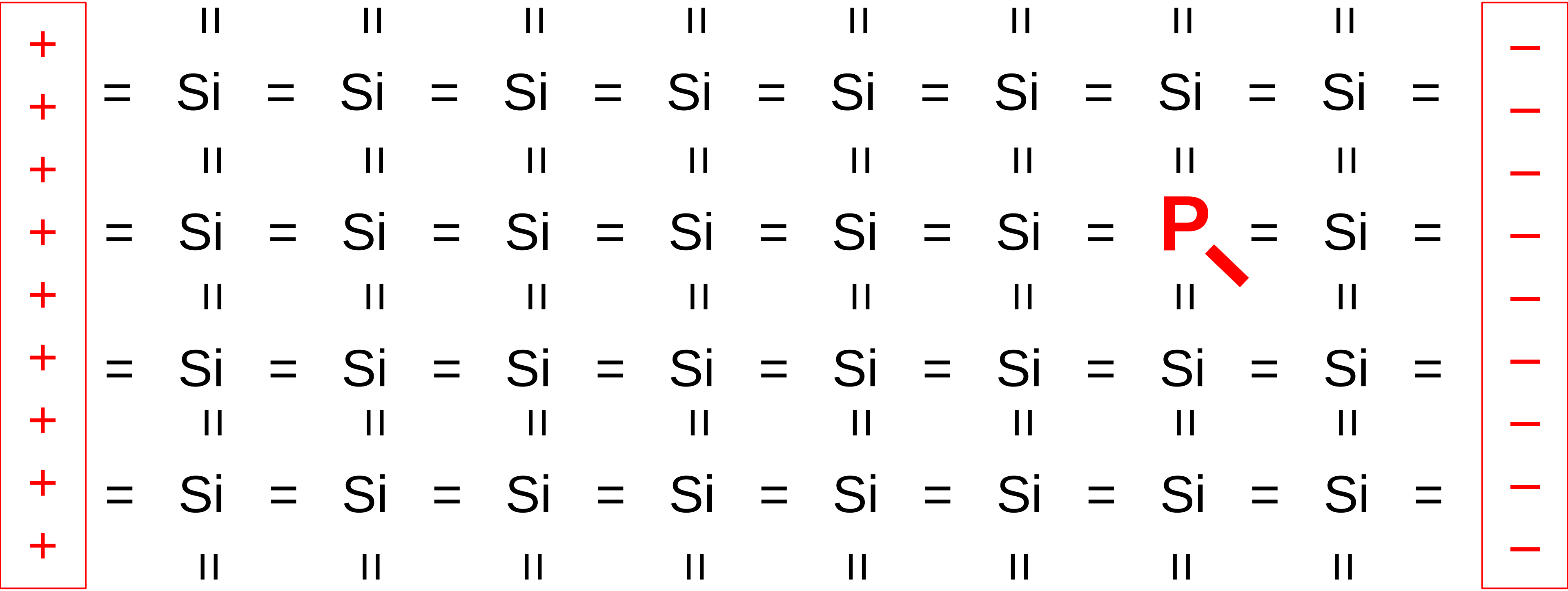
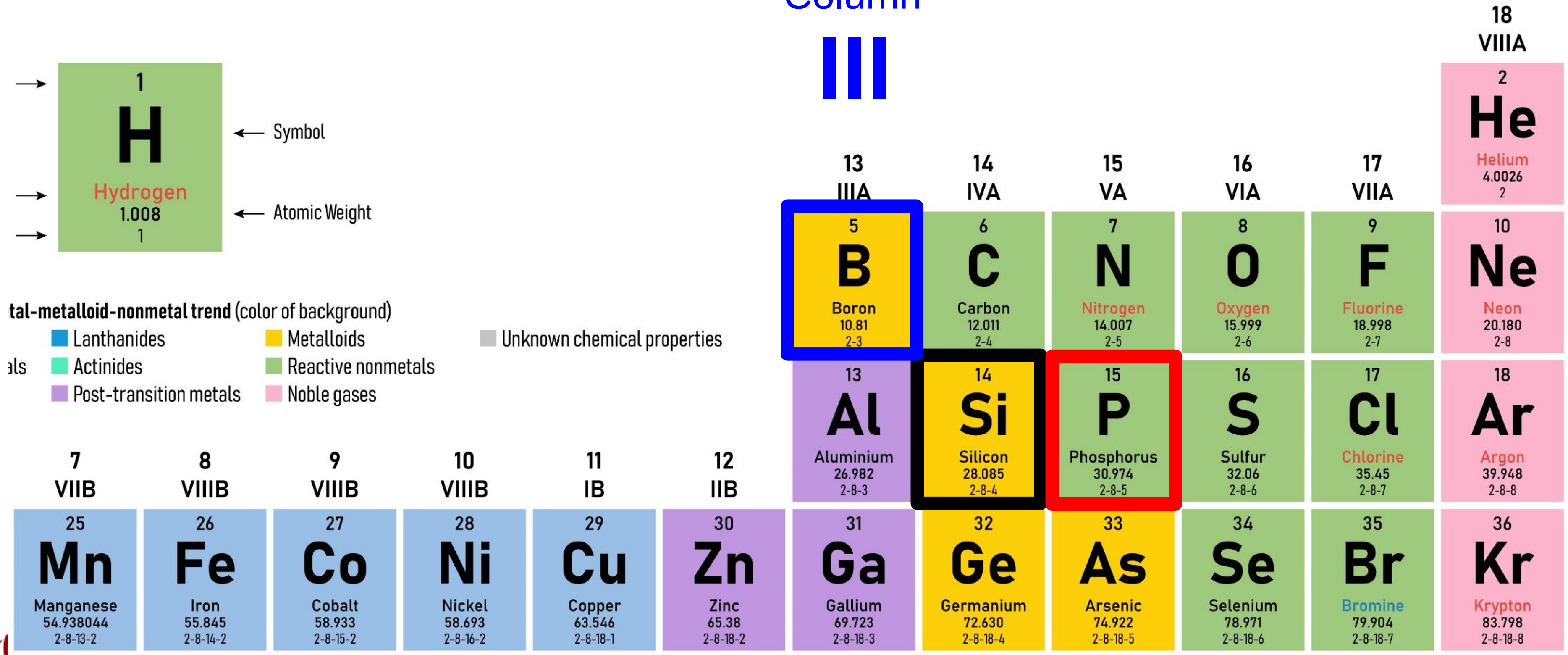
Phosphorus Has One Extra Valence Electron Greatly Increases Conductivity of the Semiconductor



Boron Has One Fewer Valence Electron (3/8)

Column

III



Boron Has One Fewer Valence Electron (hole, h^+)

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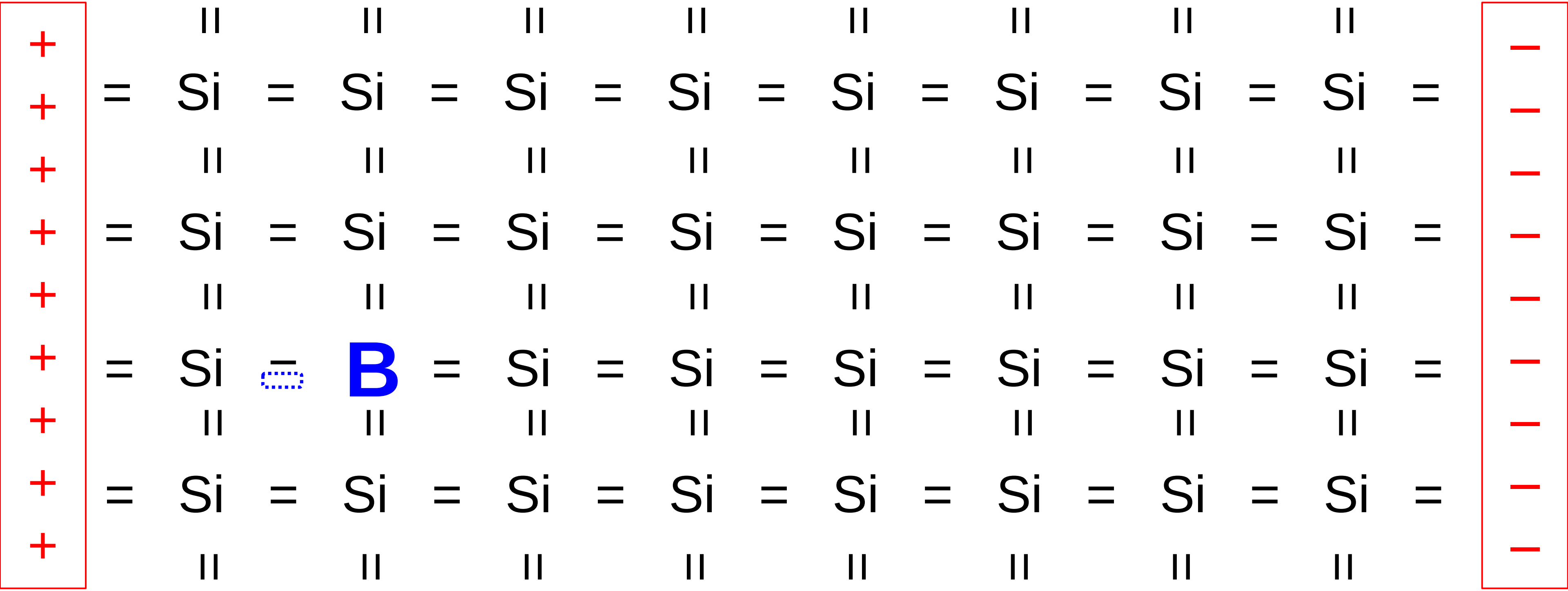
Boron Has One Fewer Valence Electron (hole, h^+) Can Still Increase Conductivity



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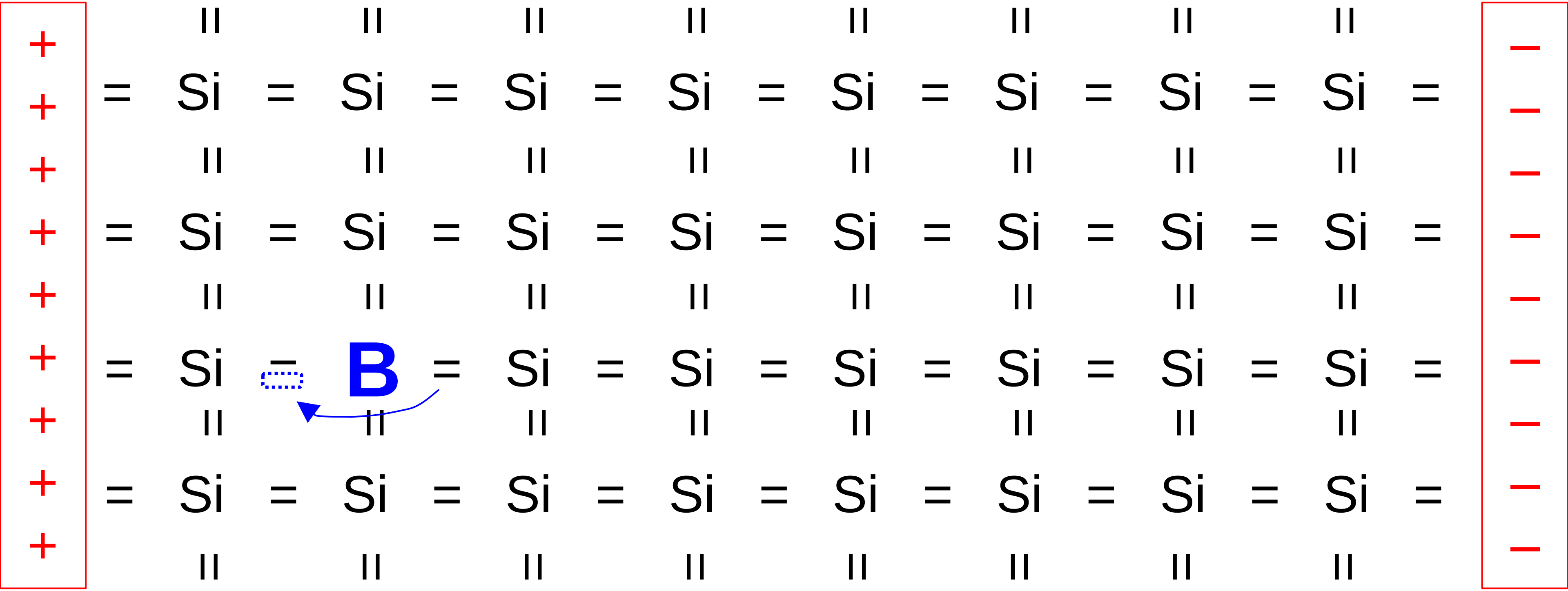

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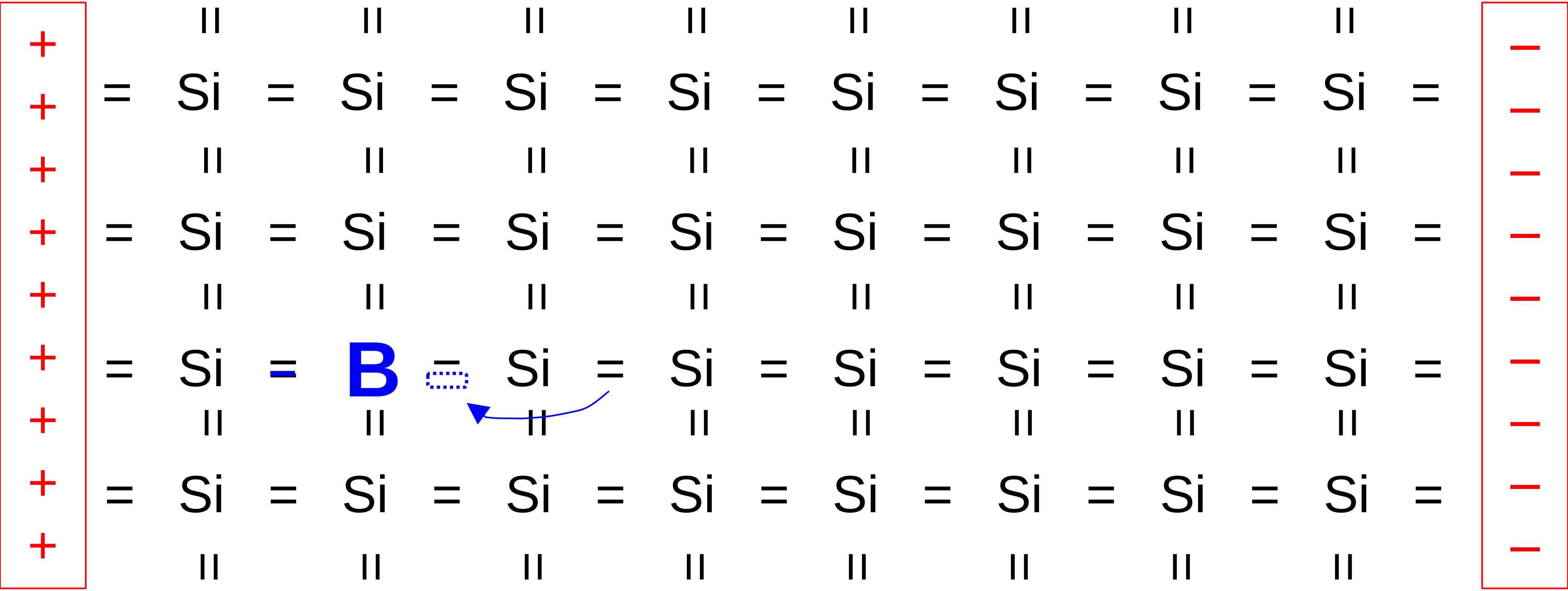

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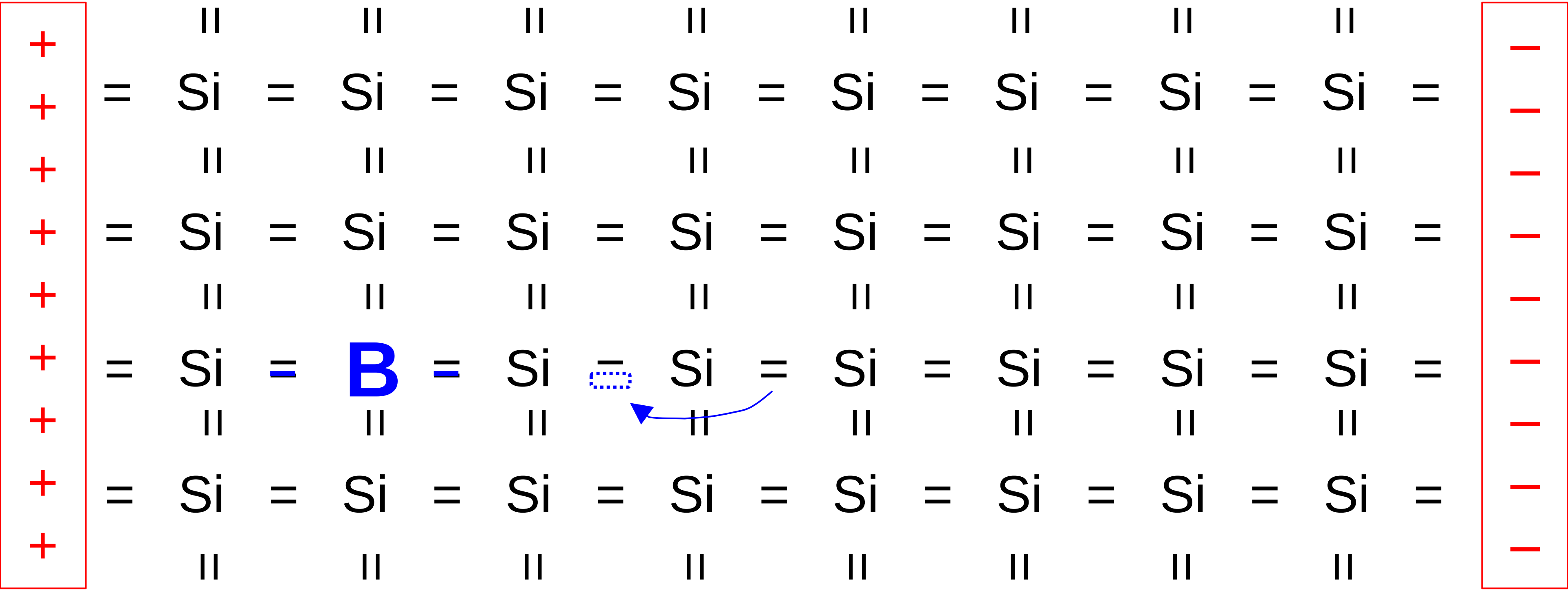

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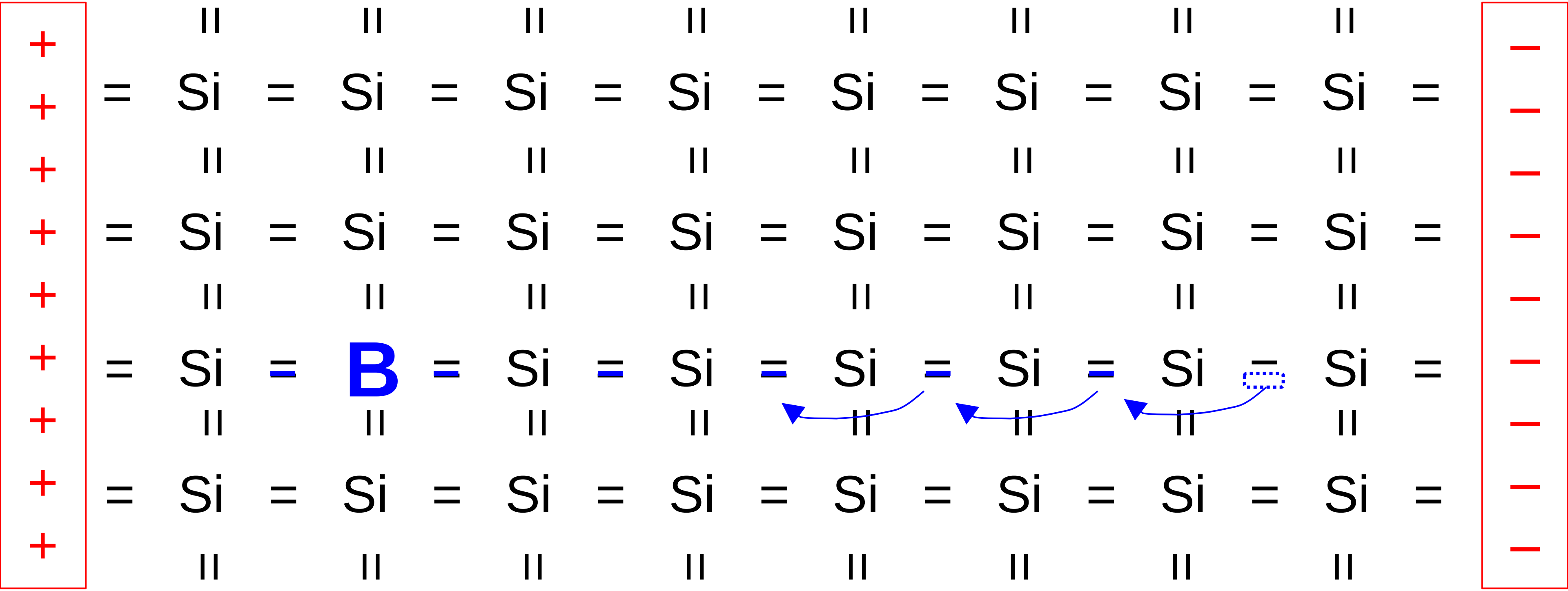
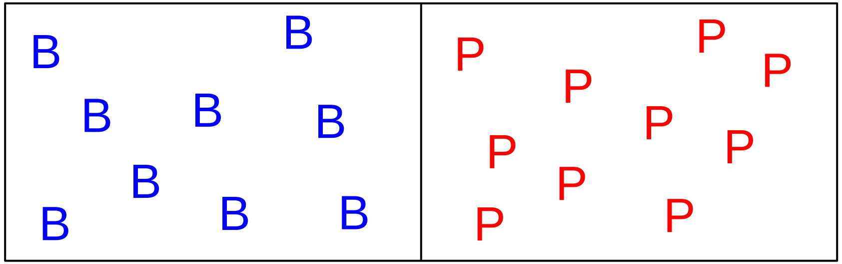


Add a Small Amount of Boron (extra h^+) and Phosphorus (extra e^-) to Separate Areas

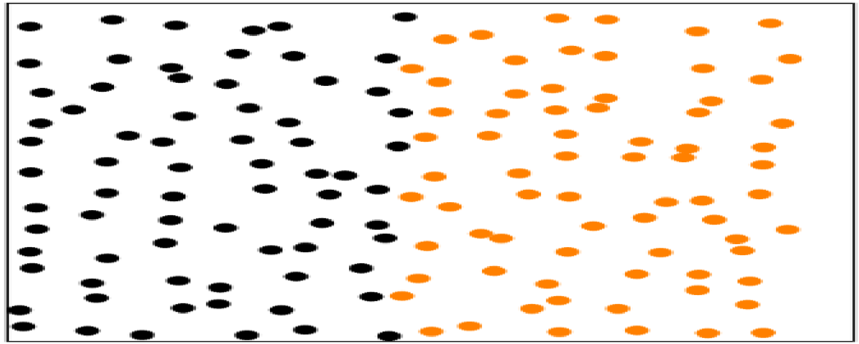


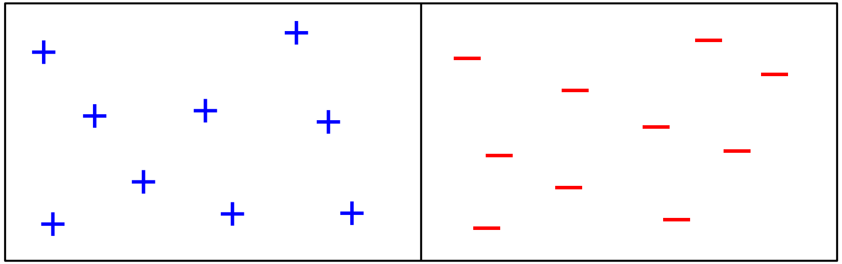
Extra Holes (h^+)
Fewer Electrons
P-Type Silicon

Extra Electrons (e^-)

N-Type Silicon

Extra (e^-) and Missing (h^+) Electrons Are Free to Diffuse (Randomly Drift Around)





Extra Holes (h^+)
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Extra Electrons (e^-)

N-Type Silicon

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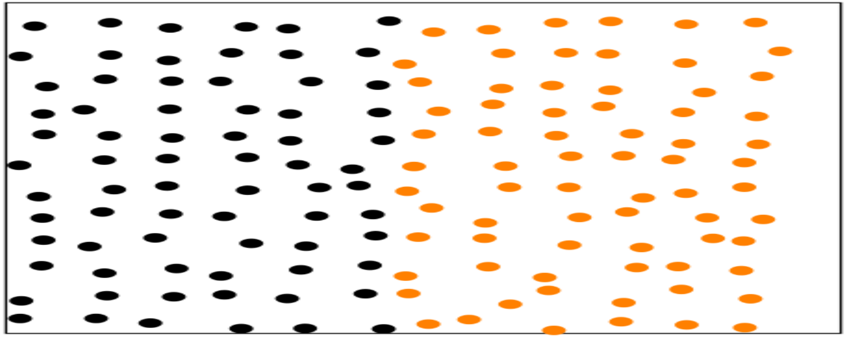
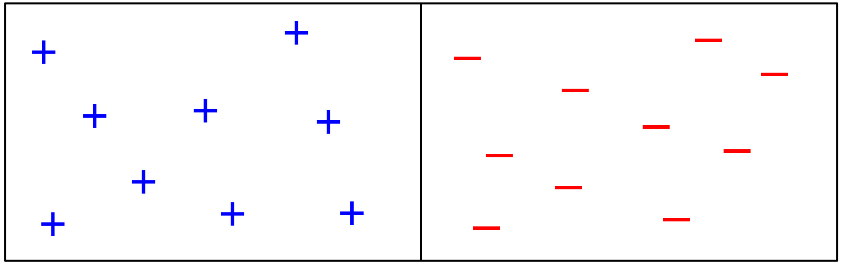




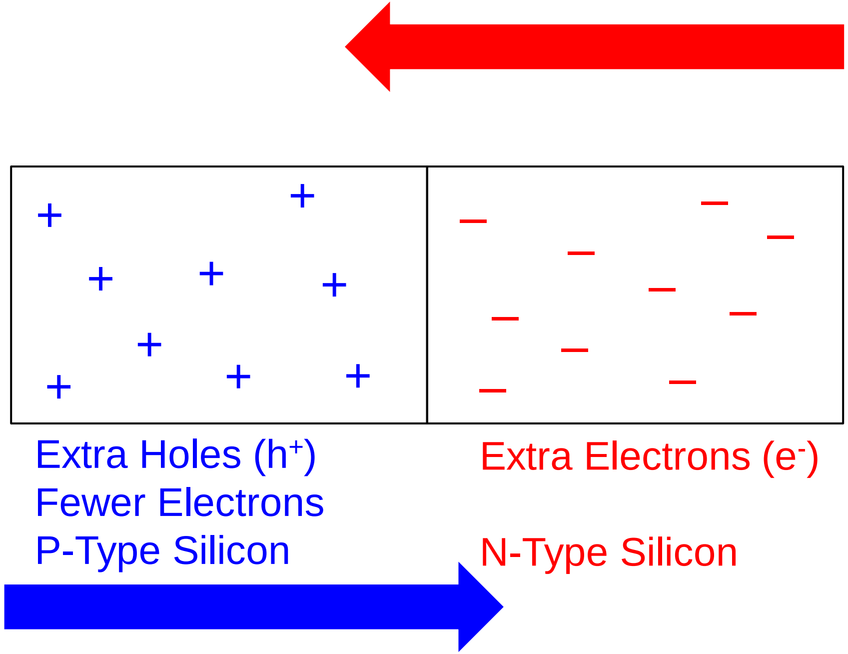
Extra Holes (h^+)
Fewer Electrons
P-Type Silicon

Extra Electrons (e^-)

N-Type Silicon

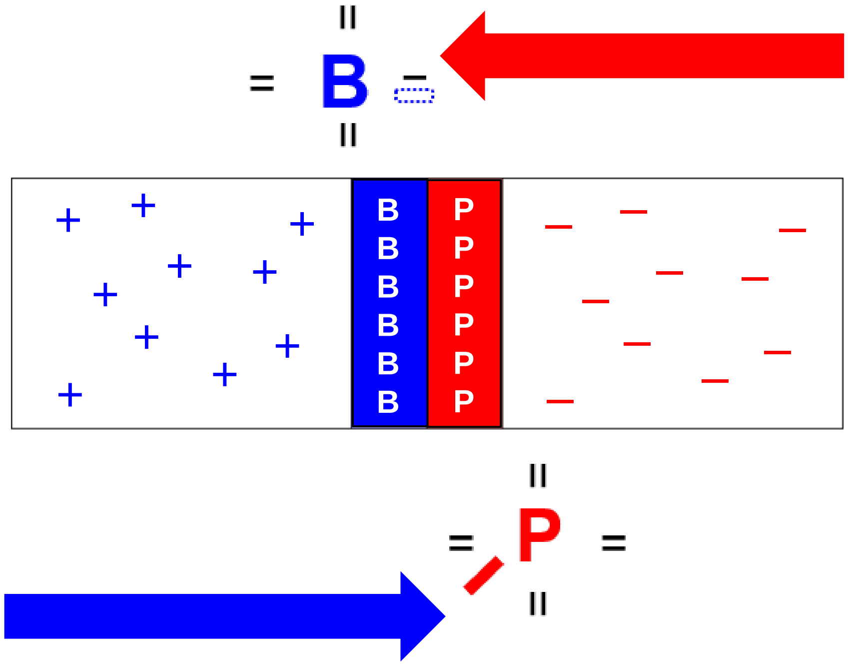
Extra (e^-) and Missing (h^+) Electrons Are Free to Diffuse (Randomly Drift Around)

Electrons diffuse to areas of lower concentration



Missing electrons (or holes) diffuse to areas of lower concentration

P **Nucleus** Has One Additional Positive Charge
B **Nucleus** Has One Less Positive Charge

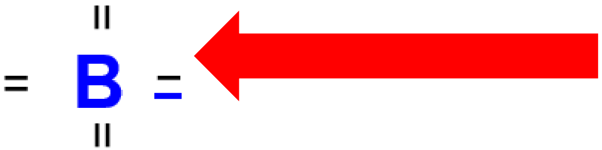


Electrons diffuse to areas of lower concentration

Missing electrons (or holes) diffuse to areas of lower concentration

P **Nucleus** Has One Additional Positive Charge
B **Nucleus** Has One Less Positive Charge

B^- is negatively charged



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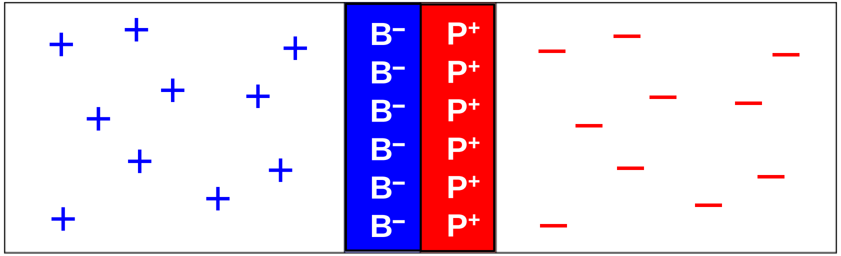

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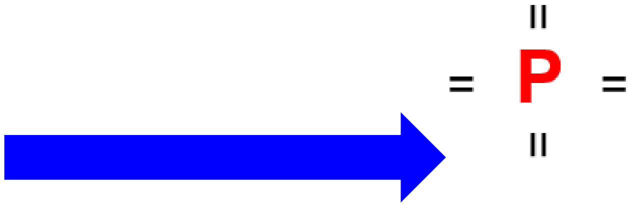
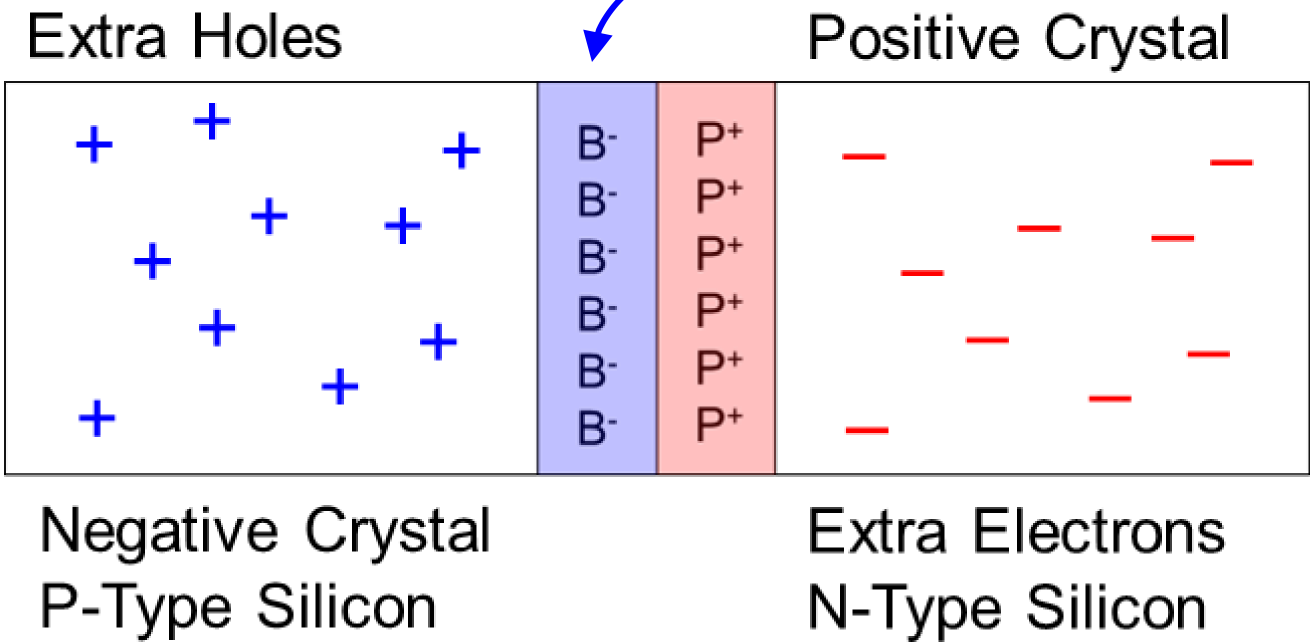


P^+ is positively charged

Charged Barrier (~0.7V) Prevents More Diffusion

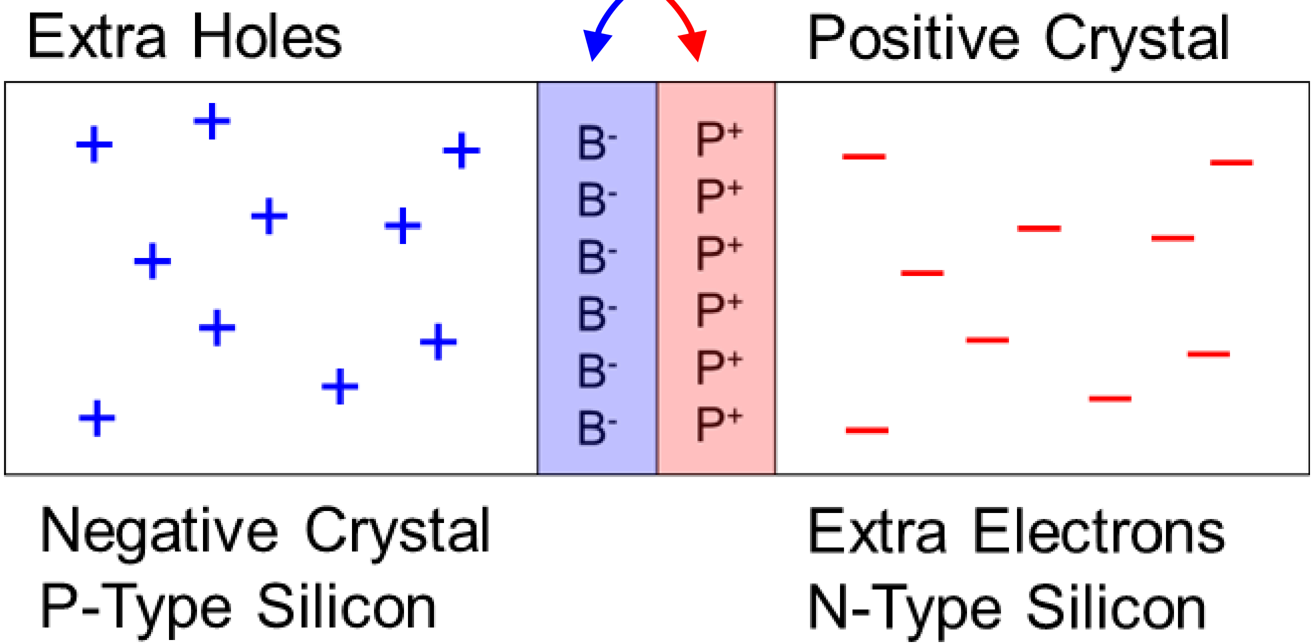
Barrier of B atoms with extra e⁻
stops more e⁻ diffusing to the left



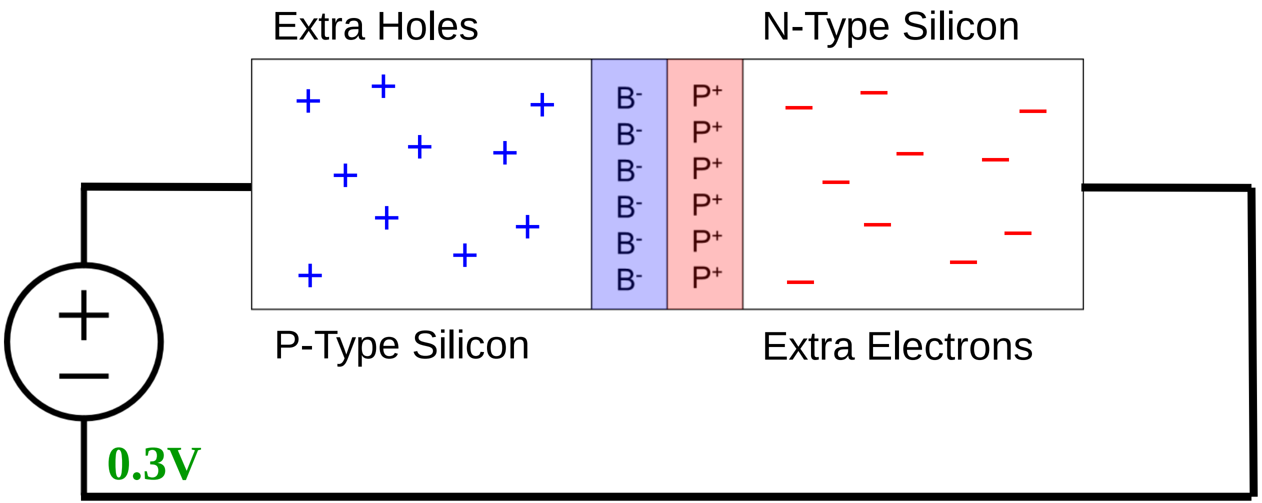
Charged Barrier (~0.7V) Prevents More Diffusion

Barrier of P atoms with less e⁻ stops more h+ diffusing to the right

Barrier of B atoms with extra e⁻ stops more e⁻ diffusing to the left



Let's Apply a Small Positive Voltage (~0.3V)



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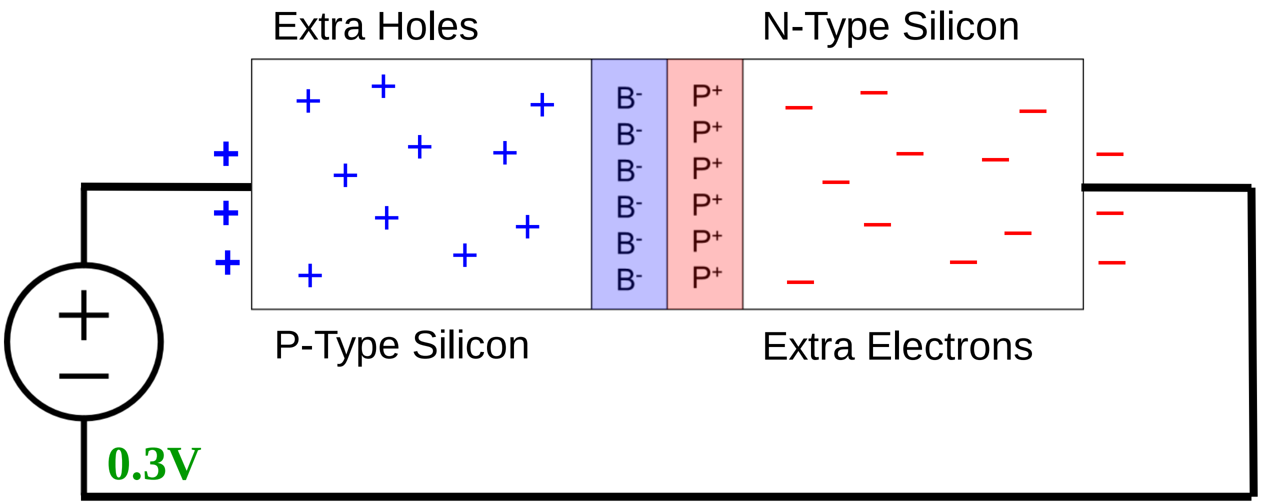

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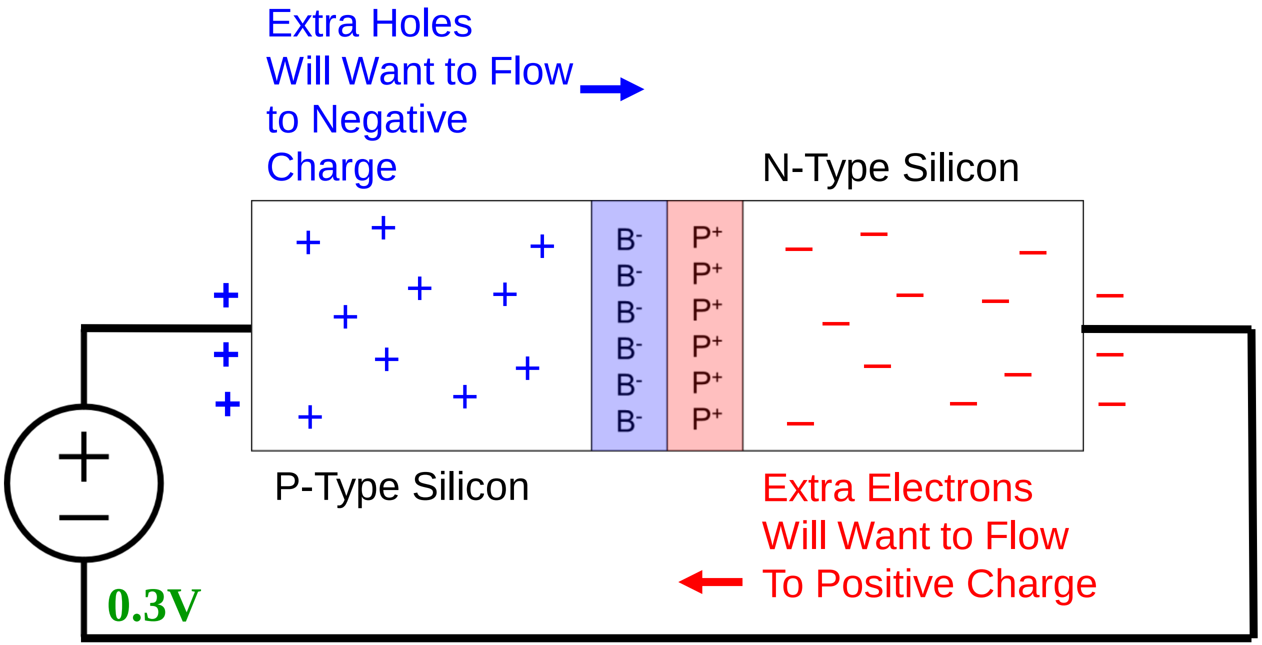

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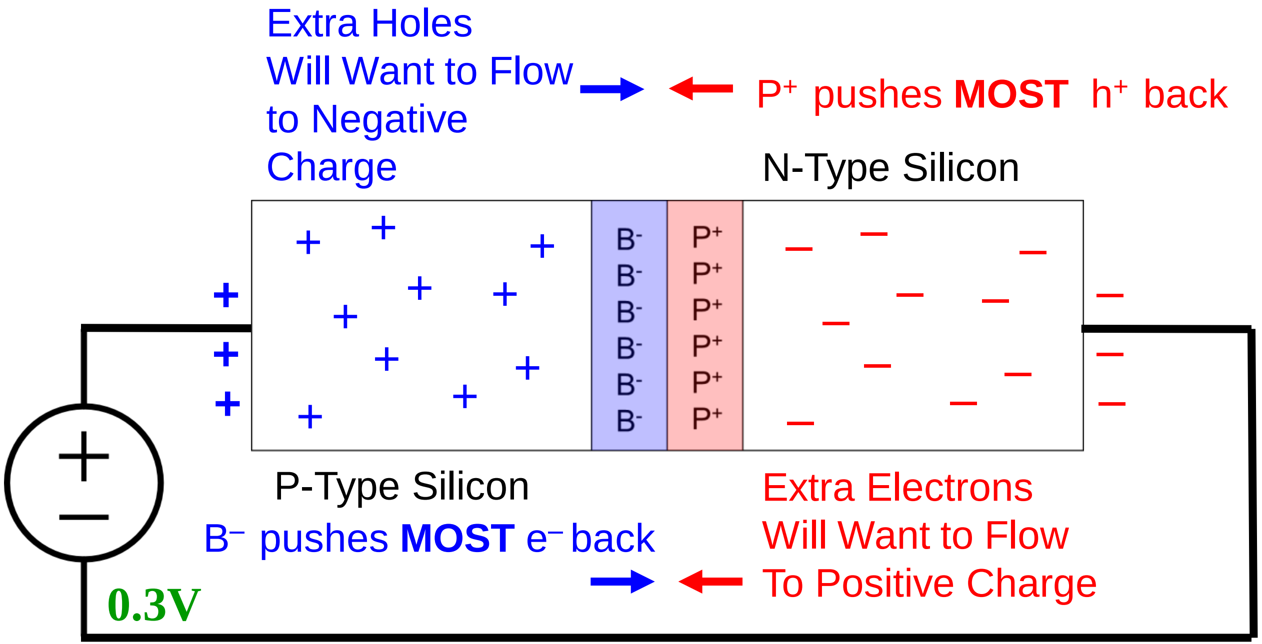
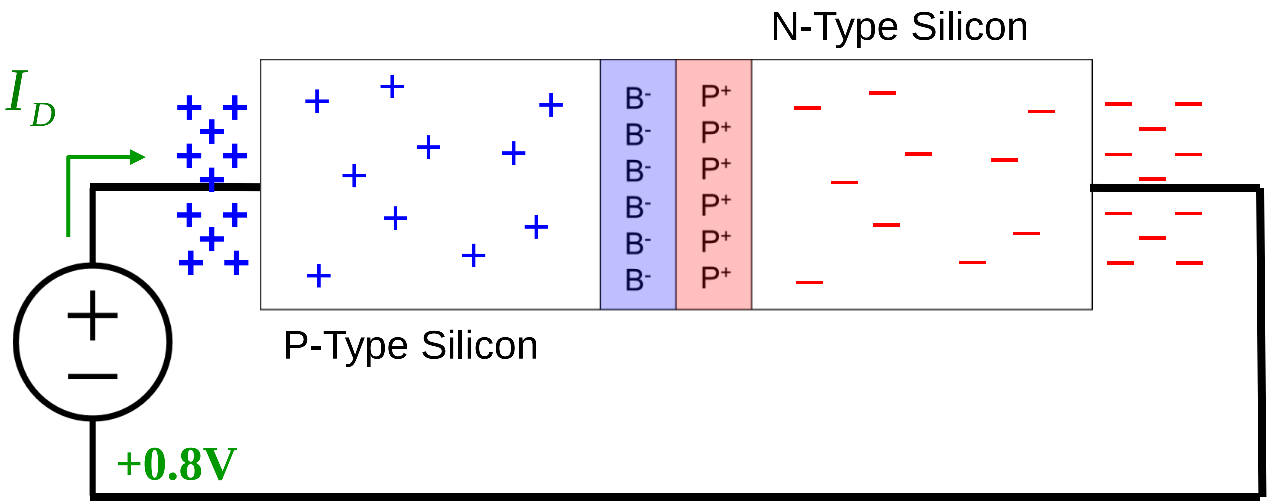
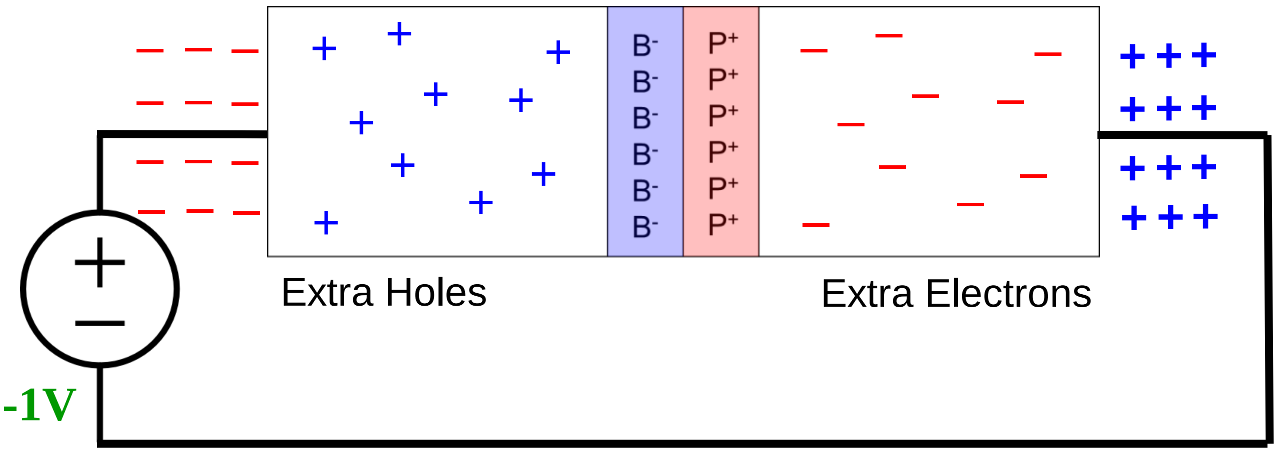


Larger Positive Voltage (+0.7V) Overcomes B^- / P^+ Barrier



Lots of current can flow

Apply a Negative Diode Voltage (–1V)
Almost No Diode Current Flows



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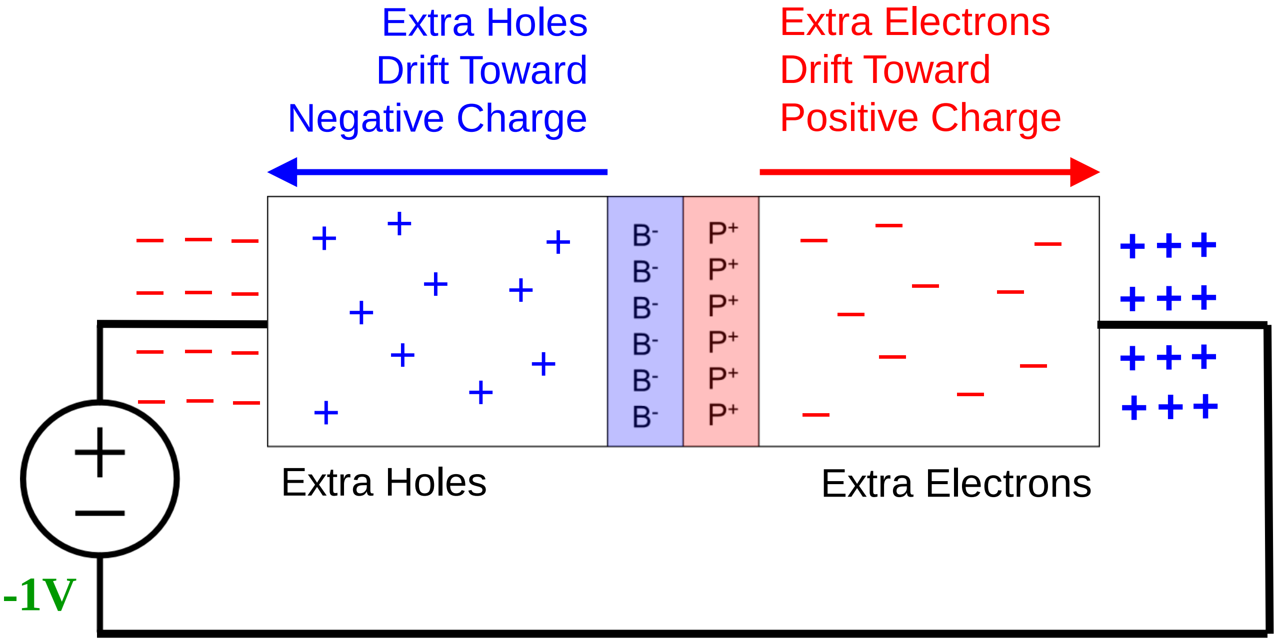
Almost No Diode Current Flows



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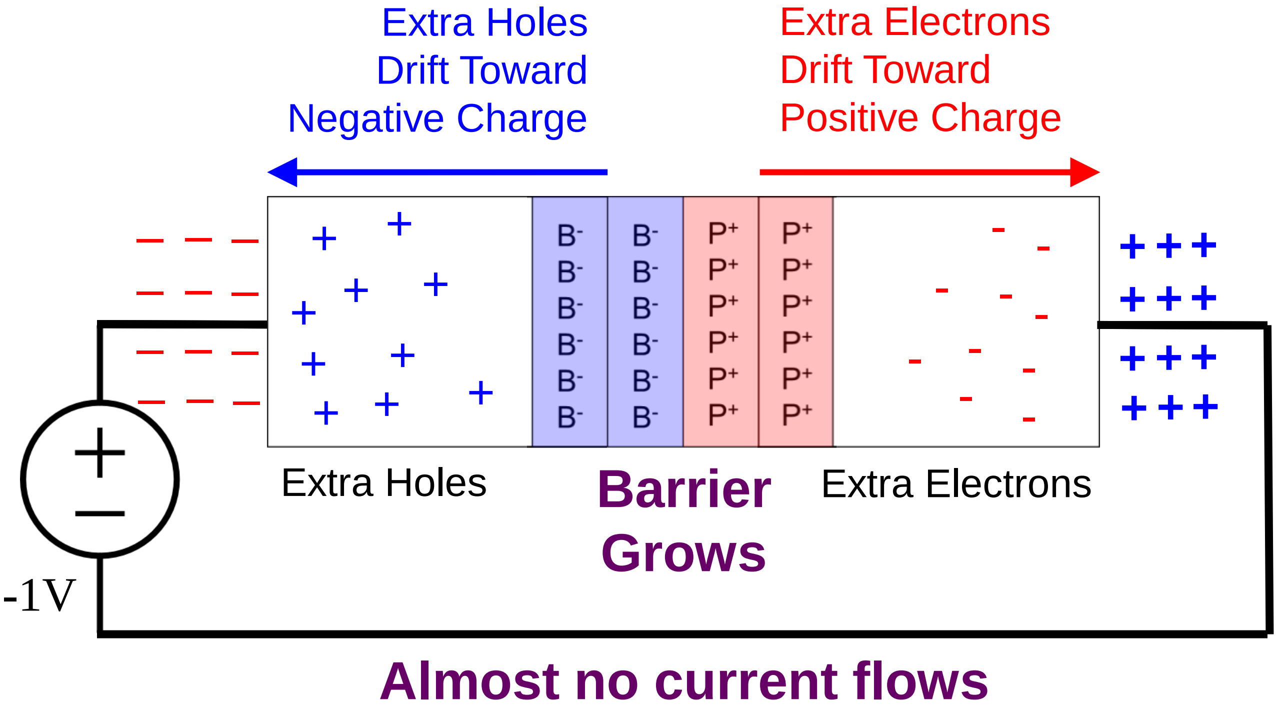
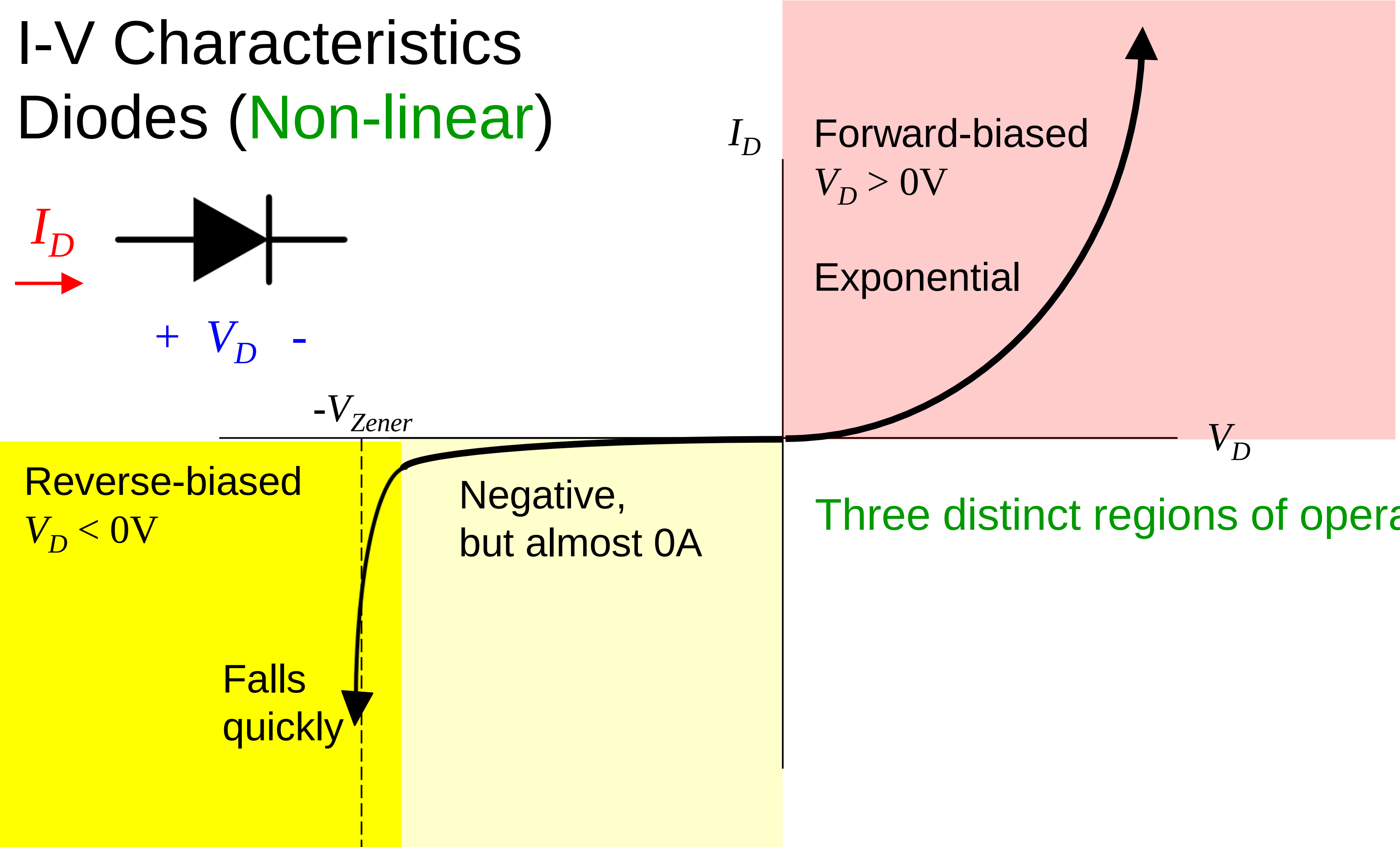
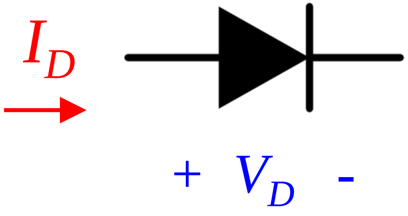


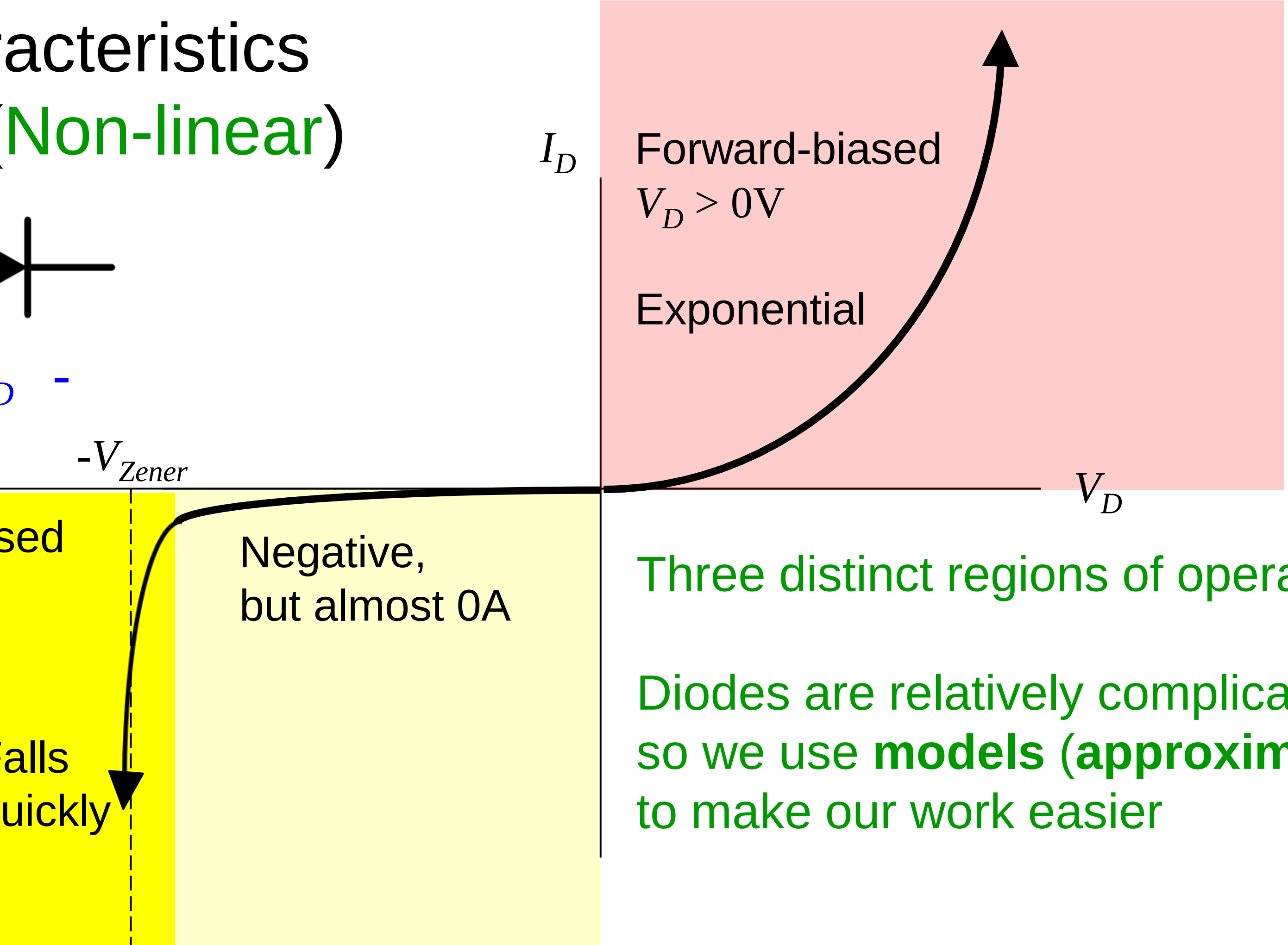
I-V Characteristics
Diodes (Non-linear)



Three distinct regions of operation

I-V Characteristics
Diodes (Non-linear)



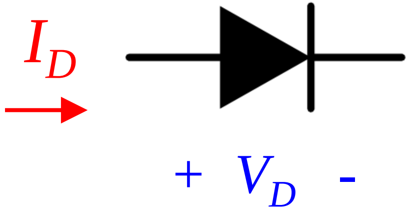


Three distinct regions of operation

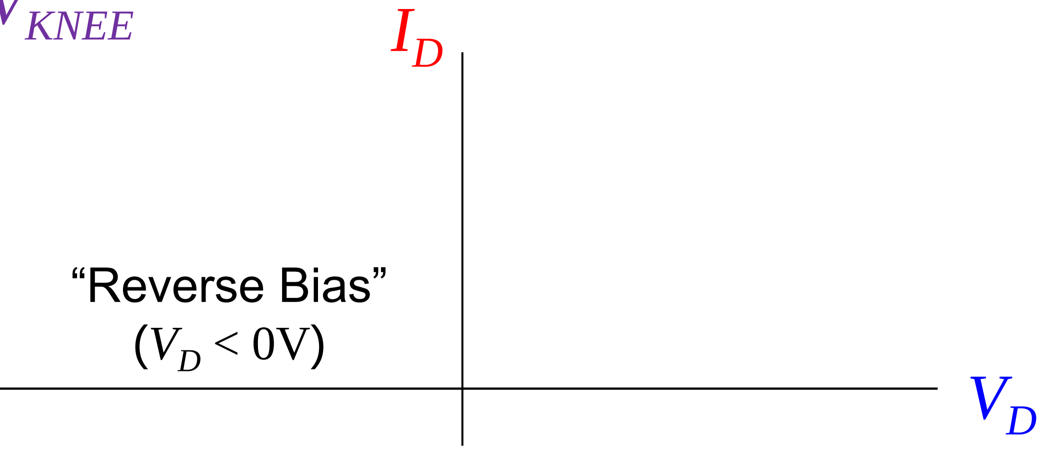
Diodes are relatively complicated, so we use **models (approximations)** to make our work easier

Knee Model 18-100

$I_D = 0\text{A}$ for $V_D \leq V_{KNEE}$



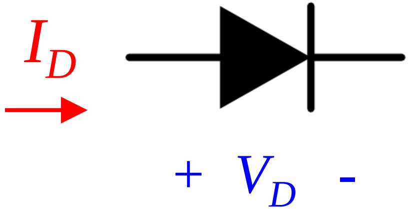
"Forward Bias" Region ($V_D > 0\text{V}$)

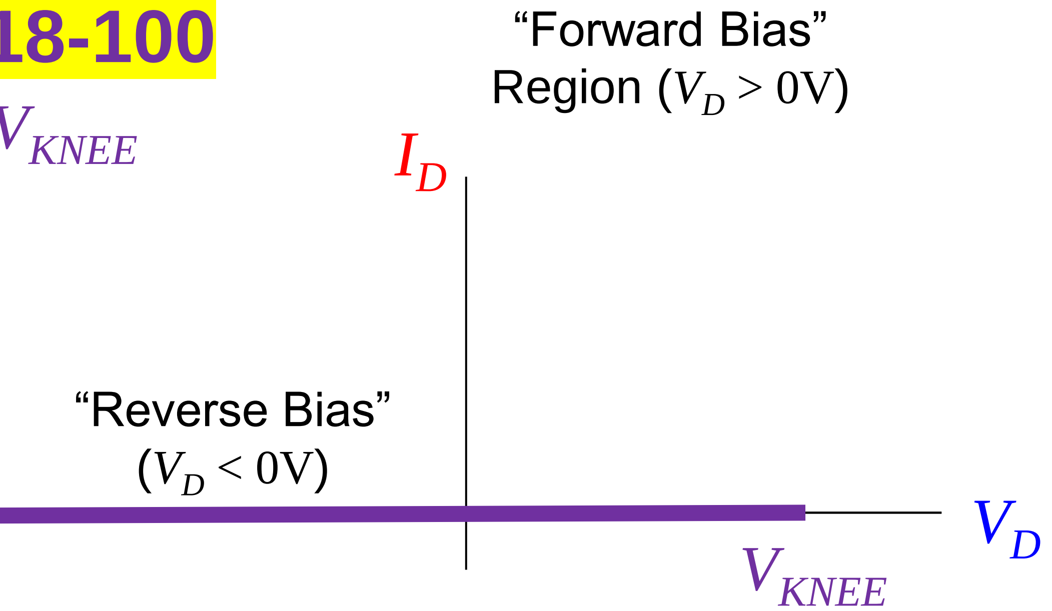


Three Rules:

Knee Model 18-100

$I_D = 0\text{A}$ for $V_D \leq V_{KNEE}$



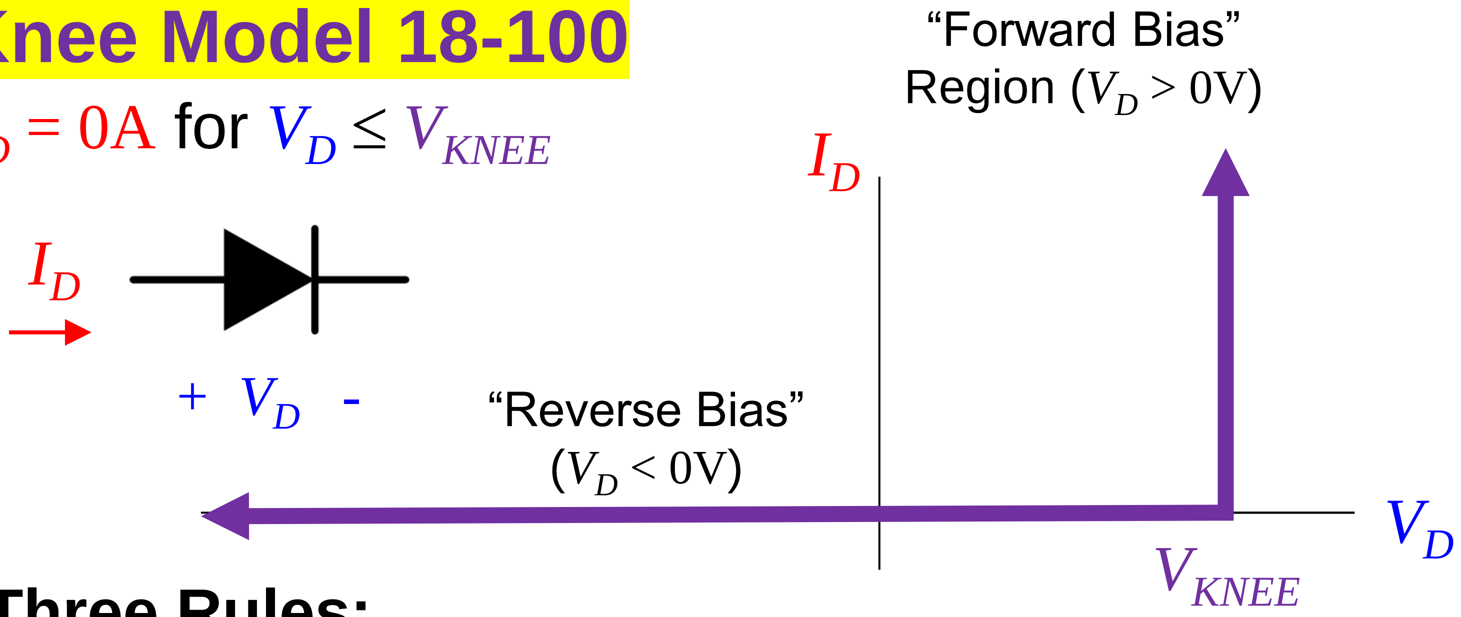


Three Rules:

- If $V_D < V_{KNEE}$, $I_D = 0\text{A}$

Knee Model 18-100

$I_D = 0\text{A}$ for $V_D \leq V_{KNEE}$

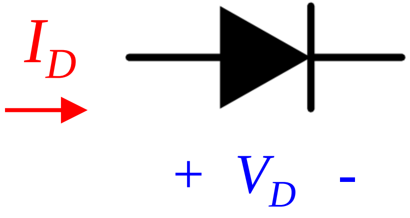


Three Rules:

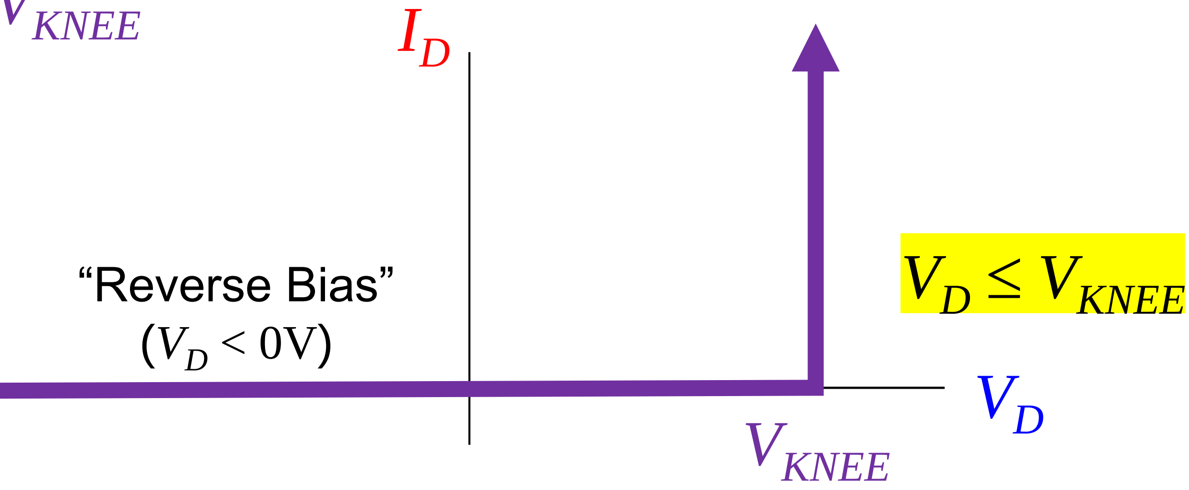
- If $V_D < V_{KNEE}$, $I_D = 0\text{A}$
- If $V_D = V_{KNEE}$, $I_D \geq 0\text{A}$

Knee Model 18-100

$I_D = 0\text{A}$ for $V_D \leq V_{KNEE}$



“Forward Bias” Region ($V_D > 0\text{V}$)



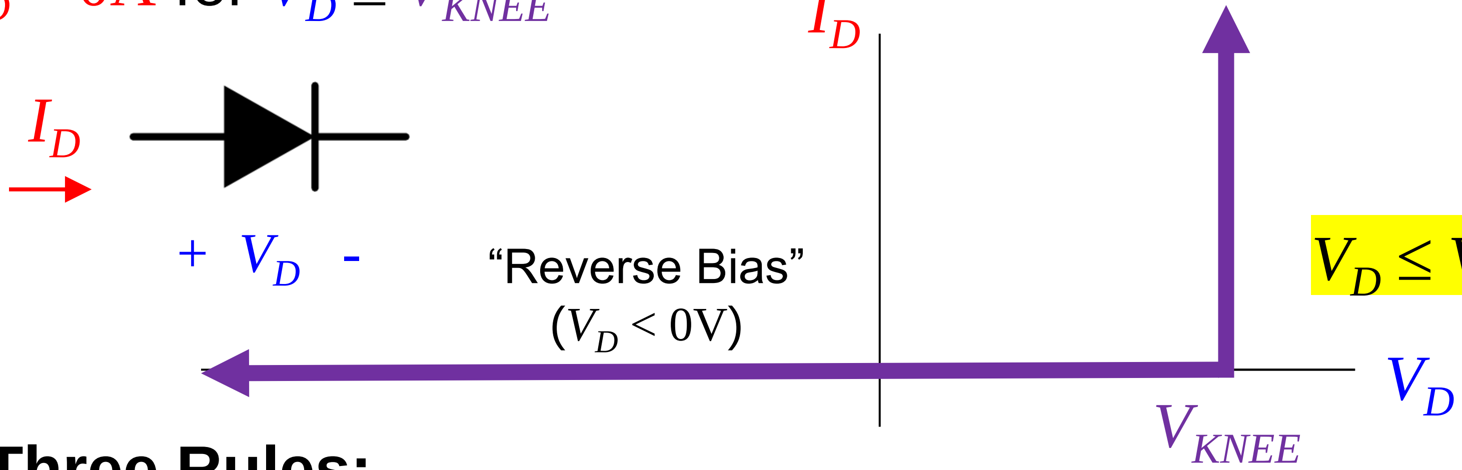
Three Rules:

- If $V_D < V_{KNEE}$, $I_D = 0\text{A}$
- If $V_D = V_{KNEE}$, $I_D \geq 0\text{A}$
- $V_D \leq V_{KNEE}$

Knee Model 18-100

$I_D = 0\text{A}$ for $V_D \leq V_{KNEE}$

"Forward Bias" Region ($V_D > 0\text{V}$)



"Reverse Bias" ($V_D < 0\text{V}$)

$V_D \leq V_{KNEE}$

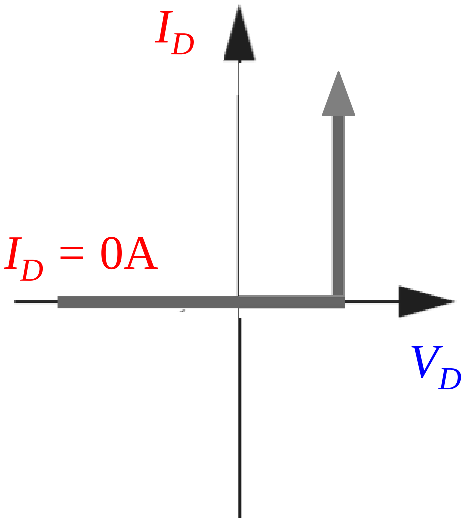
Three Rules:

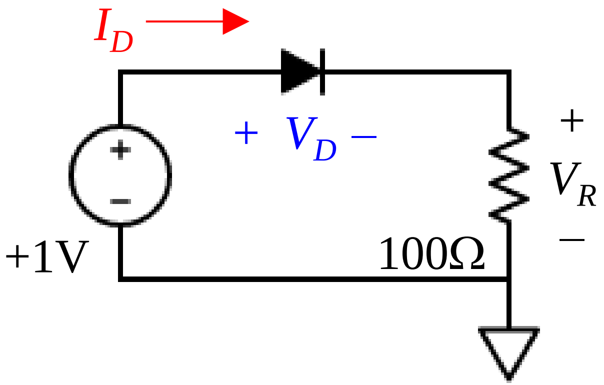
- If $V_D < V_{KNEE}$, $I_D = 0\text{A}$
- If $V_D = V_{KNEE}$, $I_D \geq 0\text{A}$
- $V_D \leq V_{KNEE}$

~0.7V for silicon diodes
~2V for red LEDs
~2.5V for green LEDs
~3V for blue LEDs

Using the Diode Knee Model

($V_{KNEE} = 0.7\text{V}$)

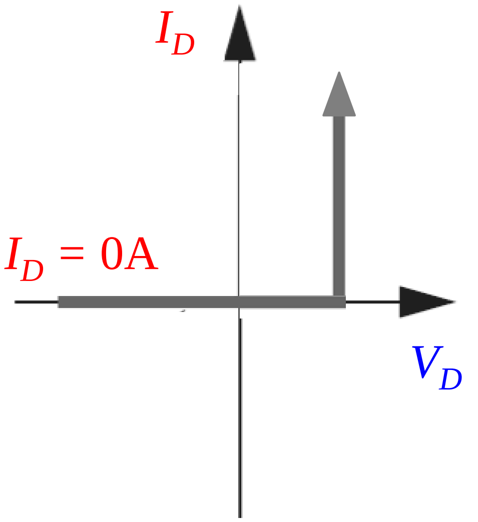


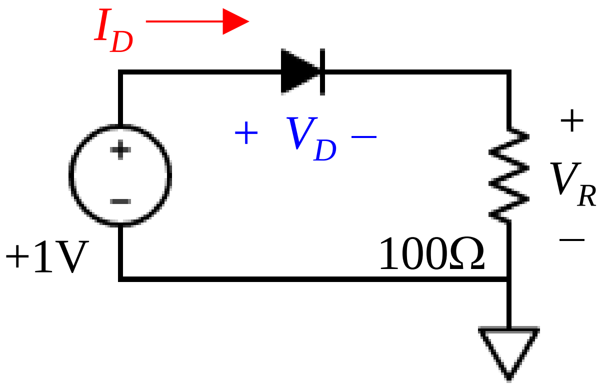


Using the Diode Knee Model (V_{KNEE} = 0.7V)

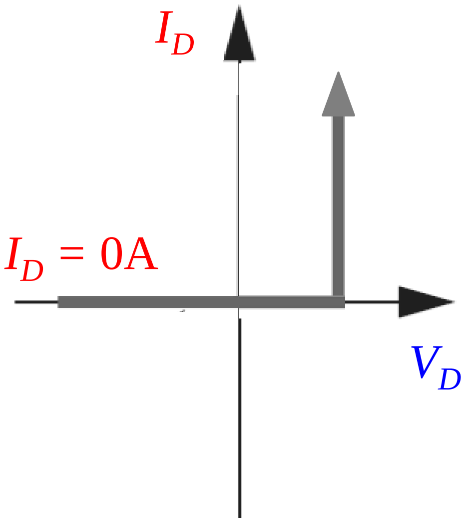
KVL is always true. It does not depend upon the diode being on.

$$+1\text{V} = V_D + V_R$$





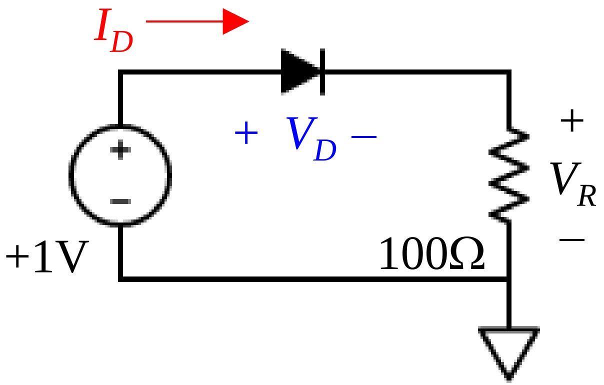
Using the Diode Knee Model ($V_{KNEE} = 0.7V$)



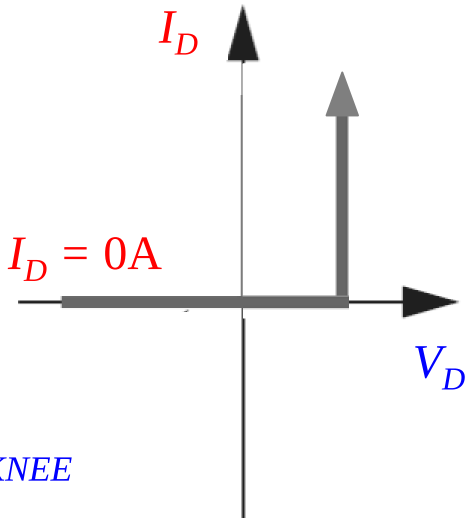
KVL is always true. It does not depend upon the diode being on.

$$+1V = V_D + V_R$$

$$+1V = V_D + (I_D)(100\Omega)$$



Using the Diode Knee Model ($V_{KNEE} = 0.7\text{V}$)



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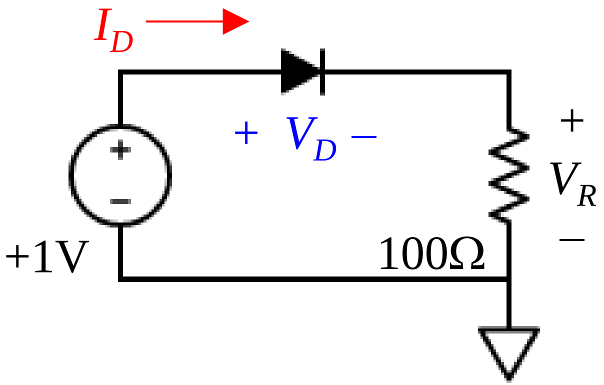
$$+1\text{V} = V_D + V_R$$

$$+1\text{V} = V_D + (I_D)(100\Omega)$$

Assume diode is on: $V_D = V_{KNEE}$



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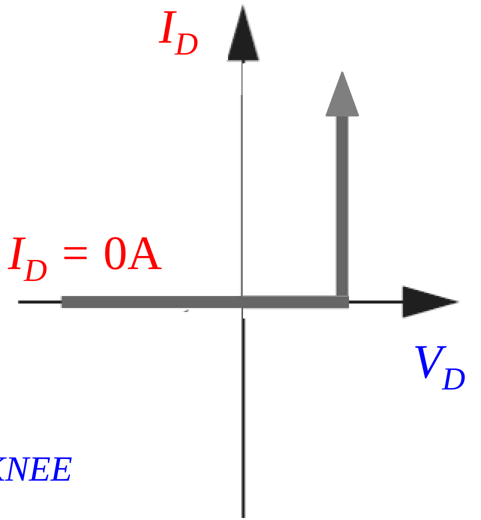

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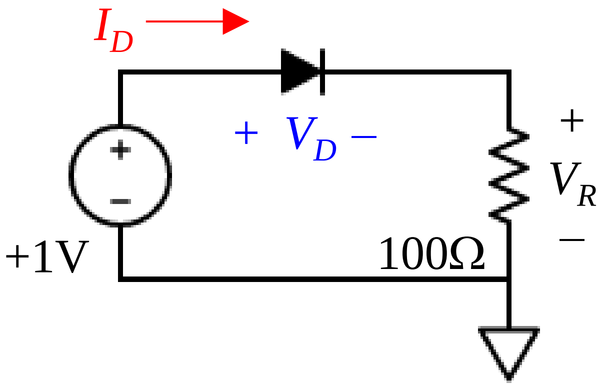

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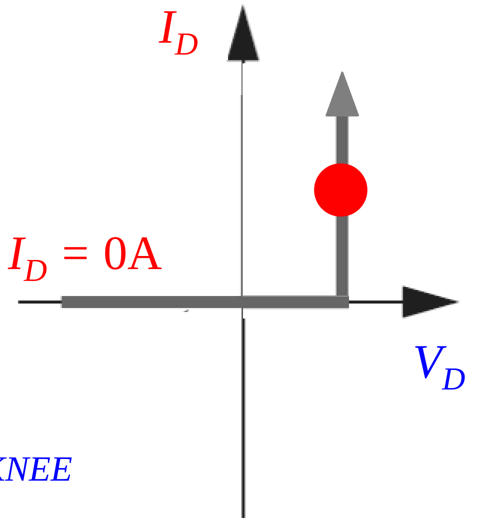

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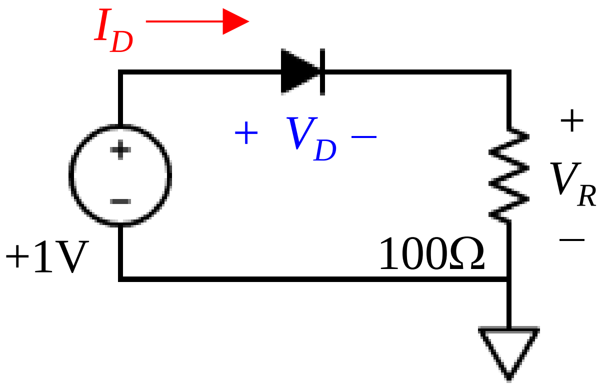
$I_D =$



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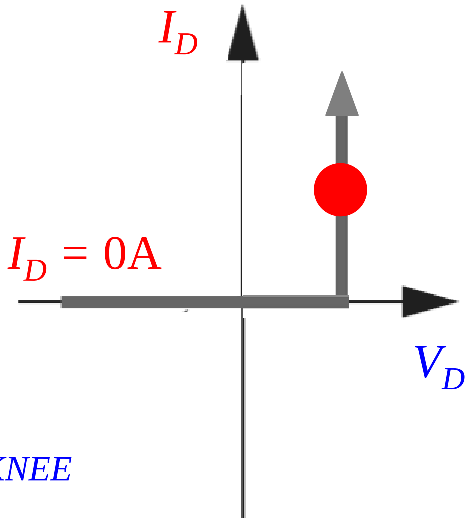

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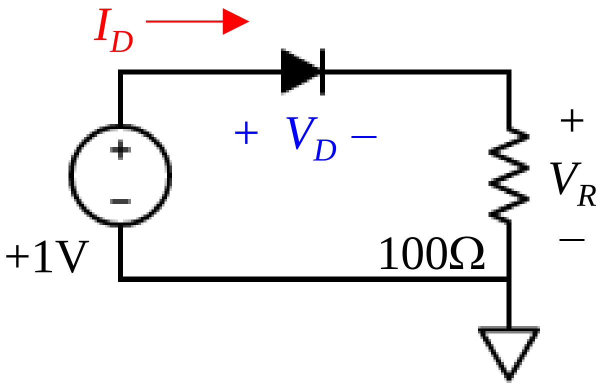
$$I_D = (1V - 0.7V)/100\Omega = 3mA$$



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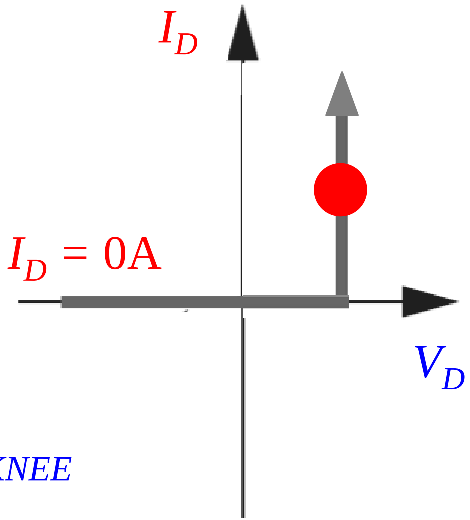

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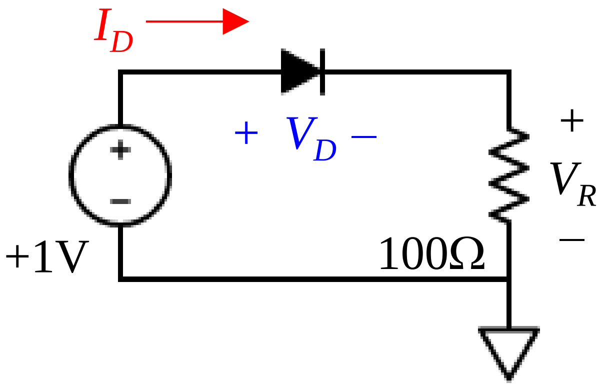
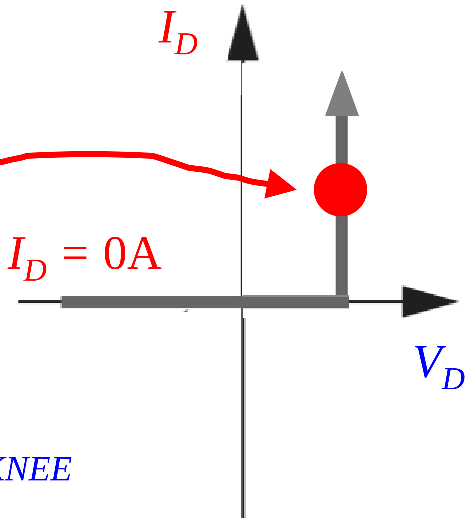


Check assumption:

Using the Diode Knee Model ($V_{KNEE} = 0.7V$)



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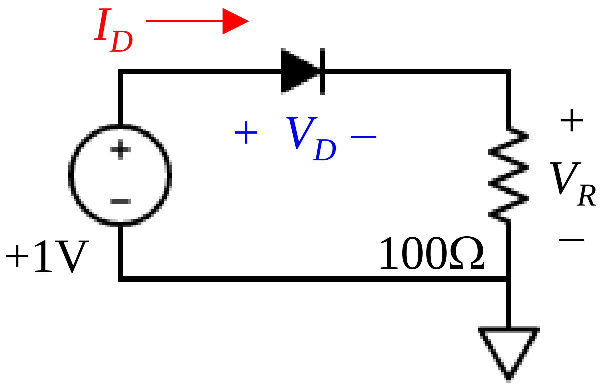
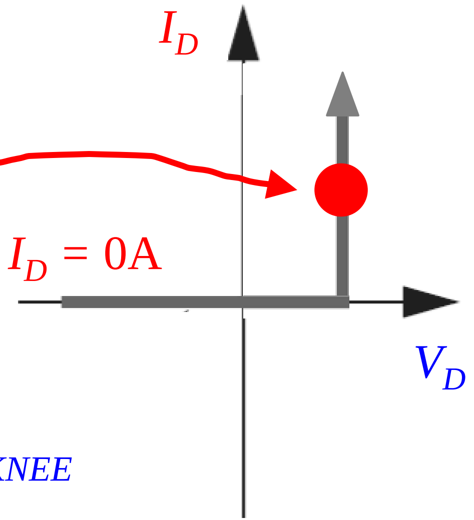


Check assumption: If diode is on, $I_D \geq 0A$

Using the Diode Knee Model ($V_{KNEE} = 0.7V$)



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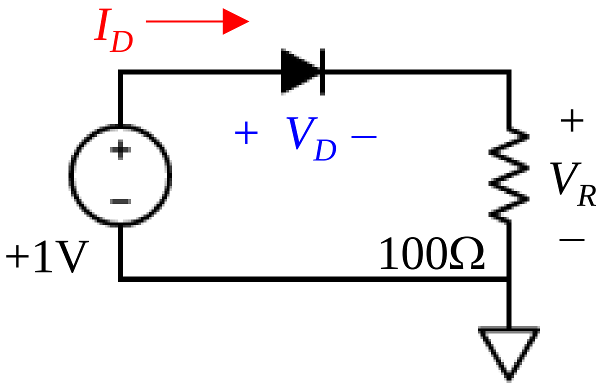
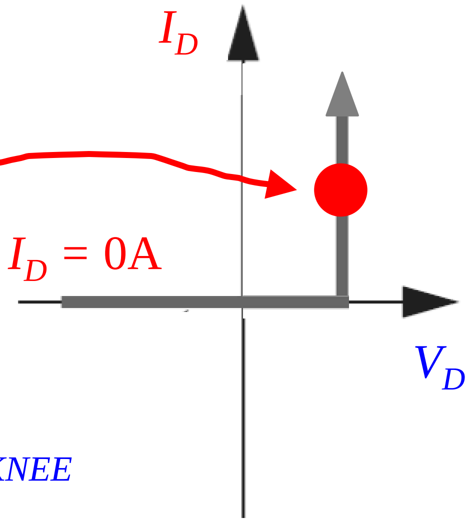


Check assumption: If diode is on, $I_D \geq 0A$

$3mA \geq 0A$, assumption confirmed!

Using the Diode Knee Model (approximation) ($V_{KNEE} = 0.7V$)



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Assume diode is on: $V_D = V_{KNEE}$

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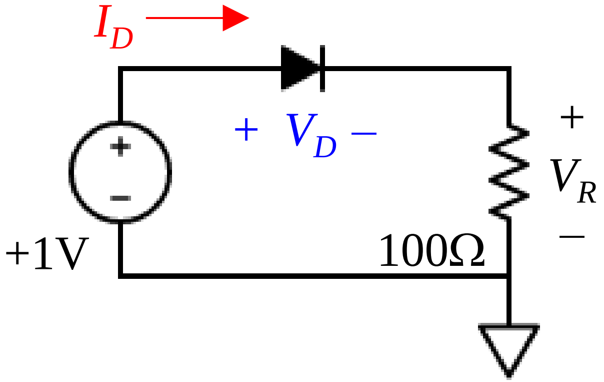

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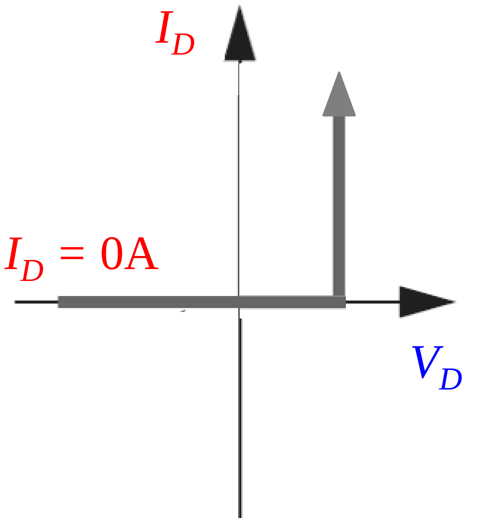
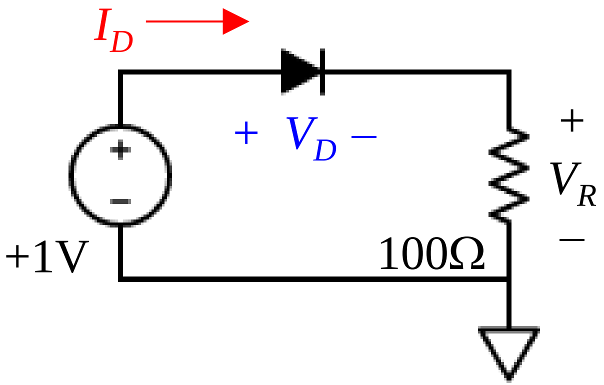
Using the Diode Knee Model ($V_{KNEE} = 0.7V$) (approximation)



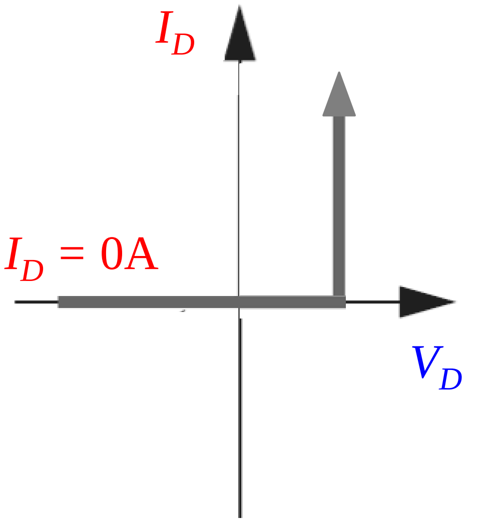
KVL is always true. It does not depend upon the diode being on.

$$+1V = V_D + V_R$$



Let's try a different input voltage

Using the Diode Knee Model ($V_{KNEE} = 0.7V$) (approximation)



KVL is always true. It does not depend upon the diode being on.

$$+0.6V = V_D + (I_D)(100\Omega)$$

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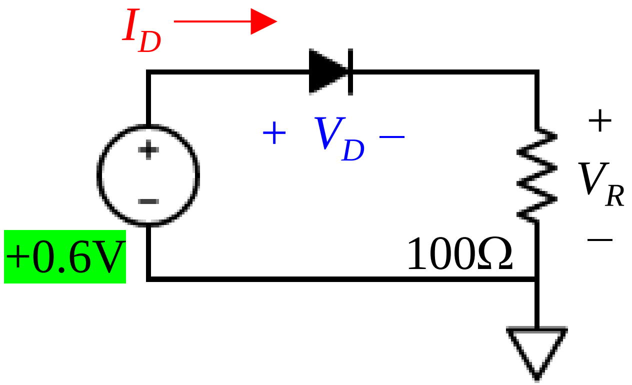

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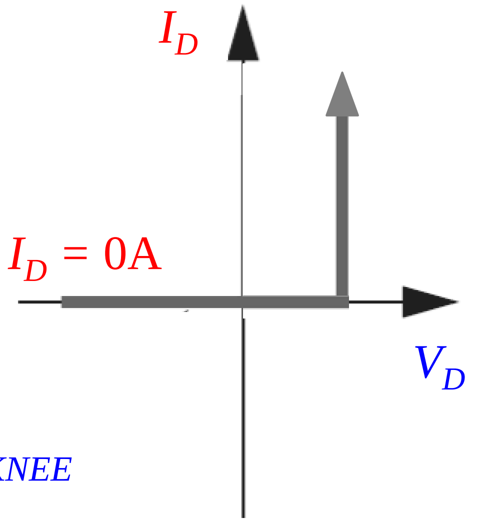

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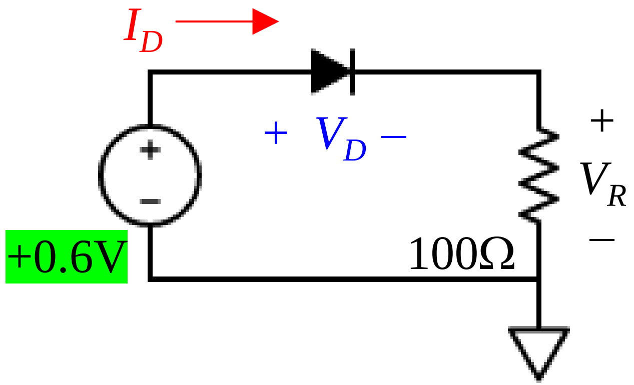
Assume diode is on: $V_D = V_{KNEE}$



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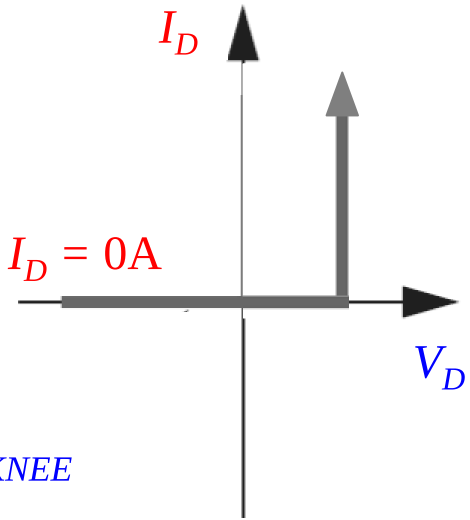

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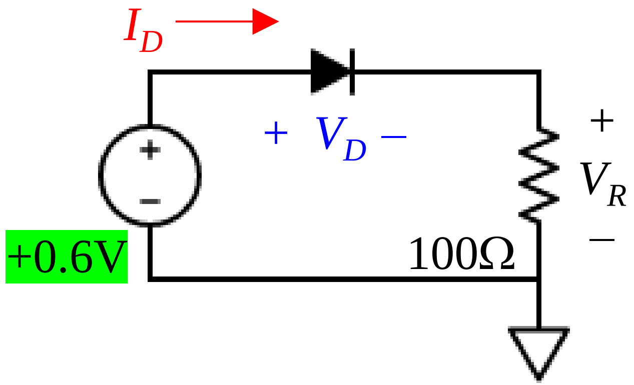

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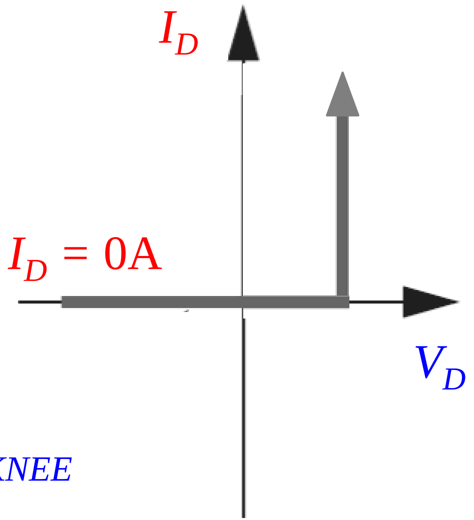

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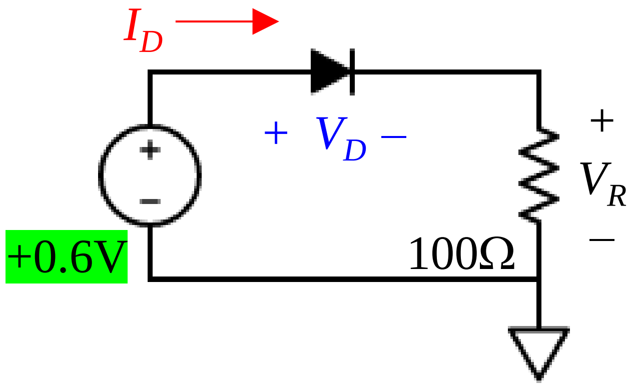
$I_D =$



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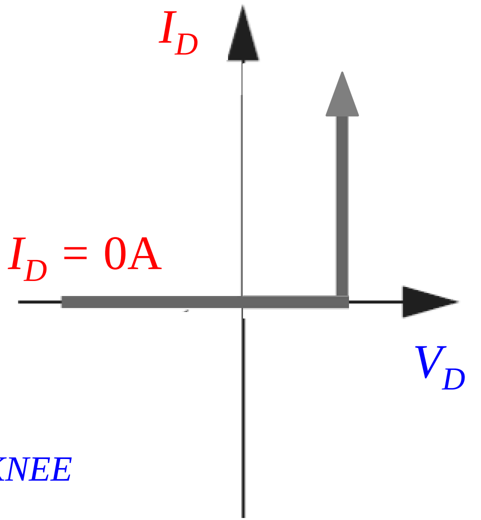

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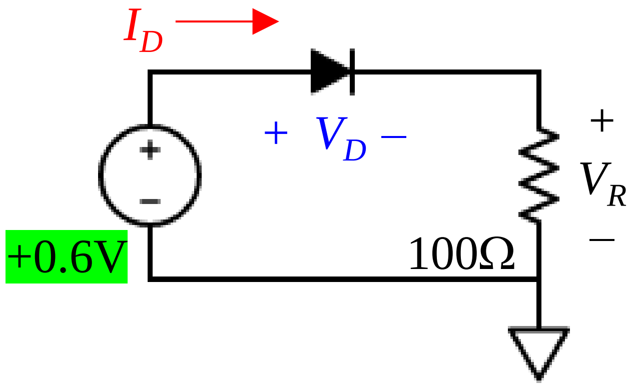
$$I_D = \left(0.6V - 0.7V\right)/100\Omega = -1mA$$



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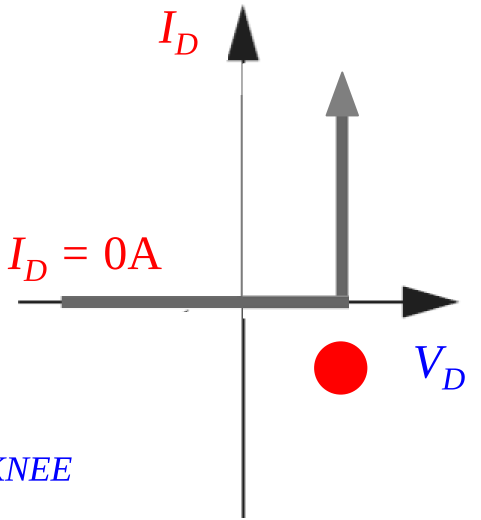

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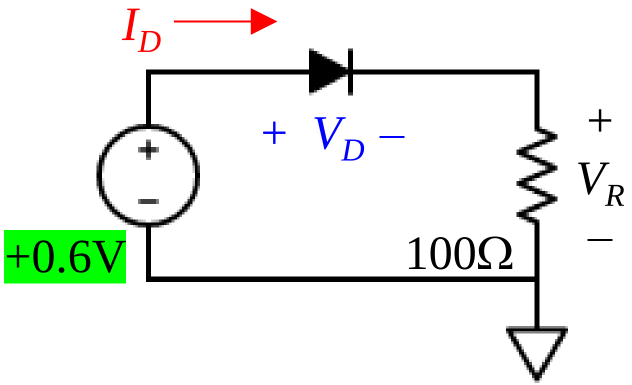
Check assumption: If diode is on, $I_D \geq 0A$



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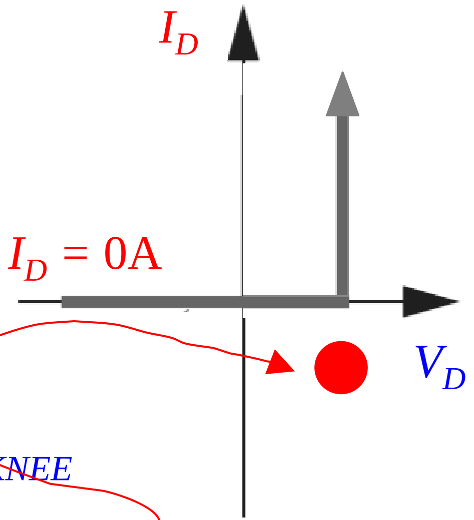

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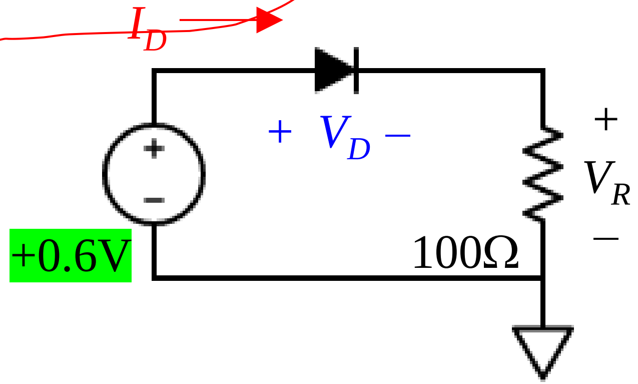


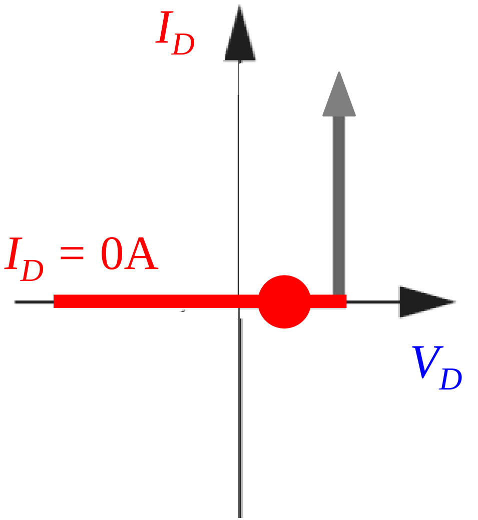
Check assumption: If diode is on, $I_D \geq 0A$

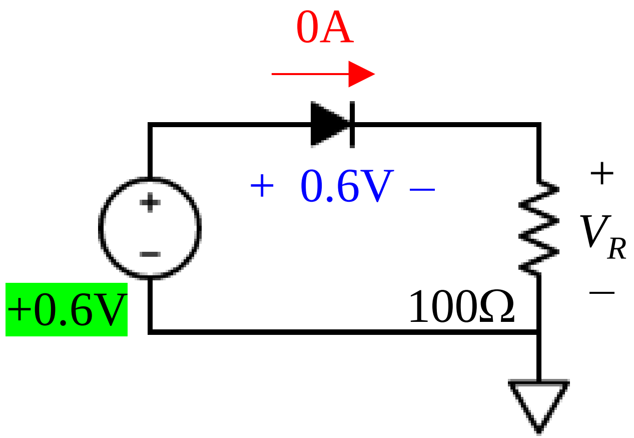
$-1mA \not\geq 0A$, assumption was wrong!

Using the Diode Knee Model ($V_{KNEE} = 0.7V$)

KVL is always true. It does not depend upon the diode being on.

Diode is off: $I_D = 0A$





Using the Diode Knee Model
($V_{KNEE} = 0.7V$)

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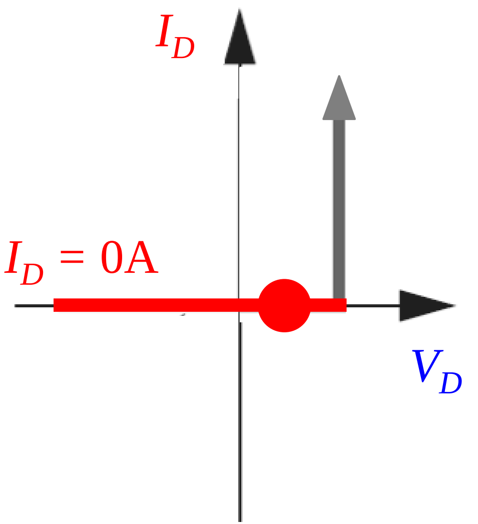
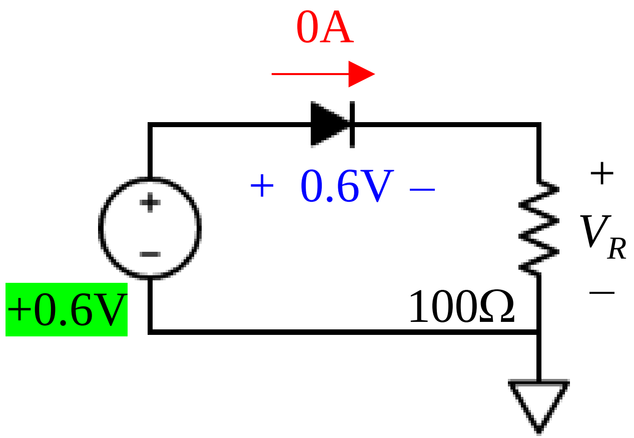
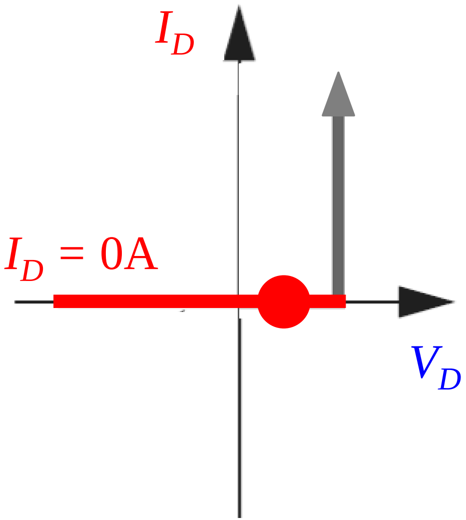




Using the Diode Knee Model ($V_{KNEE} = 0.7V$)



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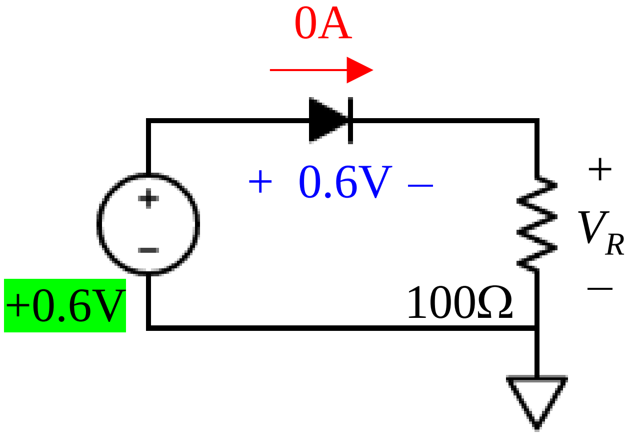

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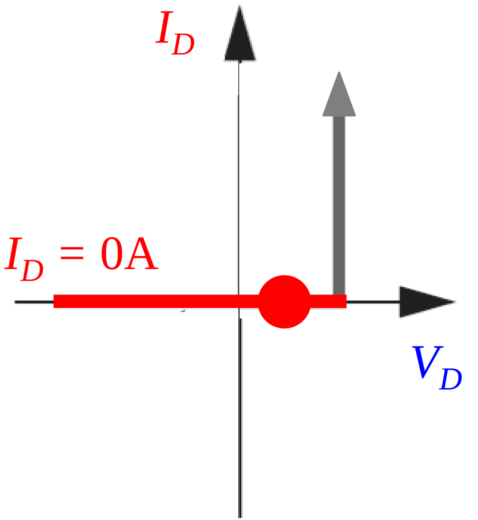

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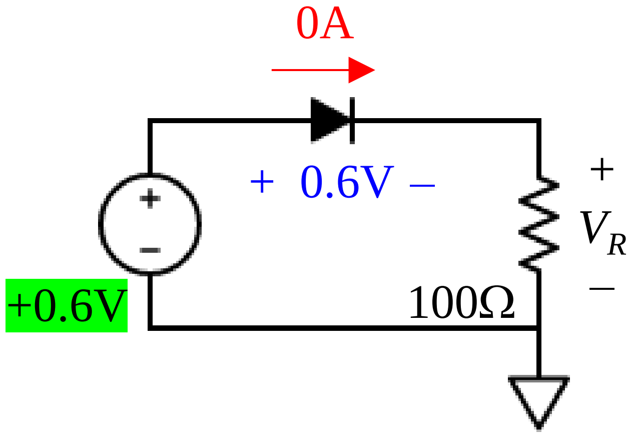
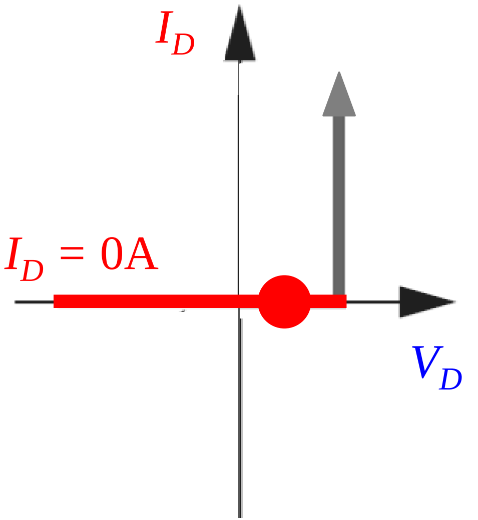
$V_D =$



Using the Diode Knee Model ($V_{KNEE} = 0.7\text{V}$)



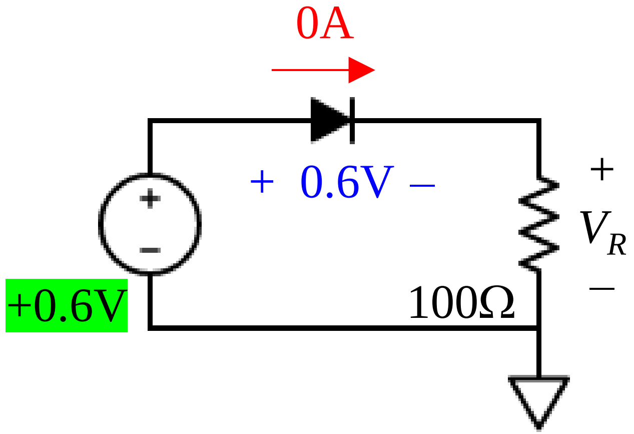
KVL is always true. It does not depend upon the diode being on.

$+0.6\text{V} = V_D + (I_D)(100\Omega)$

Diode is off: $I_D = 0\text{A}$

$+0.6\text{V} = V_D + (0\text{A})(100\Omega)$

$V_D = +0.6\text{V} - (0\text{A})(100\Omega) = +0.6\text{V}$



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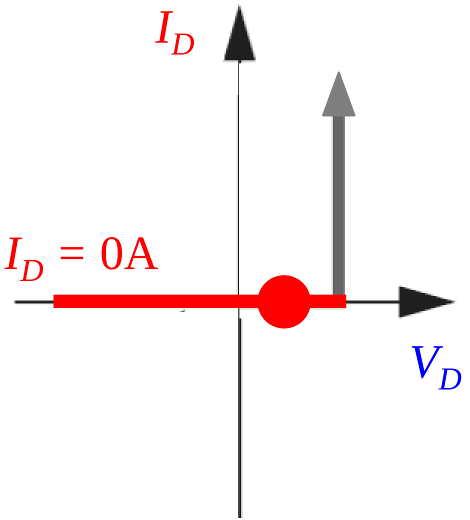


KVL is always true. It does not depend upon the diode being on.

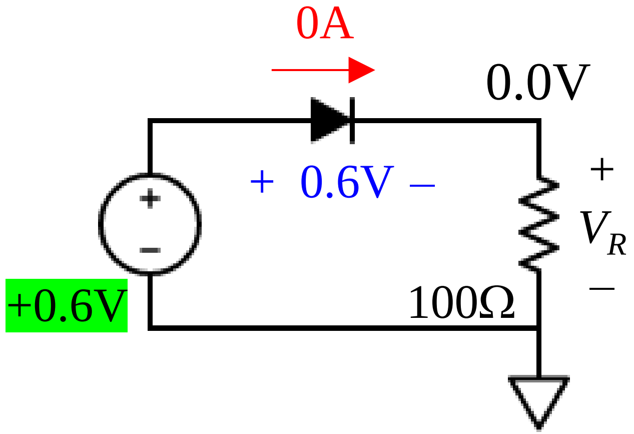
$+0.6V = V_D + (I_D)(100\Omega)$

Diode is off: $I_D = 0A$

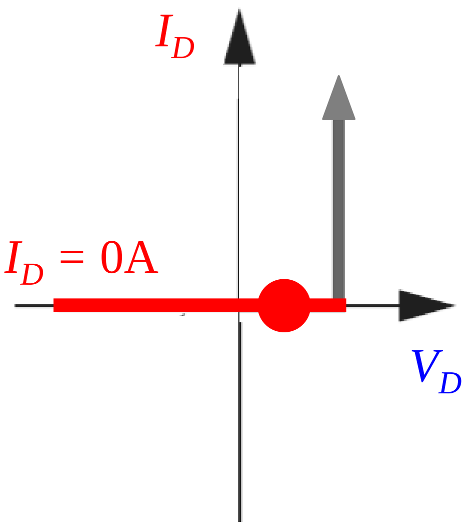
$+0.6V = V_D + (0A)(100\Omega)$

$V_D = +0.6V - (0A)(100\Omega) = +0.6V$

$V_R = 0.6V - 0.6V = 0V = (0A)(100\Omega)$



Using the Diode Knee Model ($V_{KNEE} = 0.7V$)



KVL is always true. It does not depend upon the diode being on.

$+0.6V = V_D + (I_D)(100\Omega)$

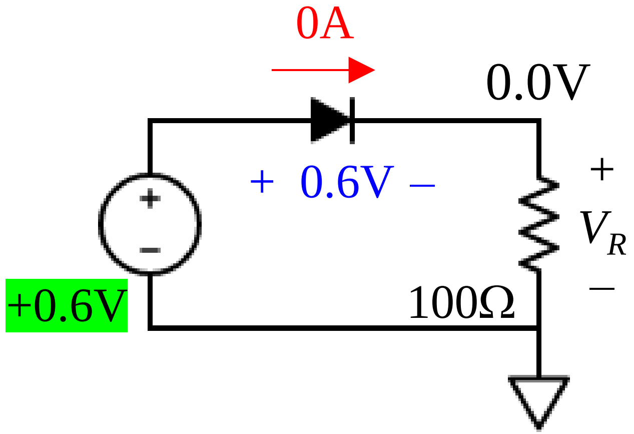
Diode is off: $I_D = 0A$

$+0.6V = V_D + (0A)(100\Omega)$

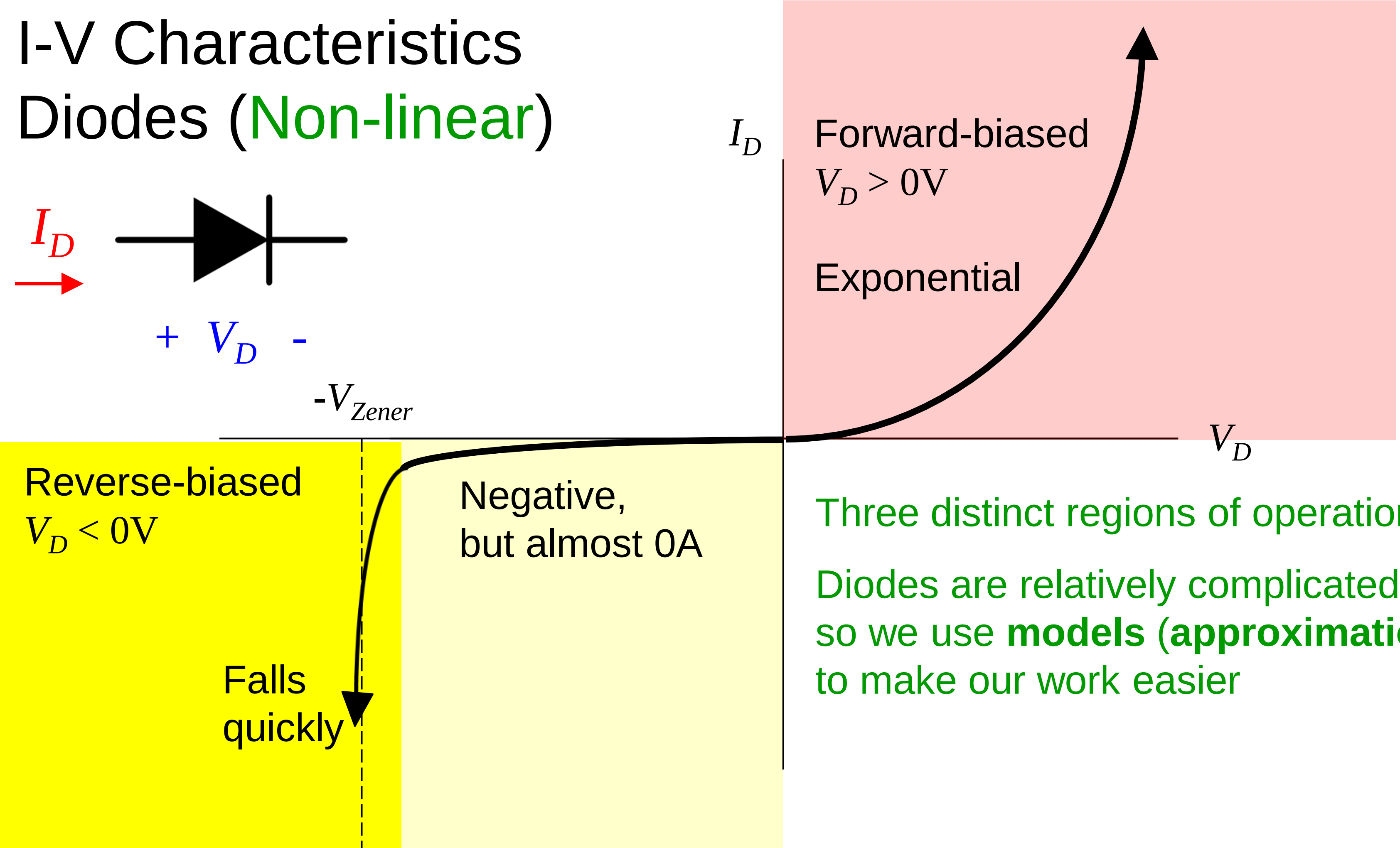
$V_D = +0.6V - (0A)(100\Omega) = +0.6V$

$V_R = 0.6V - 0.6V = 0V = (0A)(100\Omega)$

Diode is off: $I_D = 0A$, and $V_D = 0.6V < V_{KNEE}$



I-V Characteristics
Diodes (Non-linear)

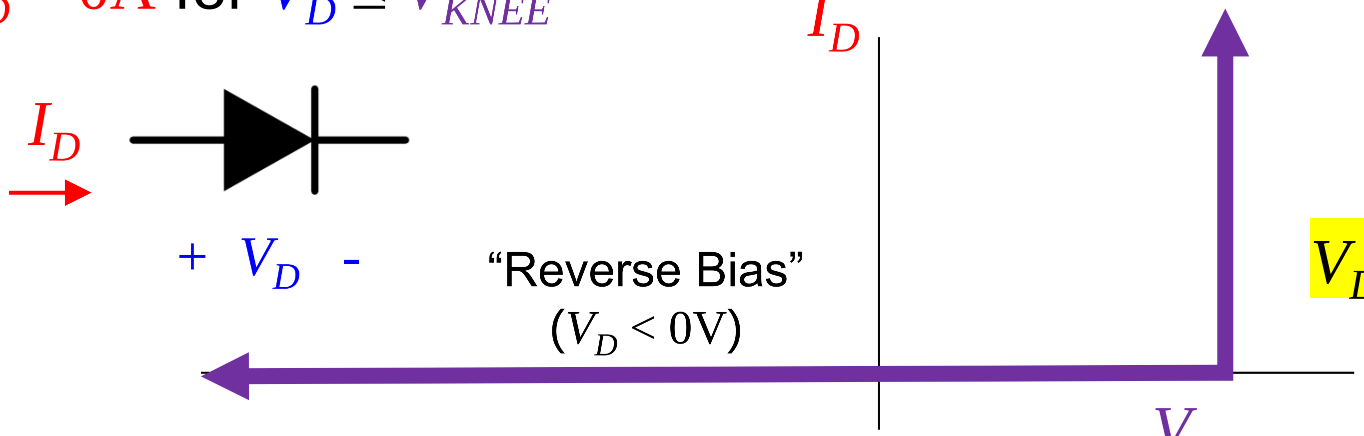


Three distinct regions of operation

Diodes are relatively complicated, so we use **models (approximations)** to make our work easier

Knee Model 18-100

$I_D = 0\text{A}$ for $V_D \leq V_{KNEE}$



Three Rules:

- If $V_D < V_{KNEE}$, $I_D = 0\text{A}$
- If $V_D = V_{KNEE}$, $I_D \geq 0\text{A}$
- $V_D \leq V_{KNEE}$

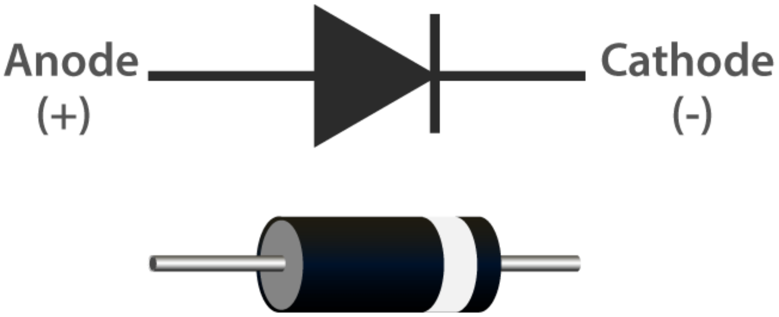
~0.7V for silicon diodes

~2V for red LEDs

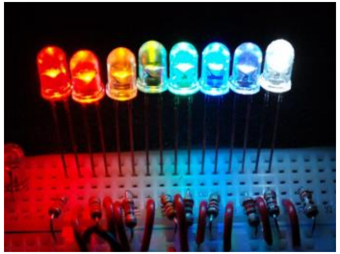
~2.5V for green LEDs

~3V for blue LEDs

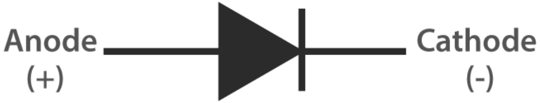
Diodes IRL (In Real Life)



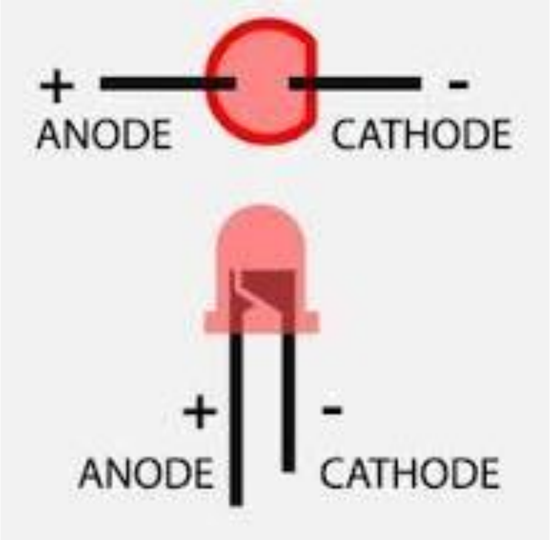
Light Emitting Diodes (LEDs)


Lighting

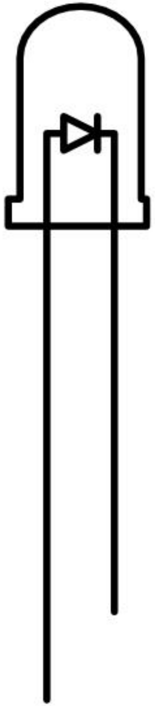


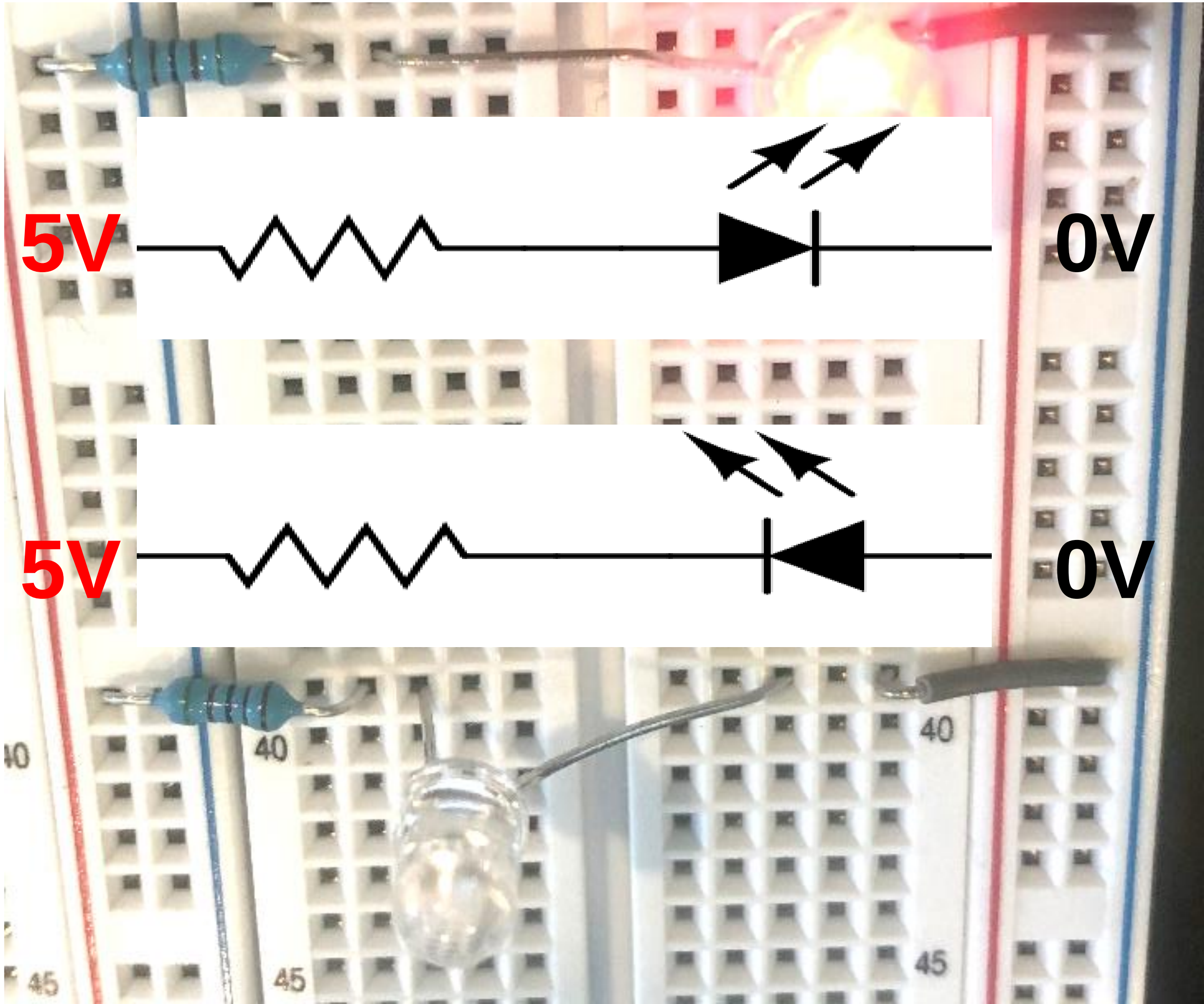

Display



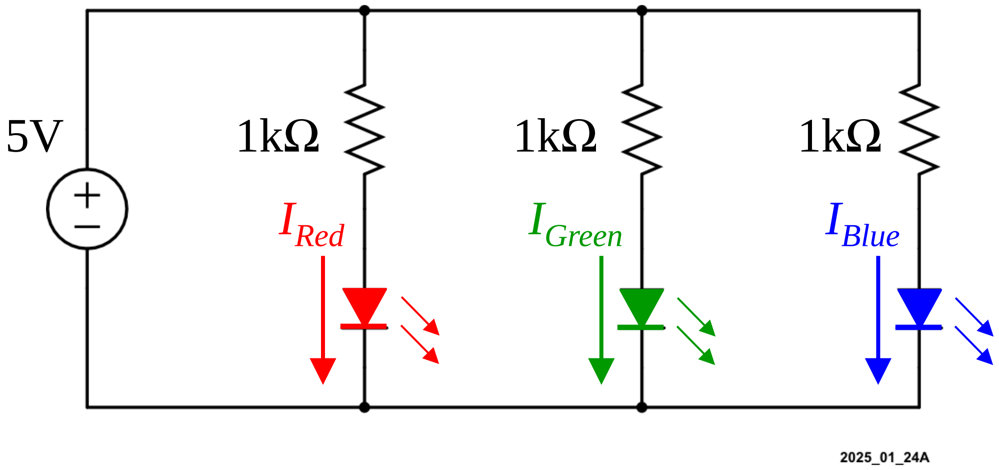
Micro-LED Display

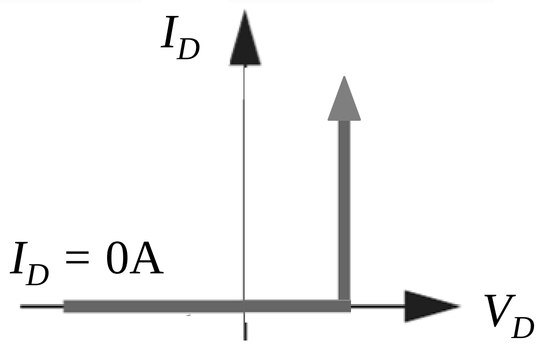
Wiring Diodes



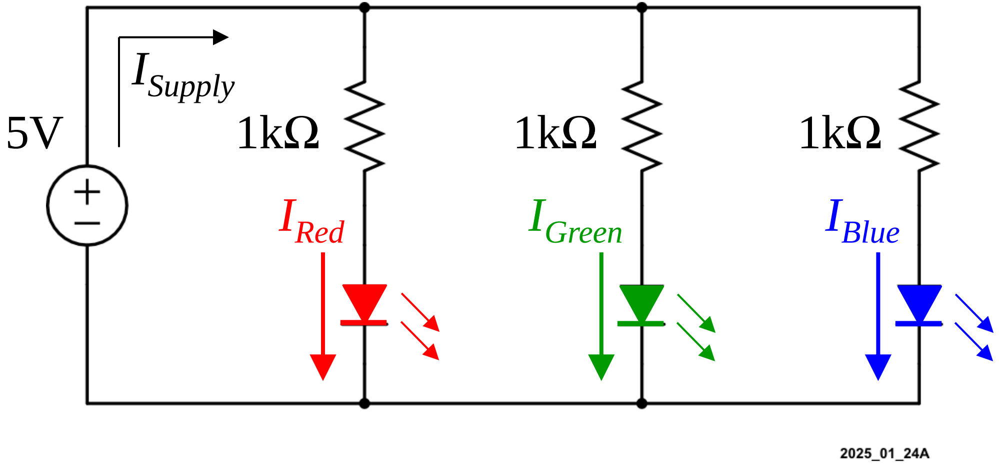


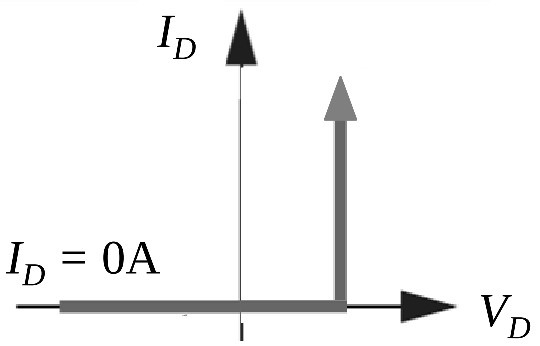
Red (V_{KNEE} = 2V)
Green (V_{KNEE} = 2.5V) &
Blue (V_{KNEE} = 3V)
LEDs



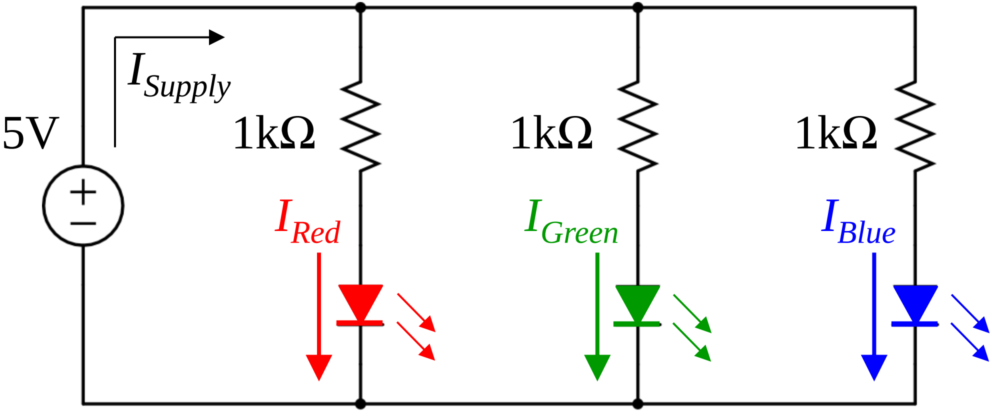


Red (V_{KNEE} = 2V)
Green (V_{KNEE} = 2.5V) &
Blue (V_{KNEE} = 3V)
LEDs: Find I_{Supply}



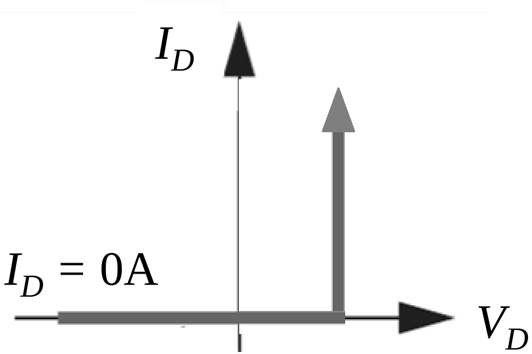


Red (V_{KNEE} = 2V) Green (V_{KNEE} = 2.5V) & Blue (V_{KNEE} = 3V) LEDs: Find I_{Supply}

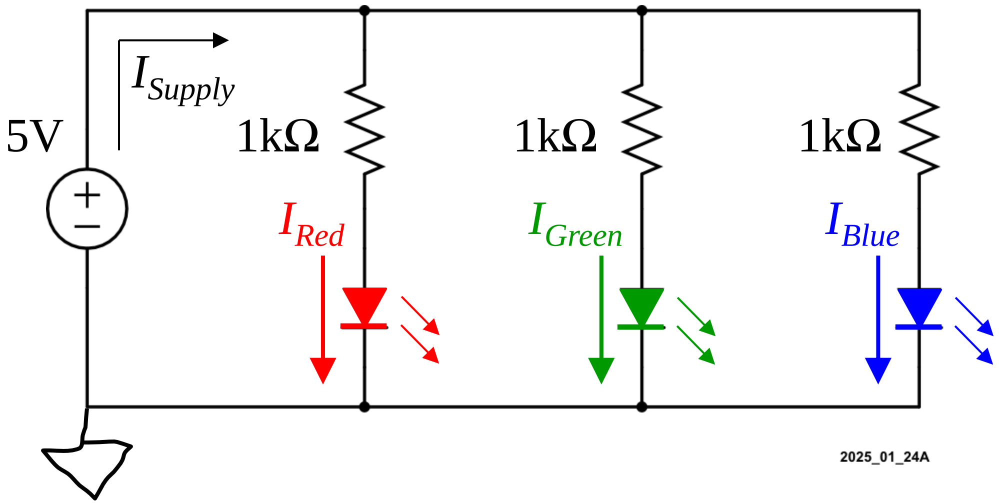


2025_01_24A

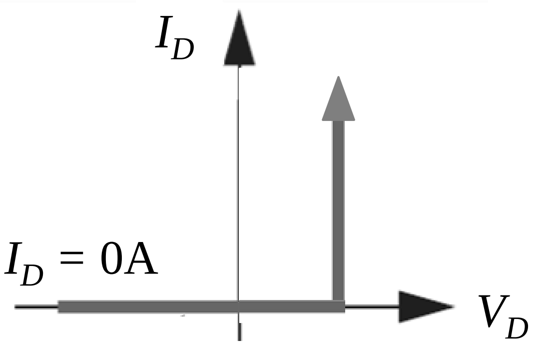
Assume On (V_D=V_{KNEE})



Red ($V_{KNEE} = 2V$) Green ($V_{KNEE} = 2.5V$) & Blue ($V_{KNEE} = 3V$) LEDs: Find I_{Supply}

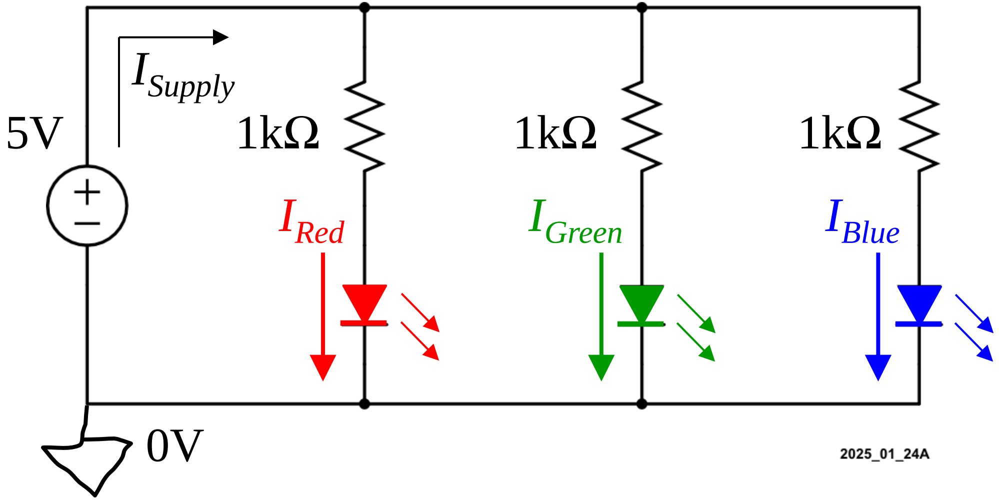


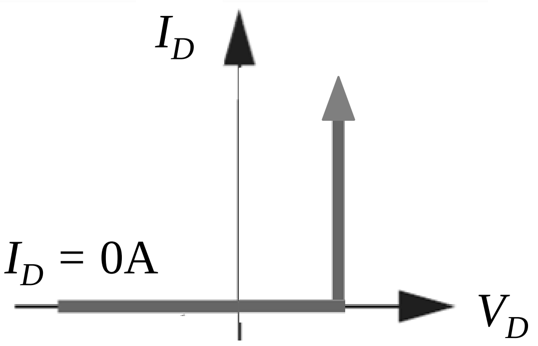
Assume On ($V_D = V_{KNEE}$)



Red (V_{KNEE} = 2V)
Green (V_{KNEE} = 2.5V) &
Blue (V_{KNEE} = 3V)
LEDs: Find I_{Supply}

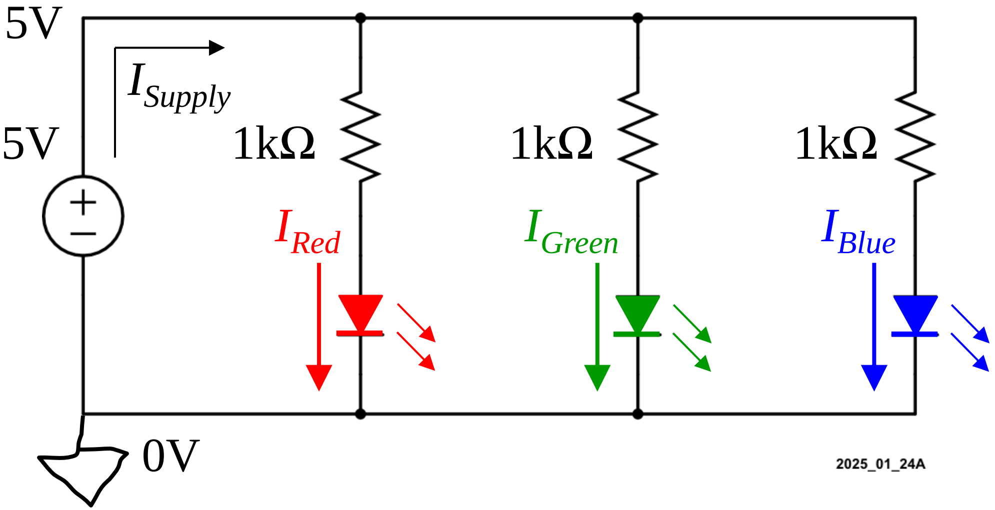
Assume On ($V_D = V_{KNEE}$)

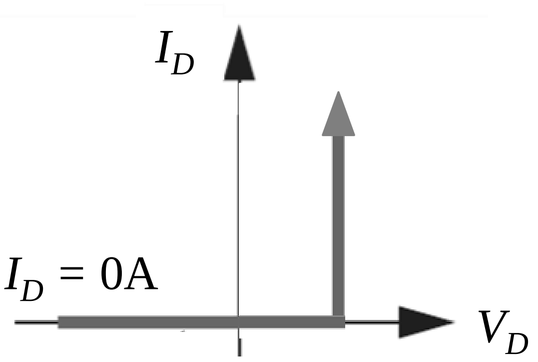




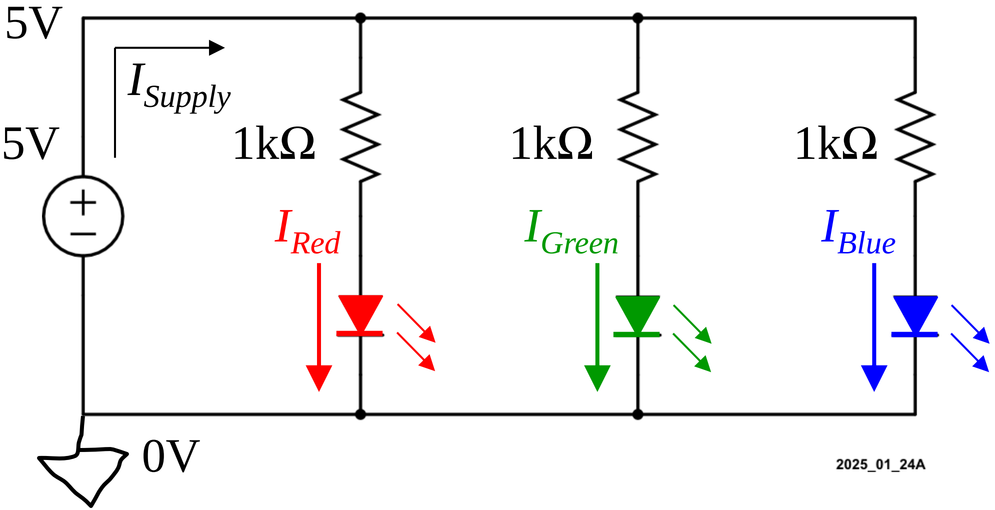
Red (V_{KNEE} = 2V)
Green (V_{KNEE} = 2.5V) &
Blue (V_{KNEE} = 3V)
LEDs: Find I_{Supply}

Assume On (V_D=V_{KNEE})



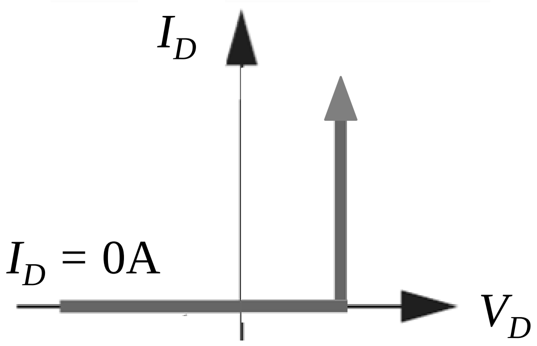


Red (V_{KNEE} = 2V)
Green (V_{KNEE} = 2.5V) &
Blue (V_{KNEE} = 3V)
LEDs: Find I_{Supply}

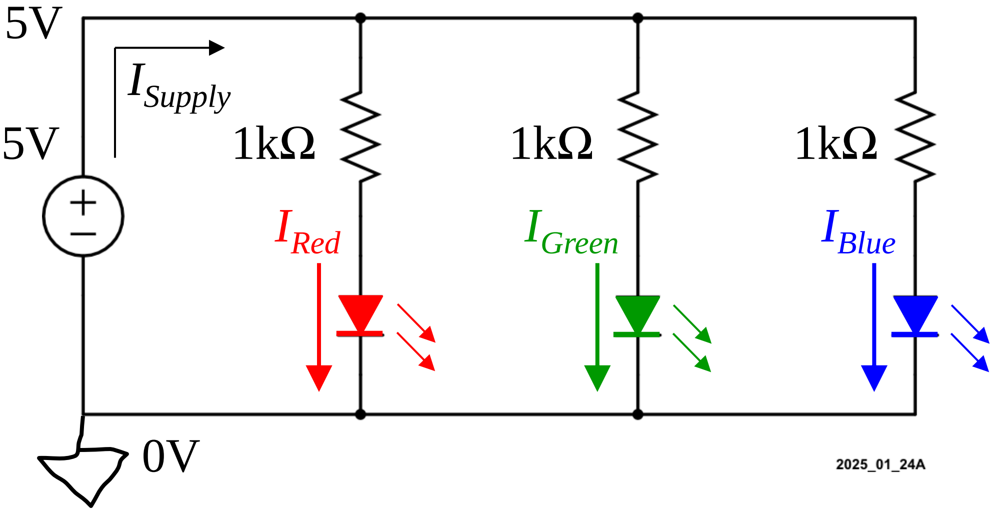


Assume On (V_D=V_{KNEE})

KVL is always true: $5\text{V} = I_{Red}(1\text{k}\Omega) + 2\text{V}$



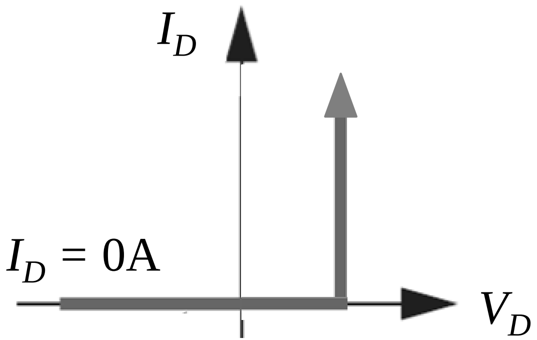
Red (V_{KNEE} = 2V) Green (V_{KNEE} = 2.5V) & Blue (V_{KNEE} = 3V) LEDs: Find I_{Supply}



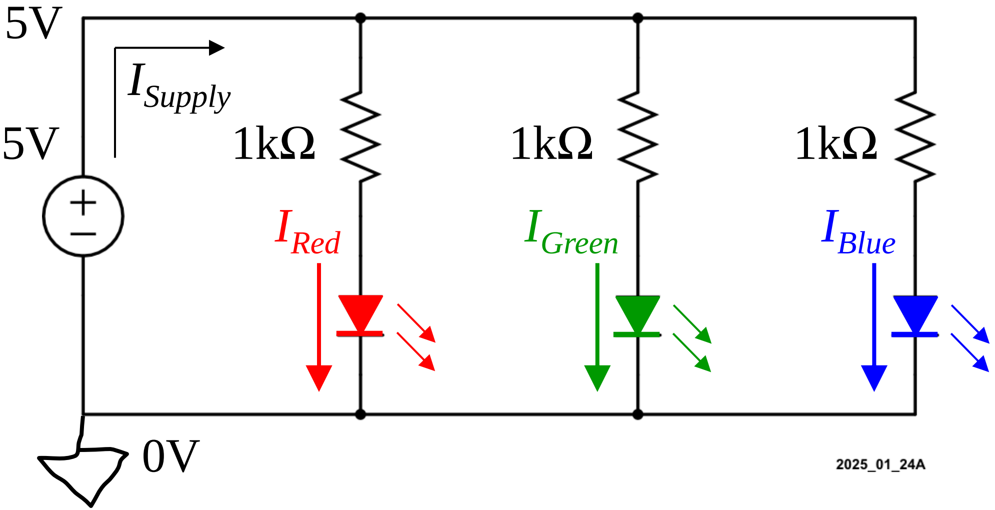
Assume On (V_D=V_{KNEE})

KVL is always true: $5V = I_{Red}(1k\Omega) + 2V$

$5V = I_{Green}(1k\Omega) + 2.5V$



Red (V_{KNEE} = 2V)
Green (V_{KNEE} = 2.5V) &
Blue (V_{KNEE} = 3V)
LEDs: Find I_{Supply}



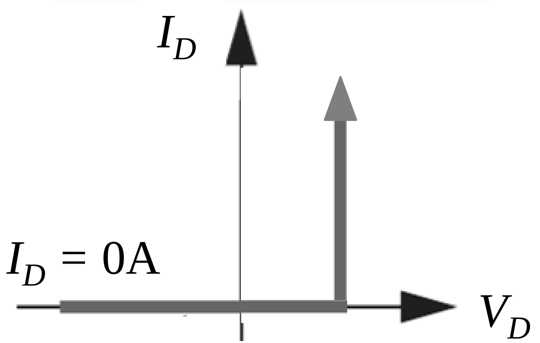
Assume On ($V_D = V_{KNEE}$)

KVL is always true:

$5V = I_{Red}(1k\Omega) + 2V$

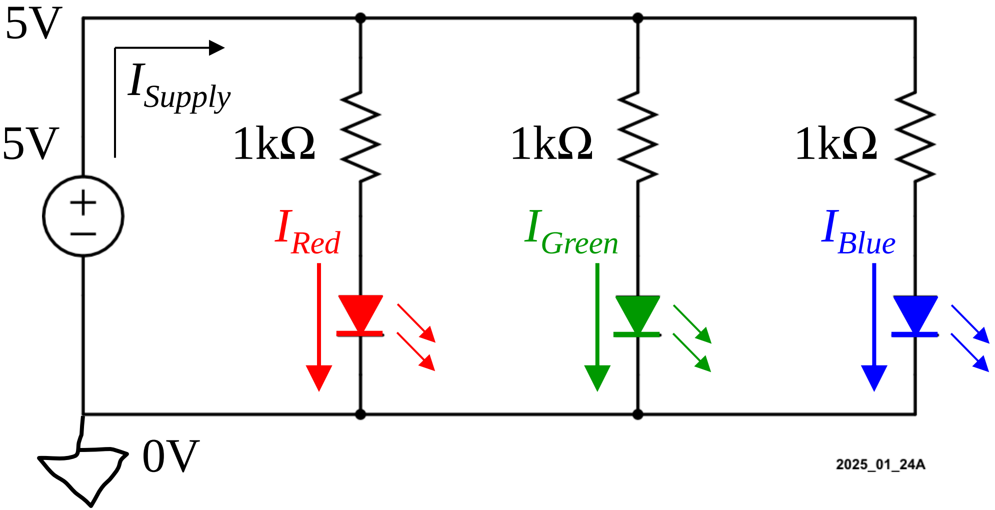
$5V = I_{Green}(1k\Omega) + 2.5V$

$5V = I_{Blue}(1k\Omega) + 3V$



Red (V_{KNEE} = 2V)
Green (V_{KNEE} = 2.5V) &
Blue (V_{KNEE} = 3V)
LEDs: Find I_{Supply}

Assume On ($V_D=V_{KNEE}$)



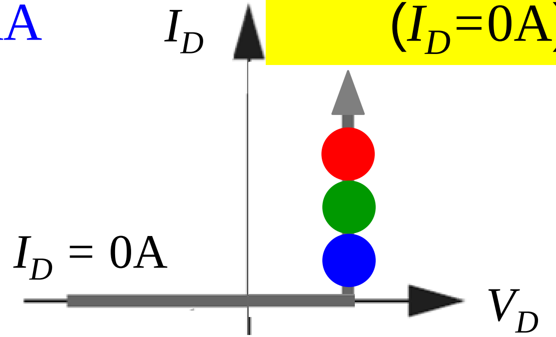
KVL is always true:

$5V = I_{Red}(1k\Omega) + 2V$ $\quad I_{Red} = 3.0mA$

$5V = I_{Green}(1k\Omega) + 2.5V$ $\quad I_{Green} = 2.5mA$

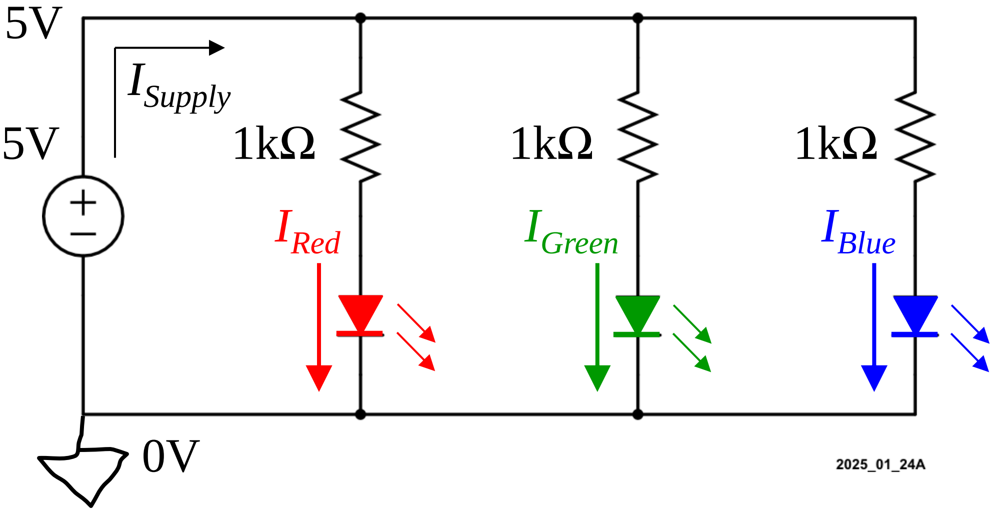
$5V = I_{Blue}(1k\Omega) + 3V$ $\quad I_{Blue} = 2.0mA$

Assumption Confirmed (I_D=0A)



Red (V_{KNEE} = 2V)
Green (V_{KNEE} = 2.5V) &
Blue (V_{KNEE} = 3V)
LEDs: Find I_{Supply}

Assume On ($V_D = V_{KNEE}$)



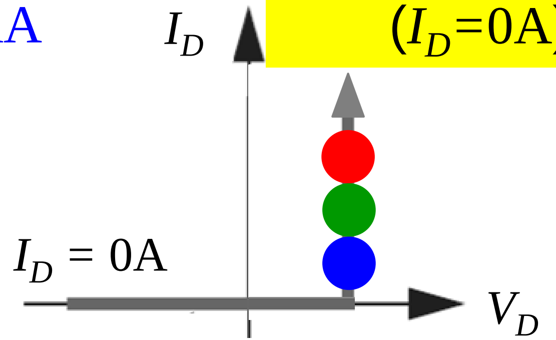
KVL is always true:

$5V = I_{Red}(1k\Omega) + 2V$ $\quad I_{Red} = 3.0mA$

$5V = I_{Green}(1k\Omega) + 2.5V$ $\quad I_{Green} = 2.5mA$

$5V = I_{Blue}(1k\Omega) + 3V$ $\quad I_{Blue} = 2.0mA$

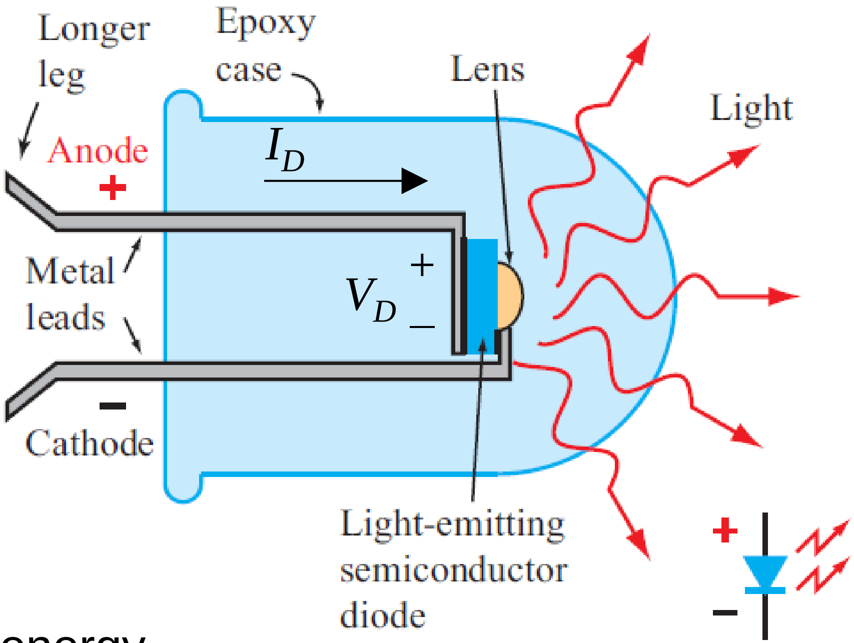
Assumption Confirmed (I_D=0A)



KCL is always true:

$I_{Supply} = 3.0mA + 2.5mA + 2.0mA$
$= 7.5mA$

Light Emitting Diode (LED)



- Converts electrical energy to photon energy

$$E_{Photon} \approx \left(e^{-}\right)\left(V_{KNEE}\right)$$

$$V_{KNEE,RED\,LED} \approx 2V$$

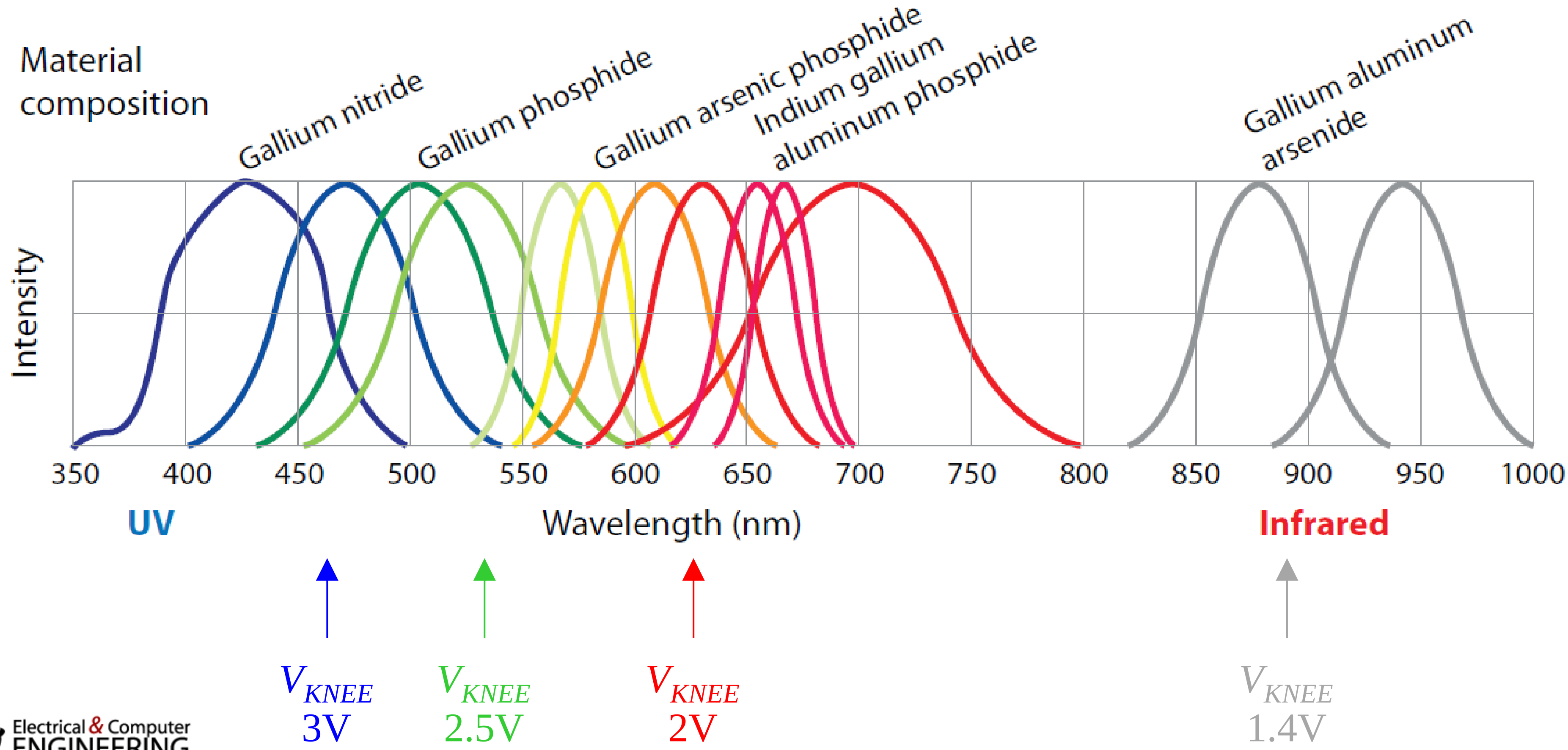
$$E_{Photon} \approx \left(1.60x10^{-19}C\right)\left(2V\right) = 3.20x10^{-19}\,J$$

- Can calculate the photon wavelength from its energy

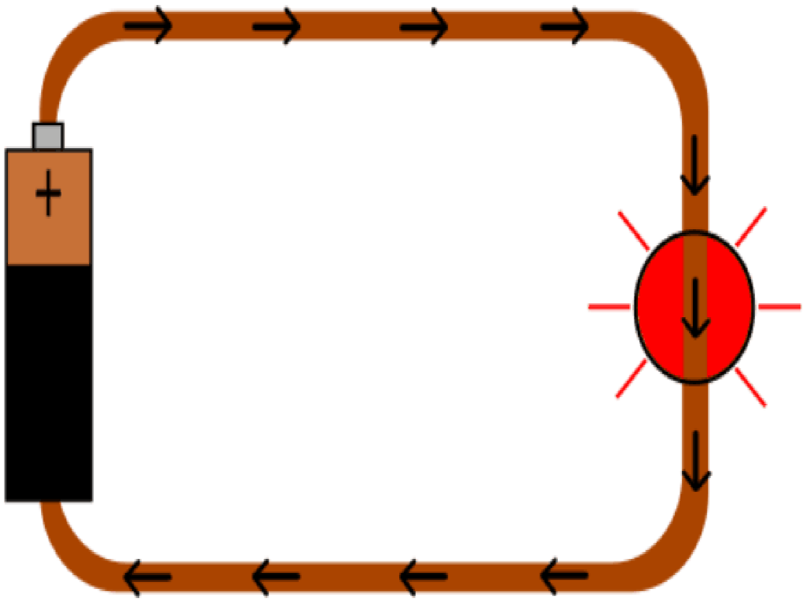
$$E_{Photon} = h\,f \qquad f = \frac{c}{\lambda} \qquad \lambda\,f = c$$

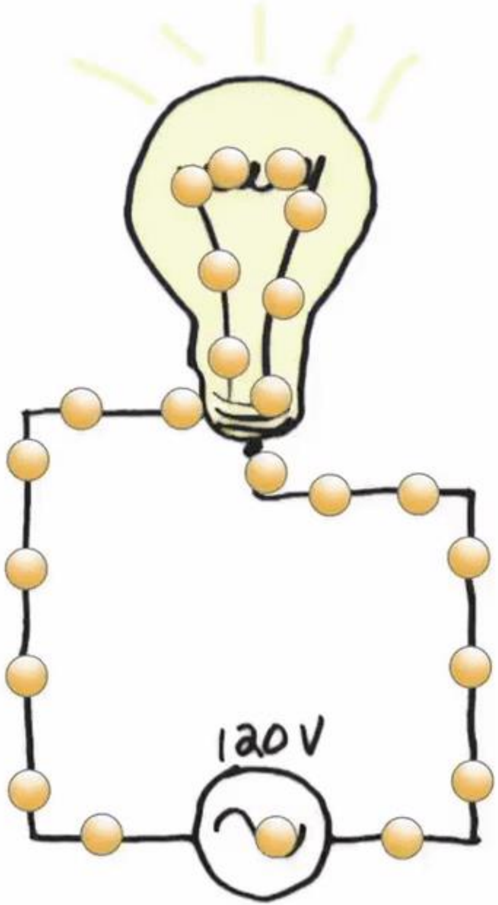
$$E_{Photon} = \frac{hc}{\lambda} \qquad 3.20x10^{-19}\,J = \frac{\left(6.63x10^{-34}\,J \cdot s\right)\left(3.00x10^{-8}\,m/s\right)}{\lambda} \qquad \lambda = 622nm$$

Light Emitting Diode (LED)



DC vs. AC Power Systems

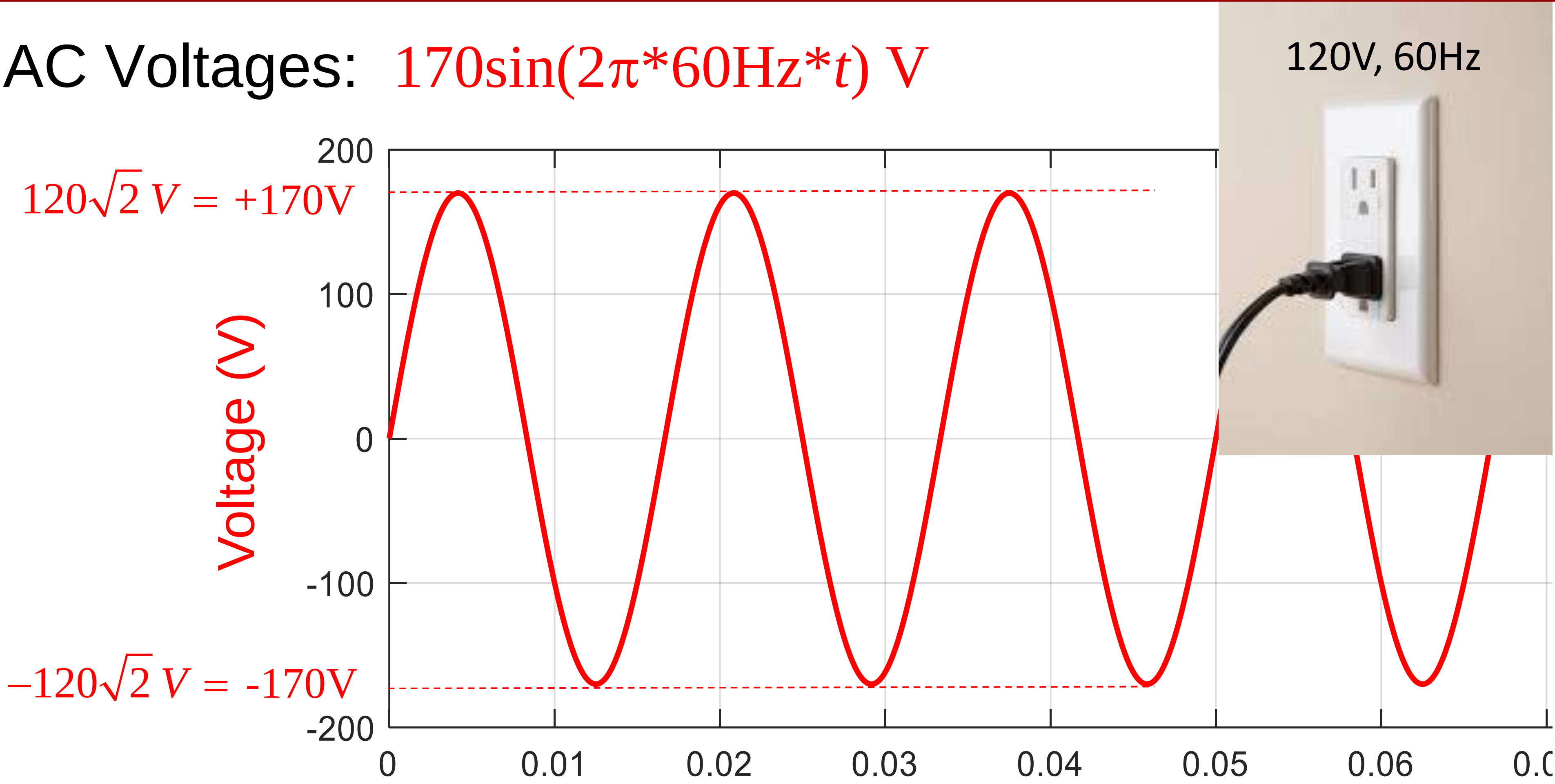




AC Voltages:

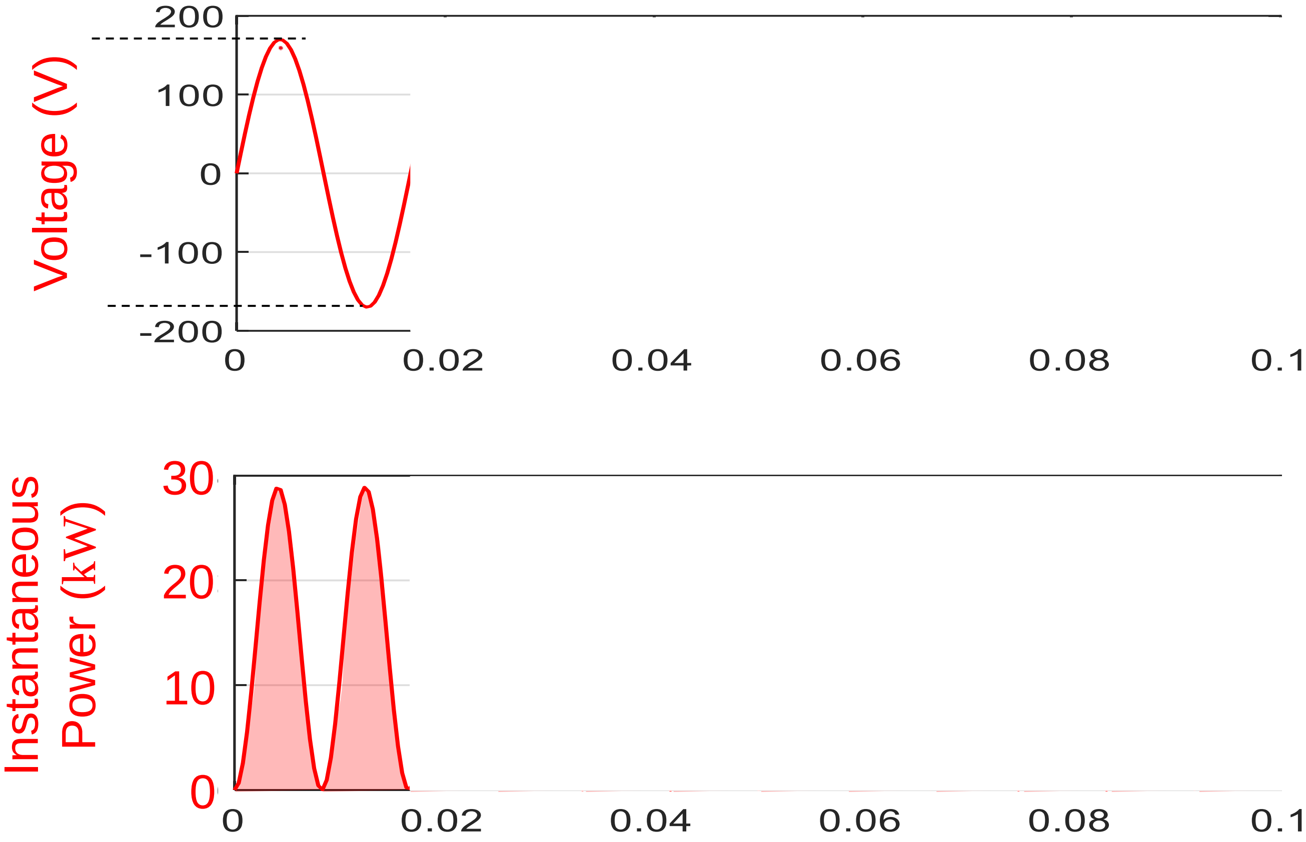
120V, 60Hz

AC Voltages: $170\sin(2\pi * 60\text{Hz} * t)$ V



Instantaneous AC Power into a 1Ω Resistance ($P = I^2R$)

$$P(t) = \frac{V^2(t)}{R}$$



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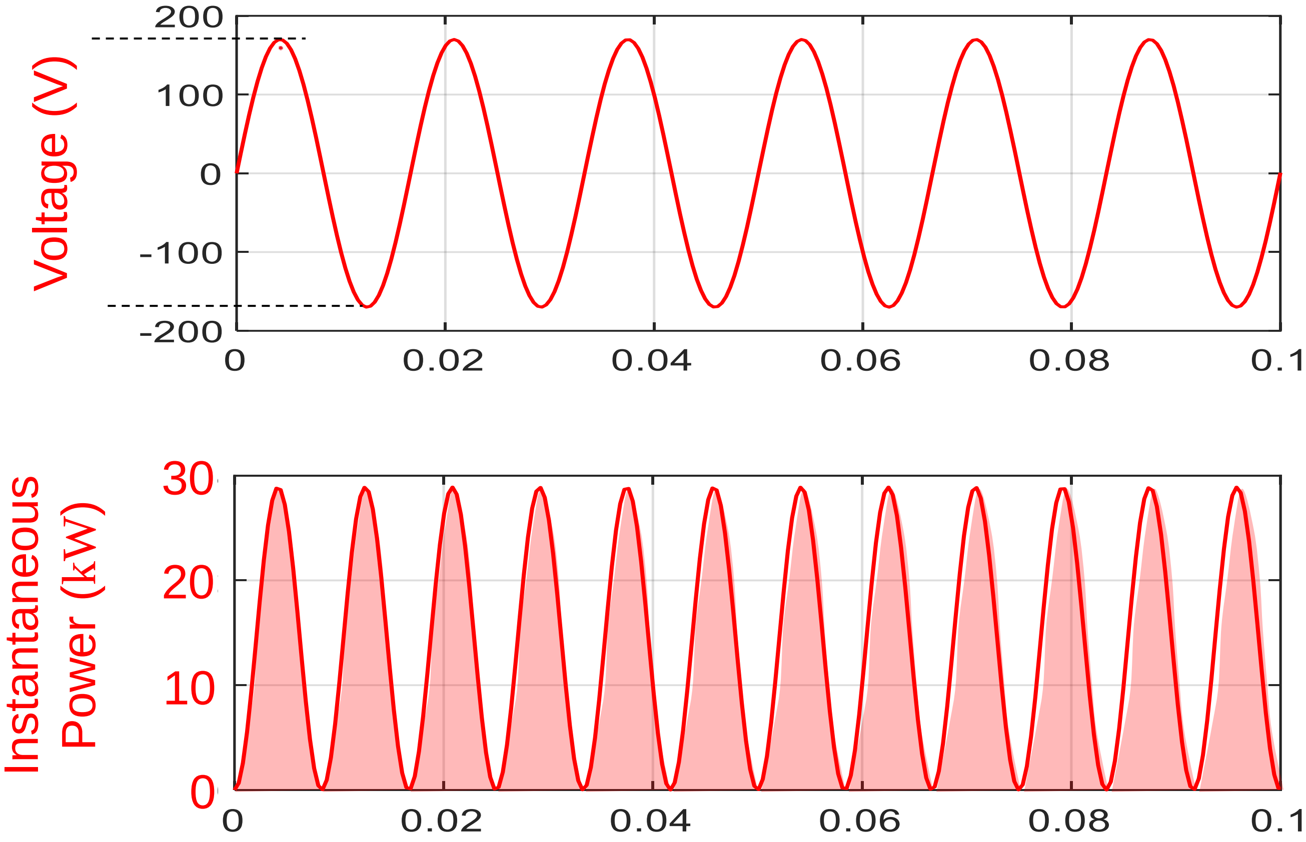

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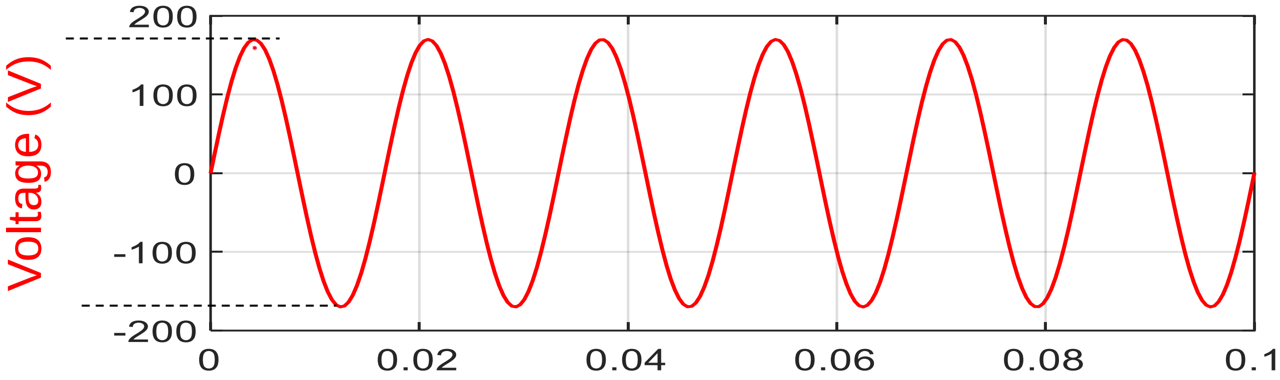

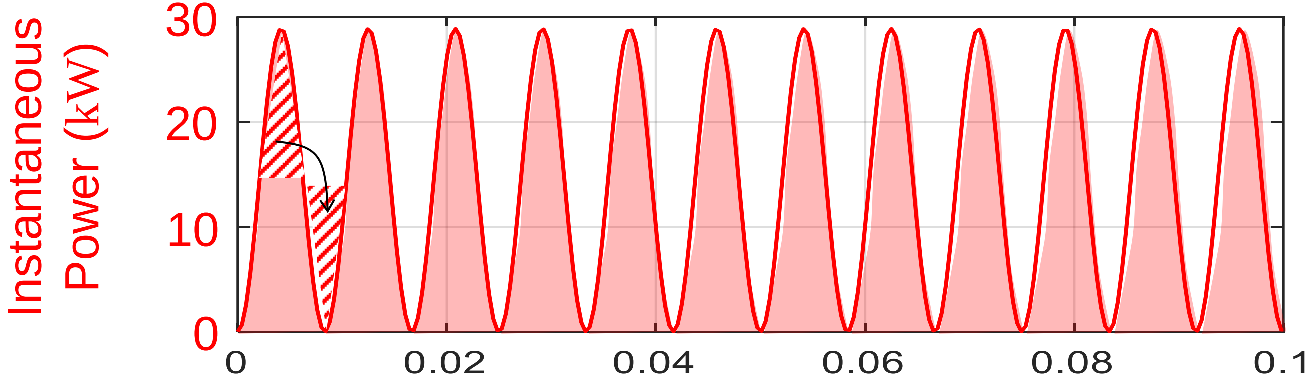

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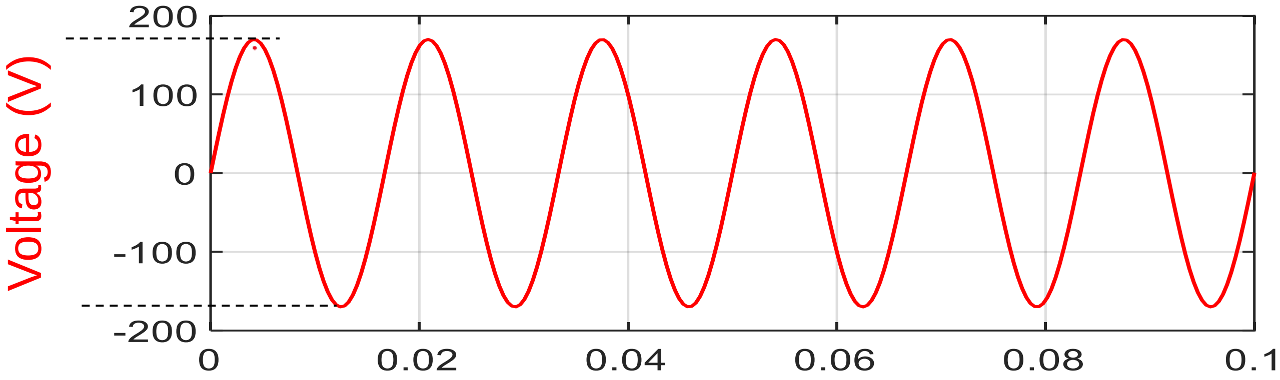
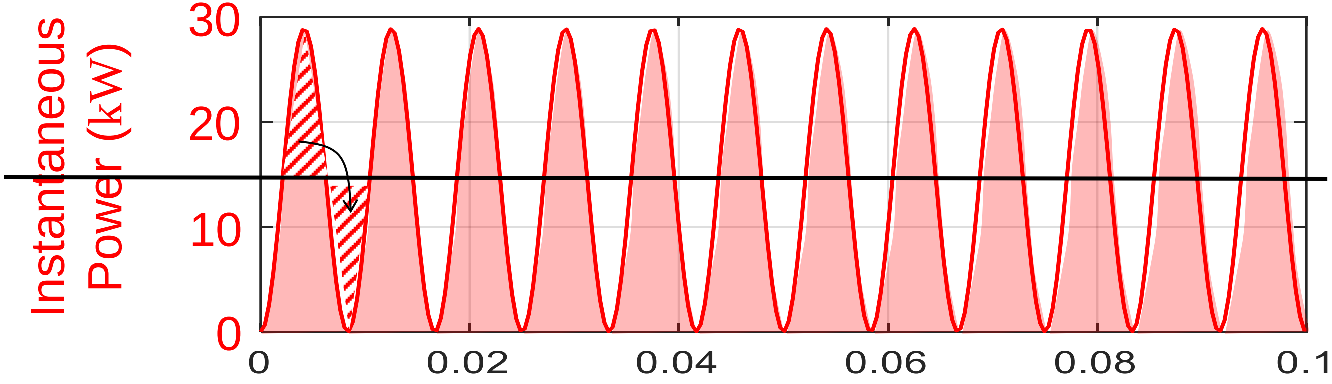
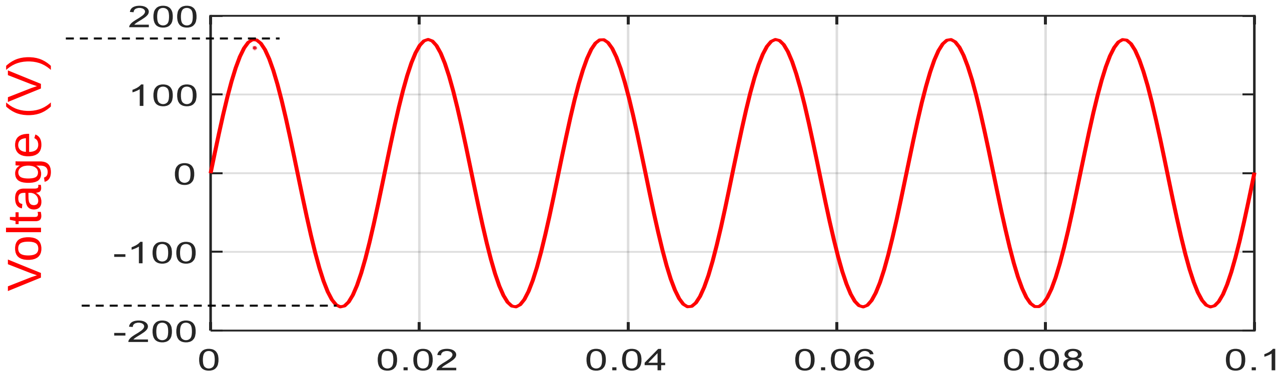


$$\frac{V_{Peak}{}^2(t)}{2R} = P_{AC,Avg}$$

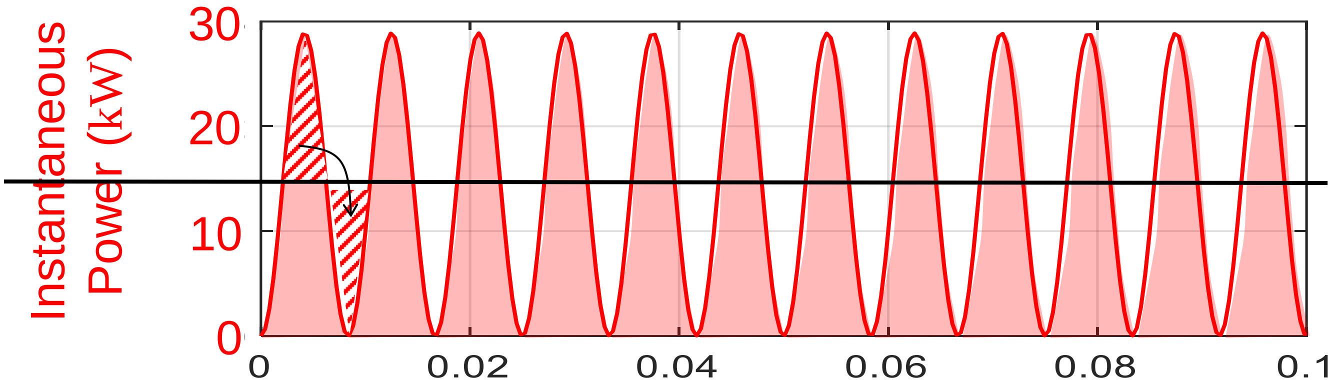


Instantaneous AC Power into a 1Ω Resistance ($P = I^2R$)

$$P(t) = \frac{V^2(t)}{R}$$



$$\frac{\left(\frac{V_{Peak}(t)}{\sqrt{2}}\right)^2}{R} = \frac{V_{Peak}{}^2(t)}{2R} = P_{AC,Avg}$$



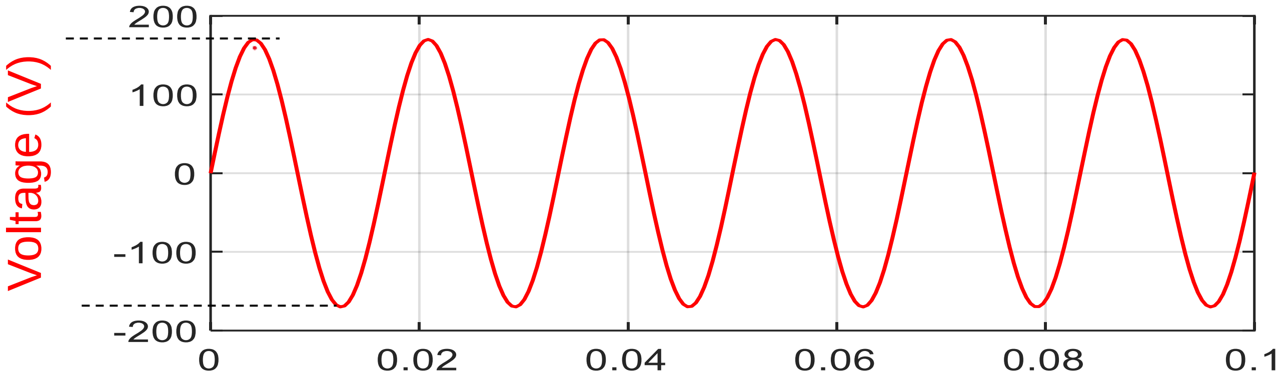
Instantaneous AC Power into a 1Ω Resistance ($P = I^2R$)

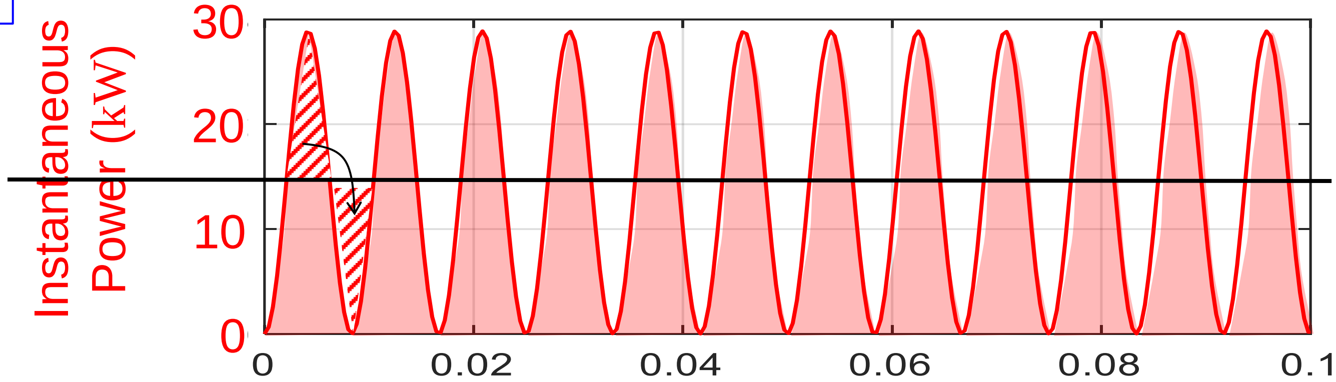
$$P(t) = \frac{V^2(t)}{R}$$

$$P_{DC,Avg} = \frac{(120V_{DC})^2}{1\Omega} = 14.4kW$$

$$P_{AC,Avg} = \frac{\left(170V/\sqrt{2}\right)^2}{1\Omega} = 14.4kW$$

$$\frac{\left(\frac{V_{Peak}(t)}{\sqrt{2}}\right)^2}{R} = \frac{V_{Peak}{}^2(t)}{2R} = P_{AC,Avg}$$





Instantaneous AC Power into a 1Ω Resistance ($P = I^2R$)

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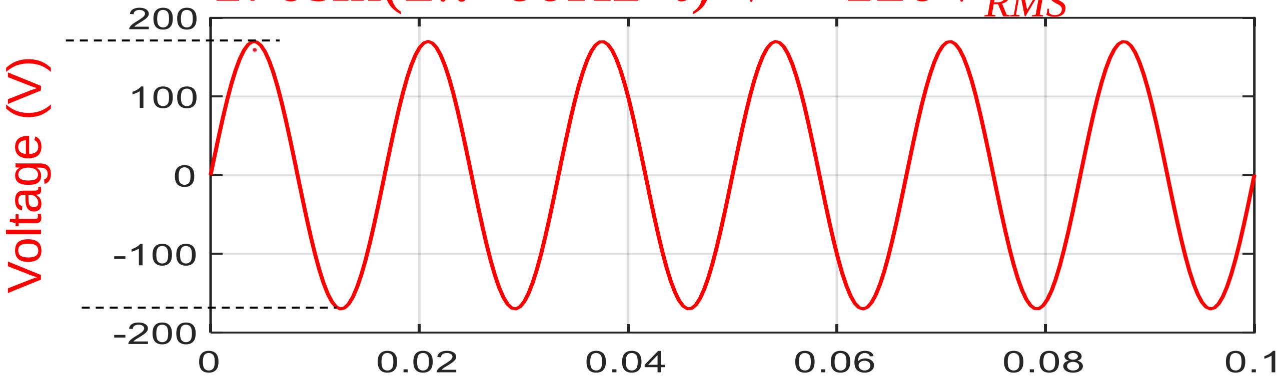
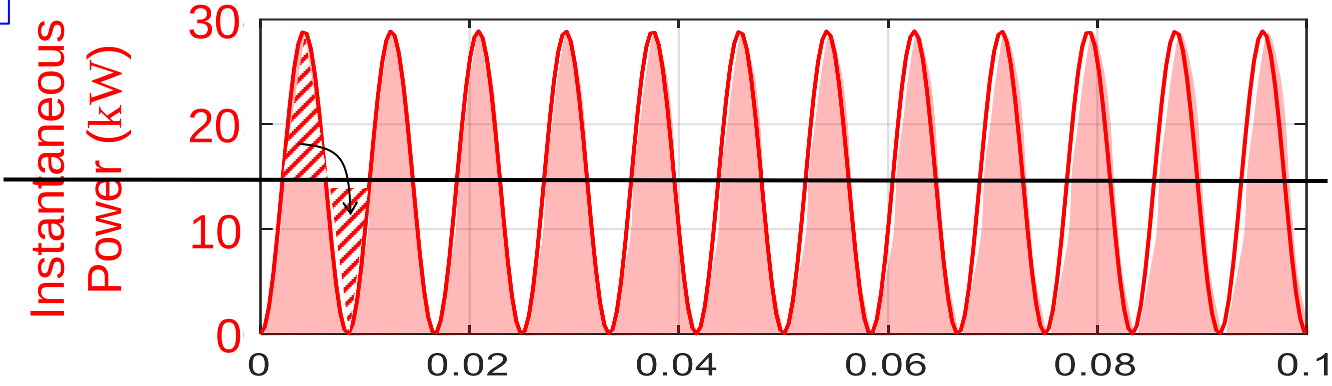
$$P_{AC,Avg} = \frac{\left(170V/\sqrt{2}\right)^2}{1\Omega} = 14.4kW$$

$$\frac{\left(\frac{V_{Peak}(t)}{\sqrt{2}}\right)^2}{R} = \frac{V_{Peak}{}^2(t)}{2R} = P_{AC,Avg}$$

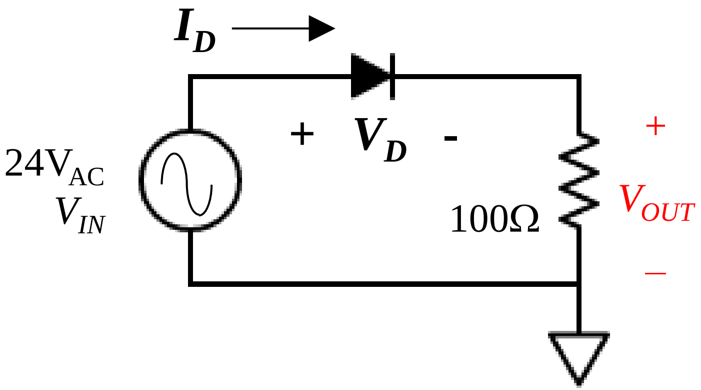
170sin(2π*60Hz*t) V = 120V$_{RMS}$

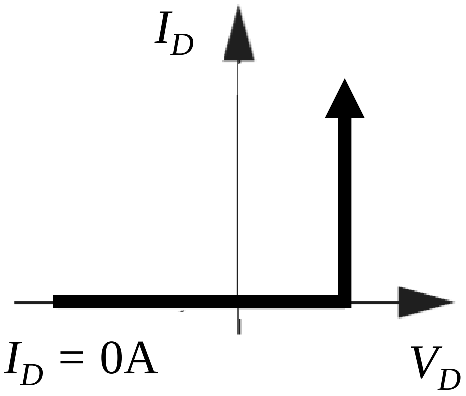


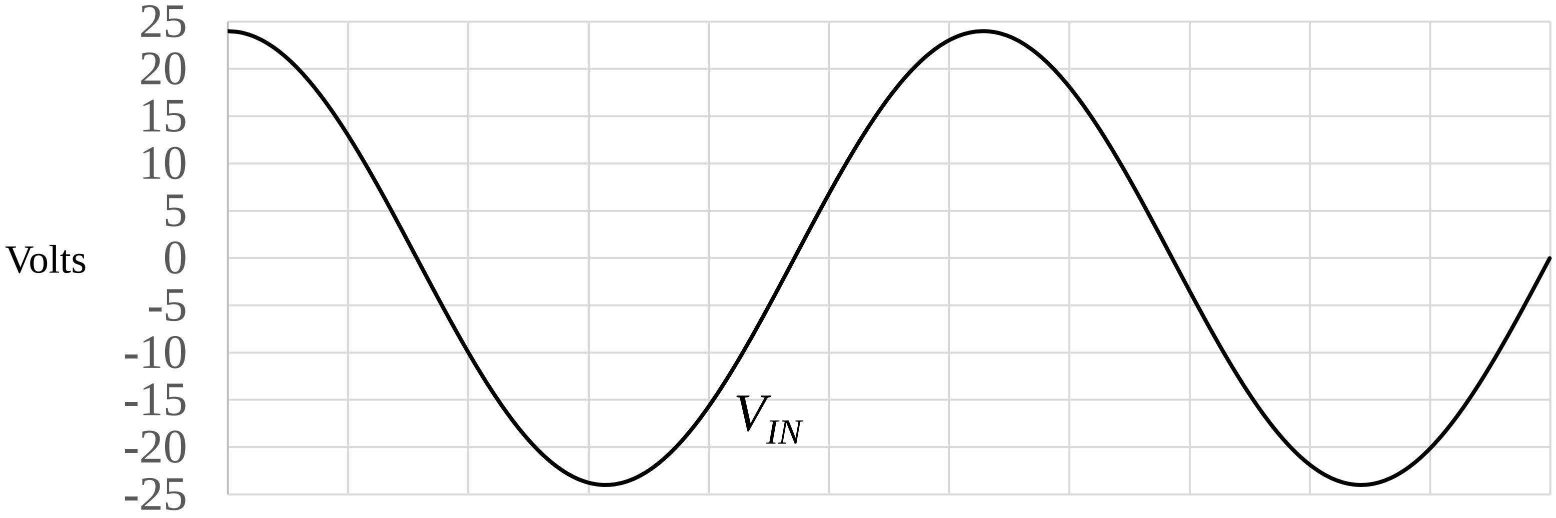


How Do We Convert AC Power to DC?

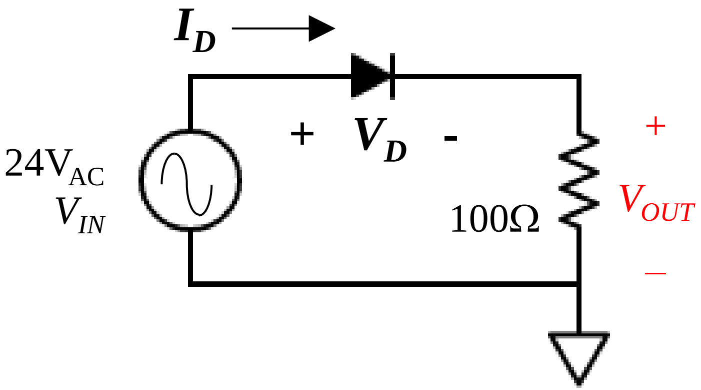
Diode Half-Wave Rectifier (Knee Model)

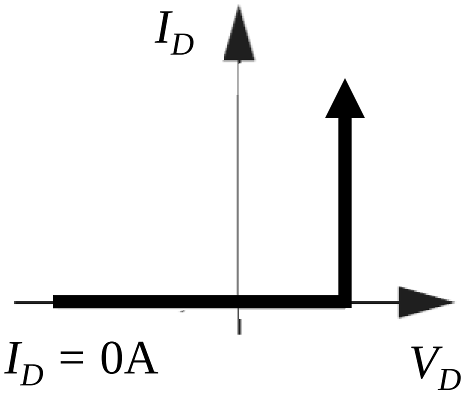


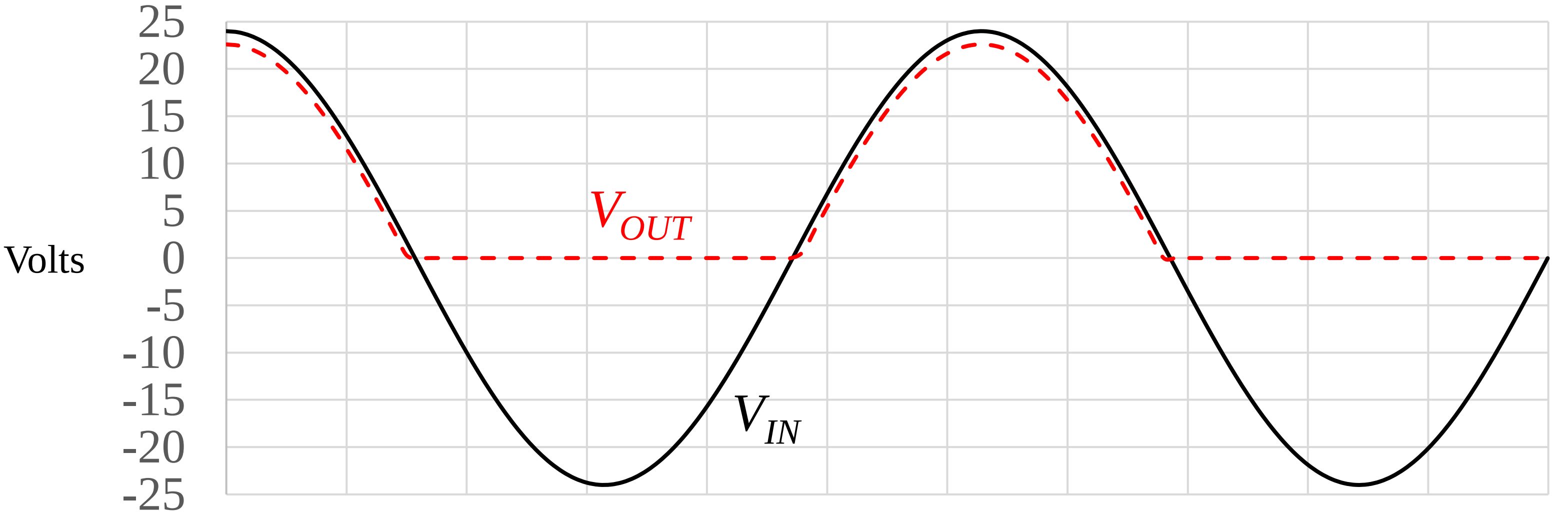




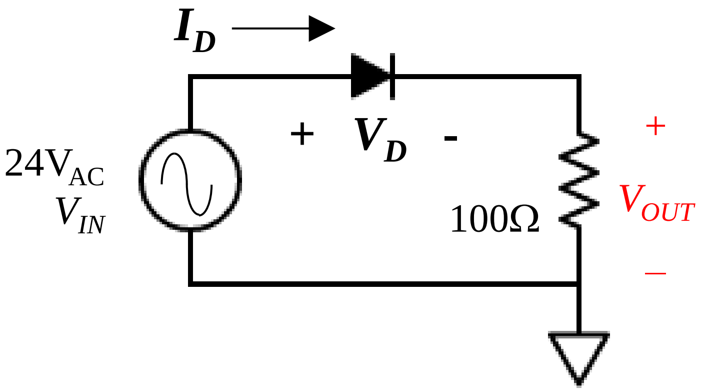
Diode Half-Wave Rectifier (Knee Model)

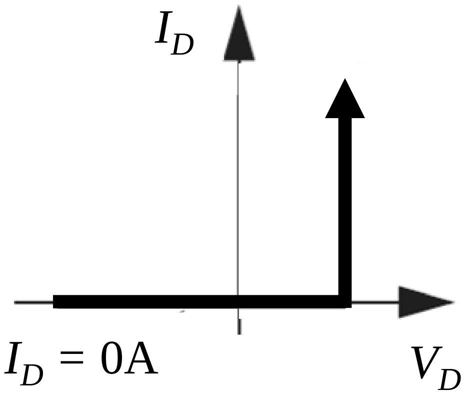


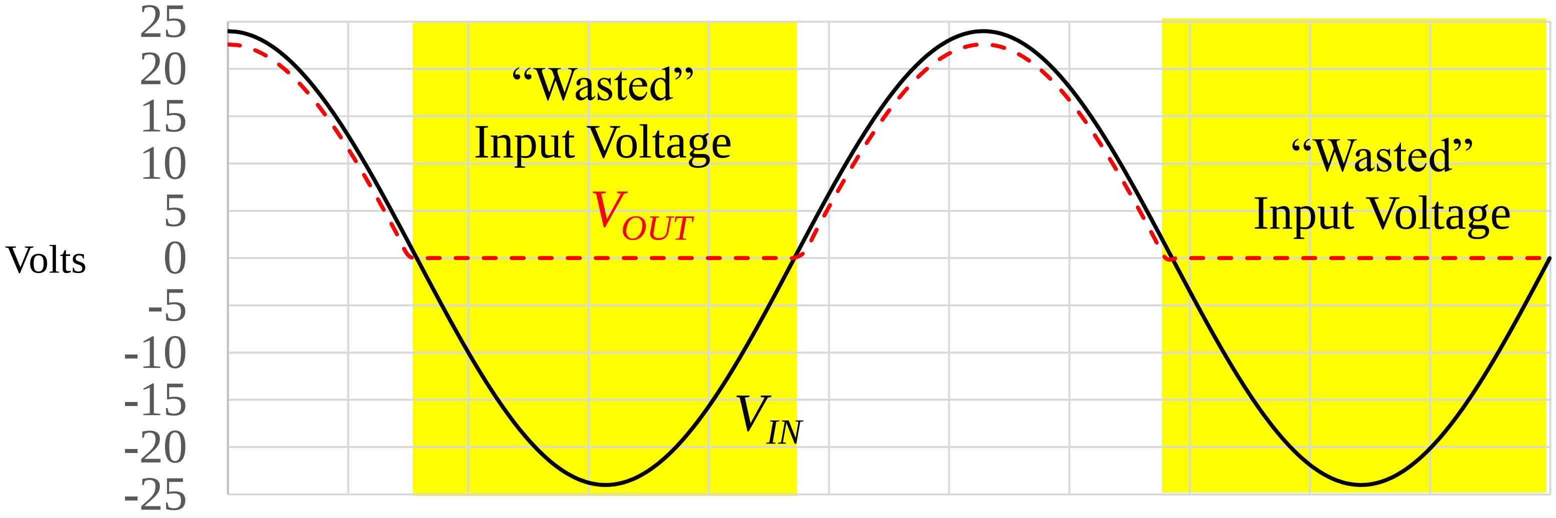




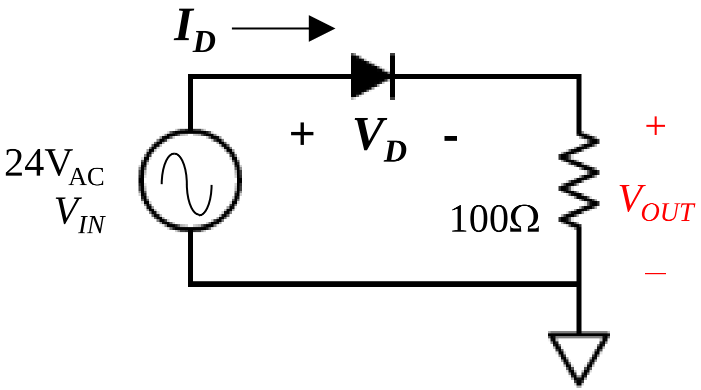
Diode Half-Wave Rectifier (Knee Model)

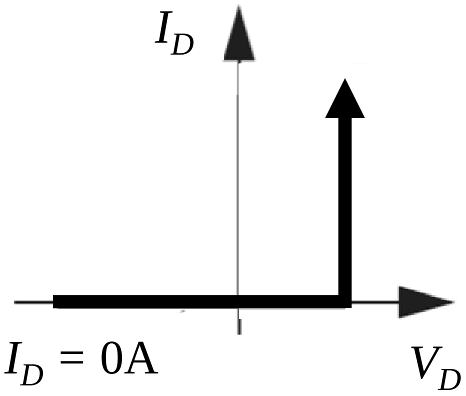


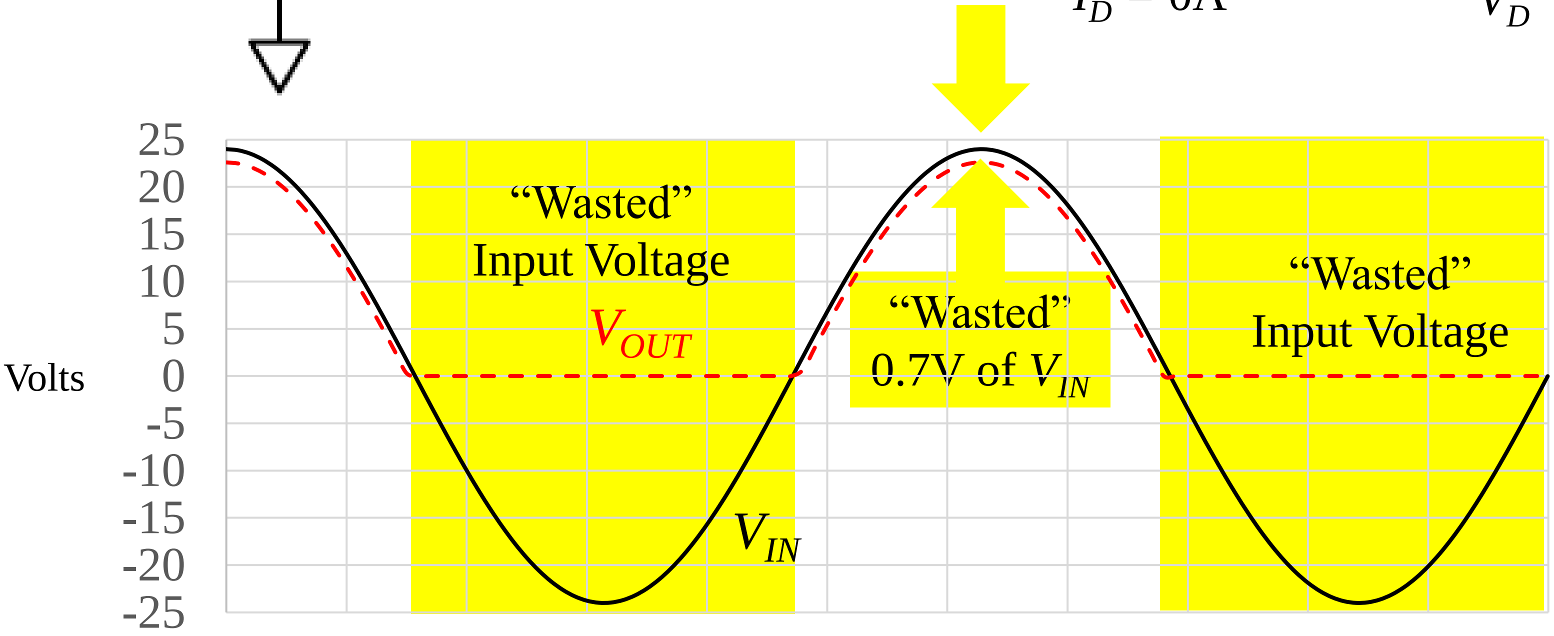




Diode Half-Wave Rectifier (Knee Model)







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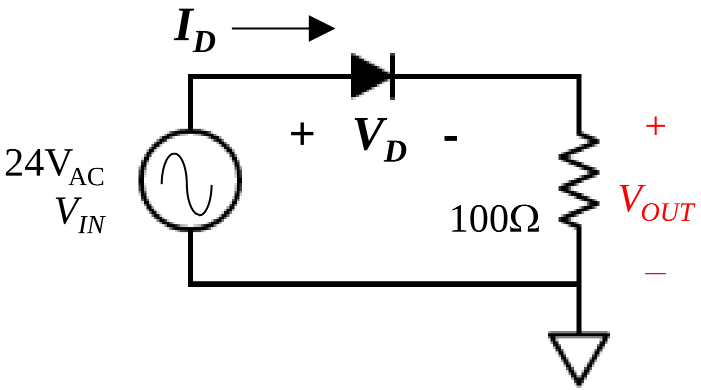
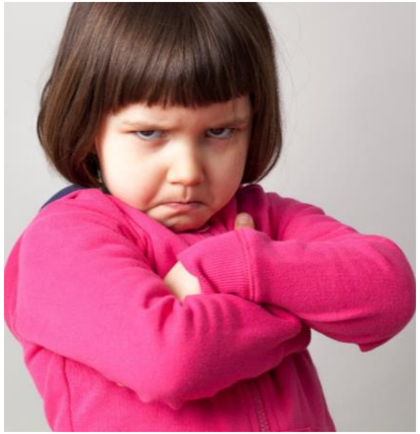
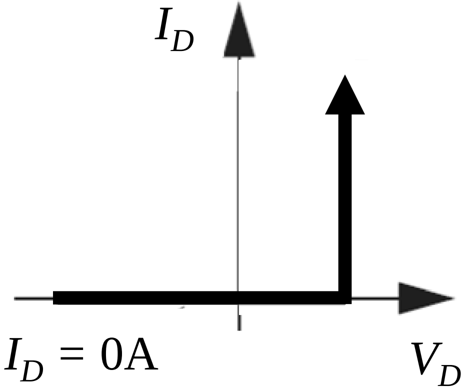
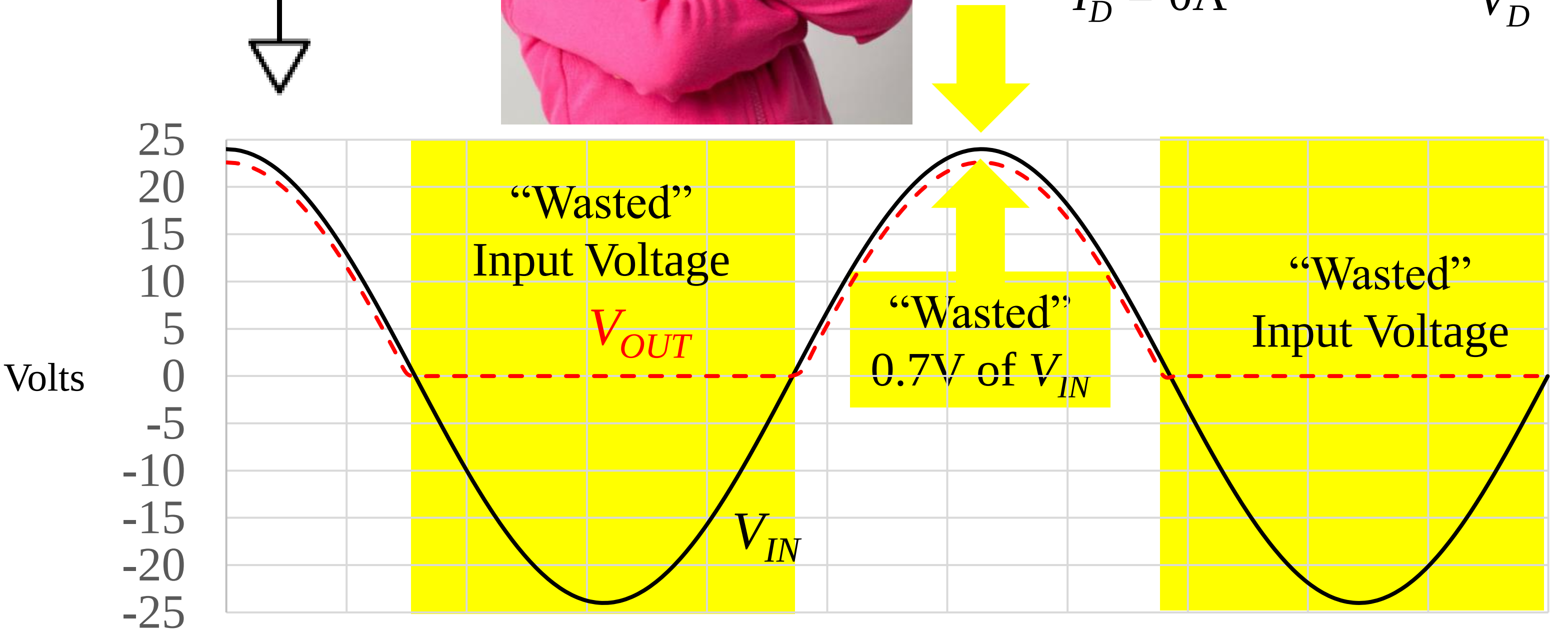
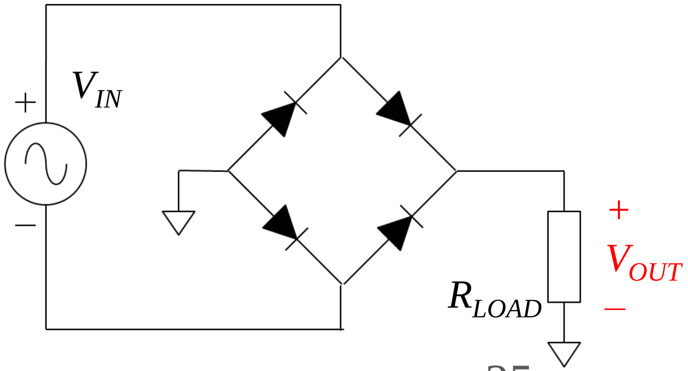


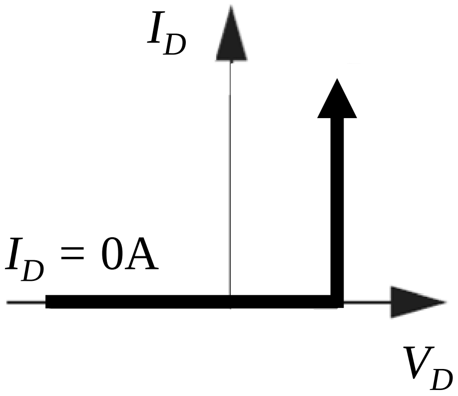


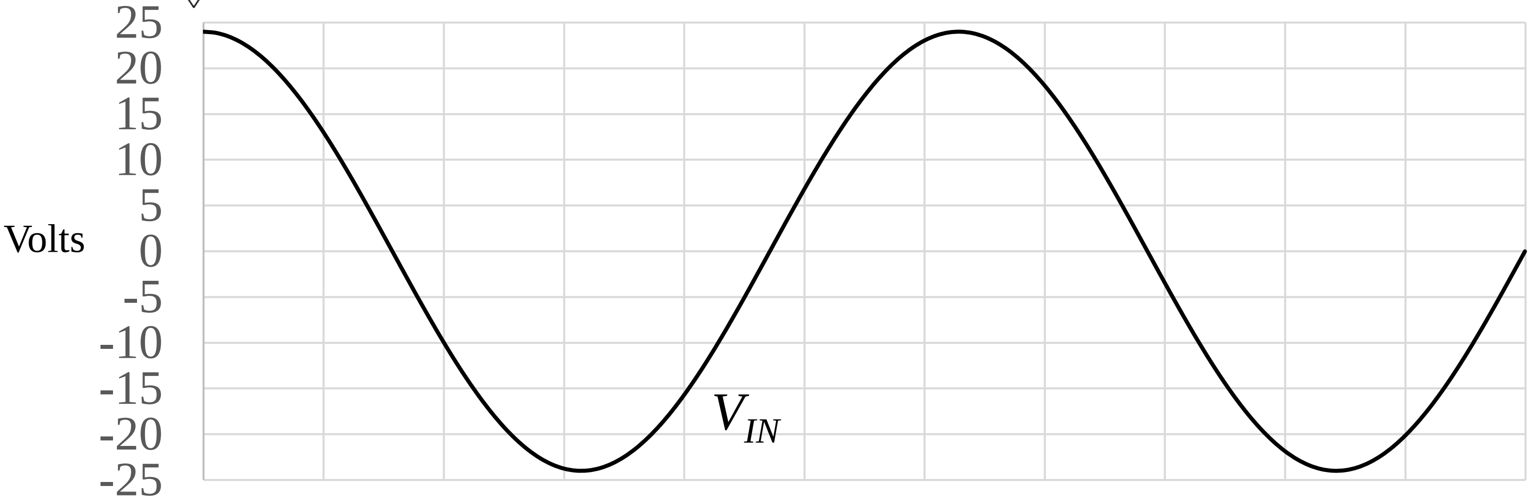




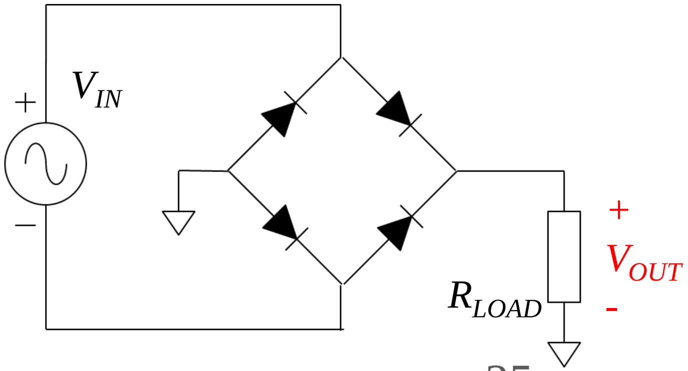
Diode Full-Wave Rectifier

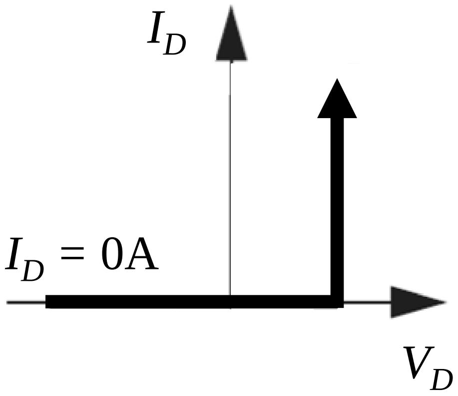


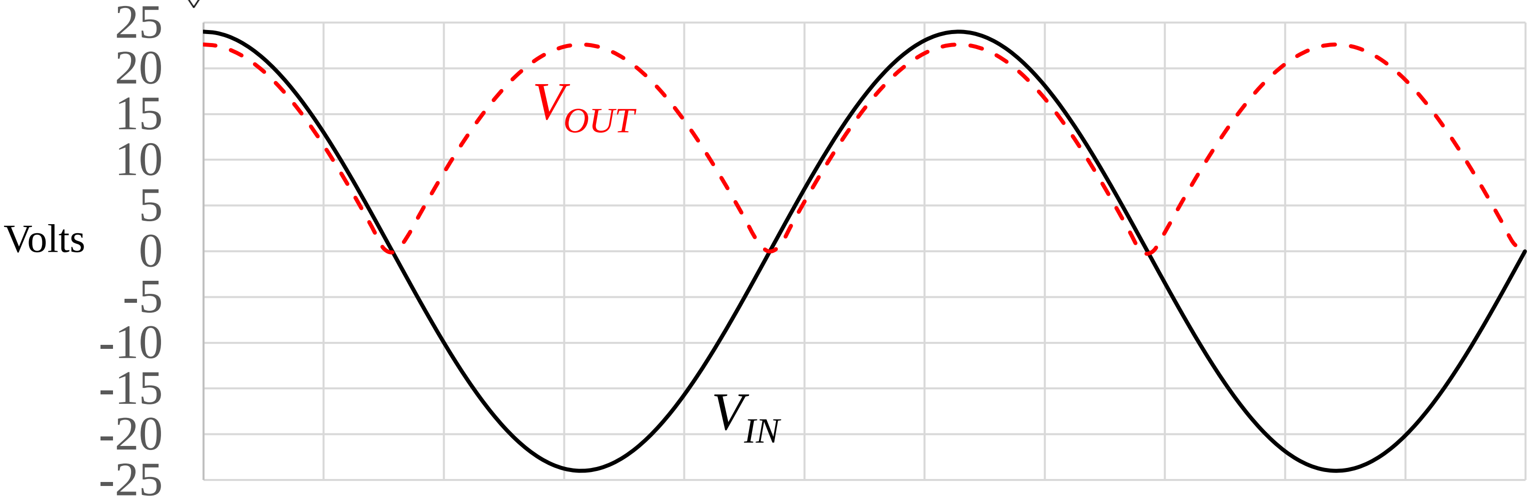




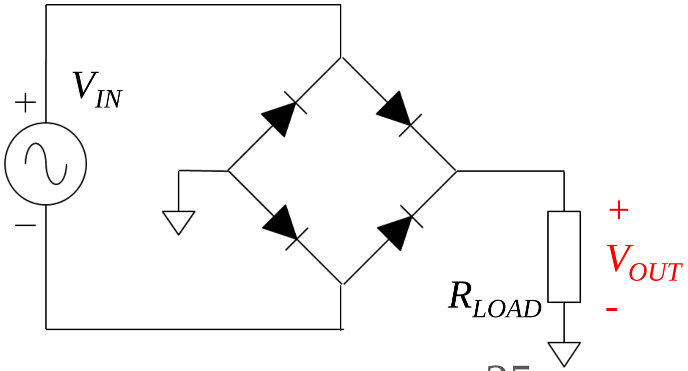
Diode Full-Wave Rectifier

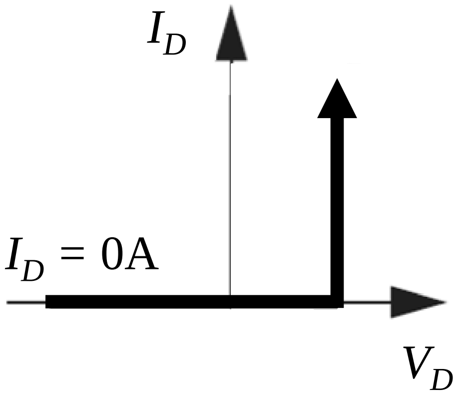


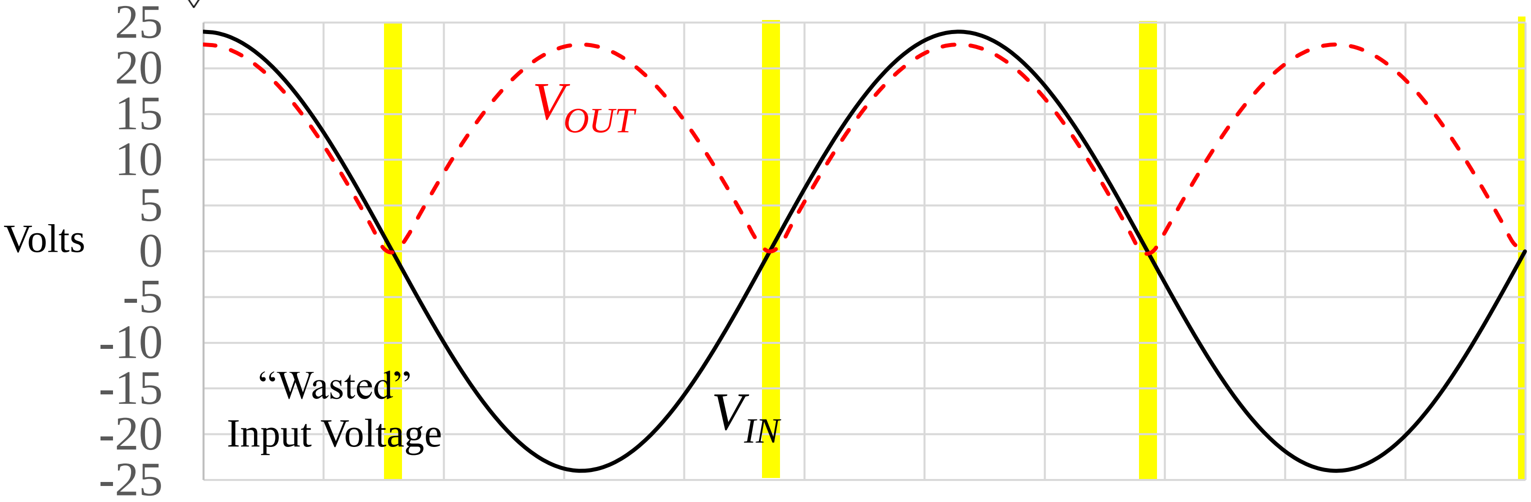




Diode Full-Wave Rectifier







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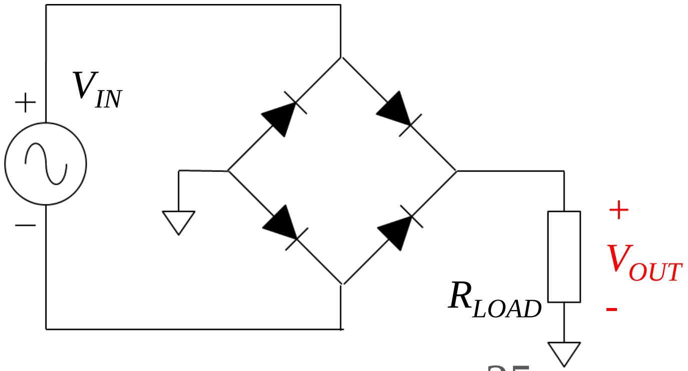

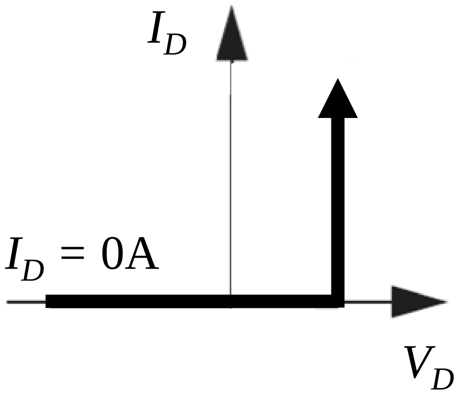

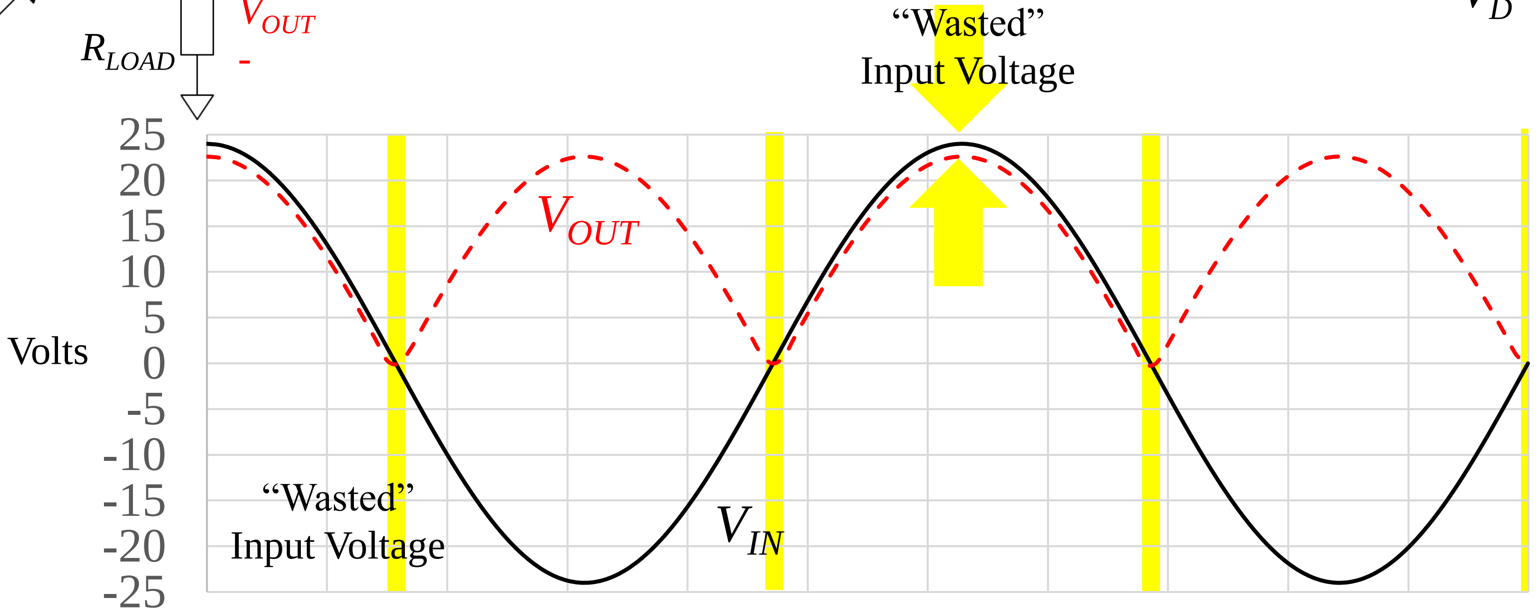

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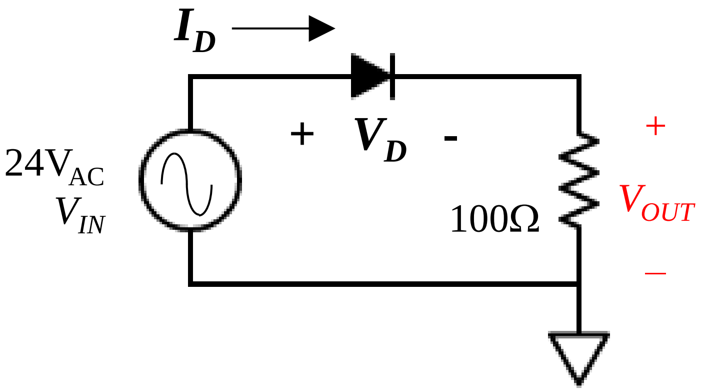
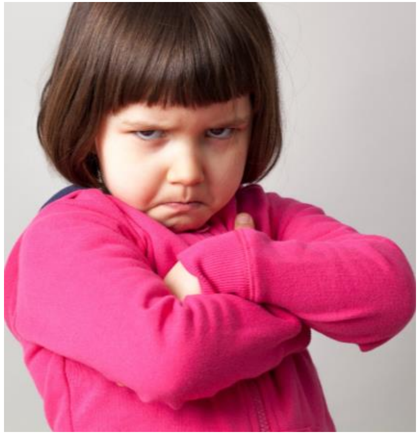
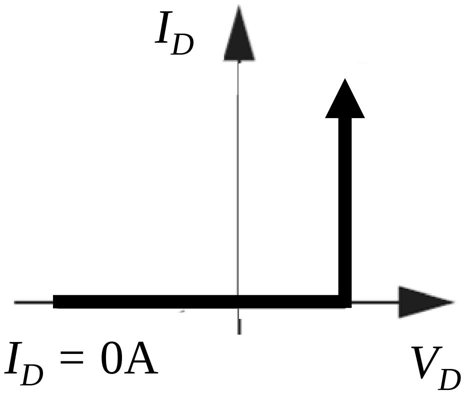
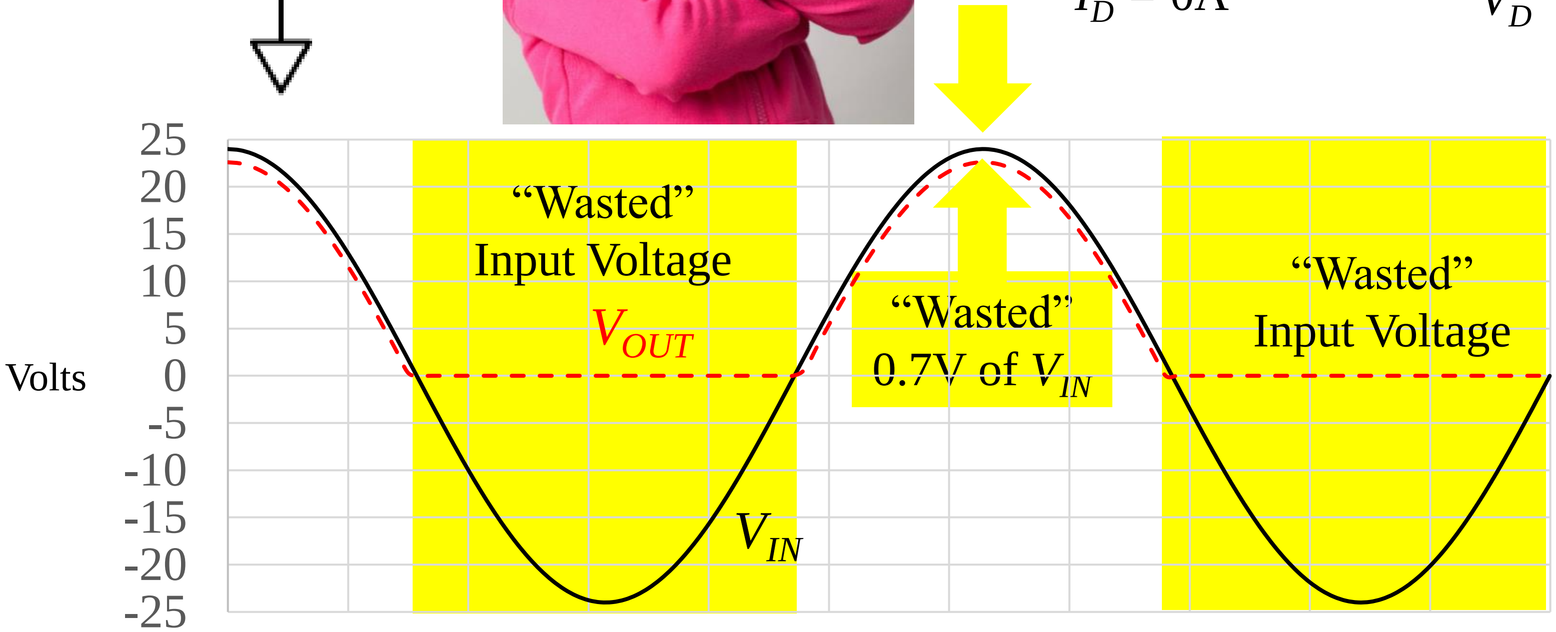
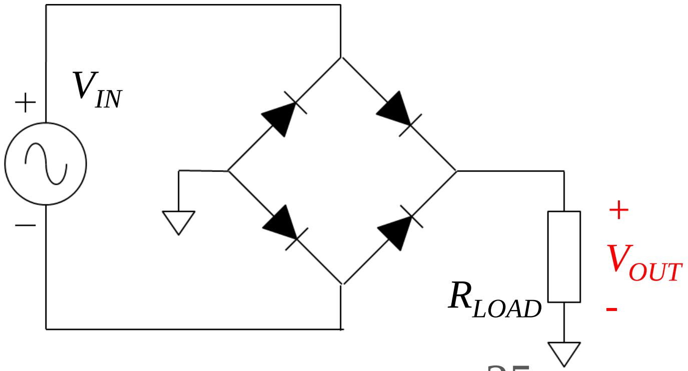


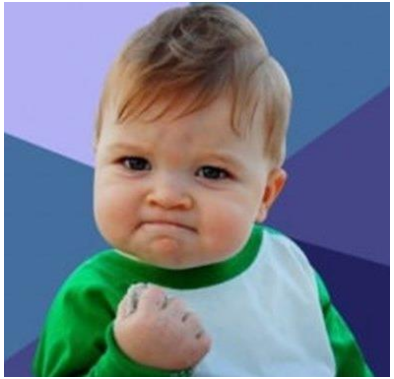


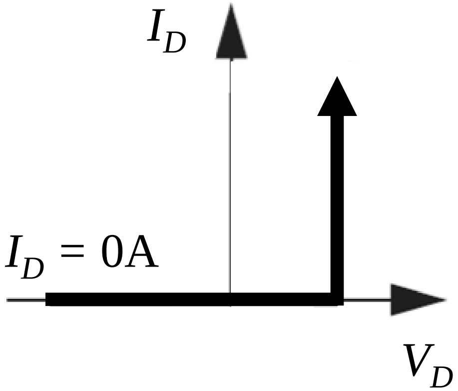


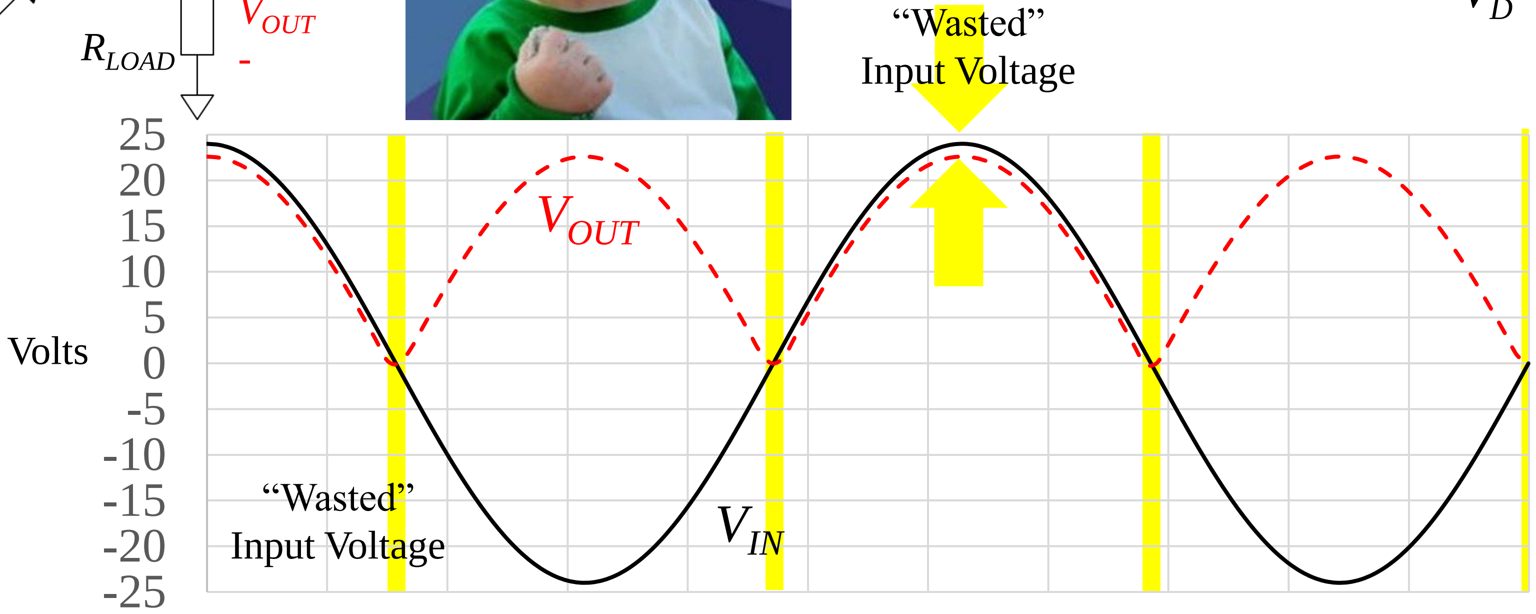


Diode Full-Wave Rectifier

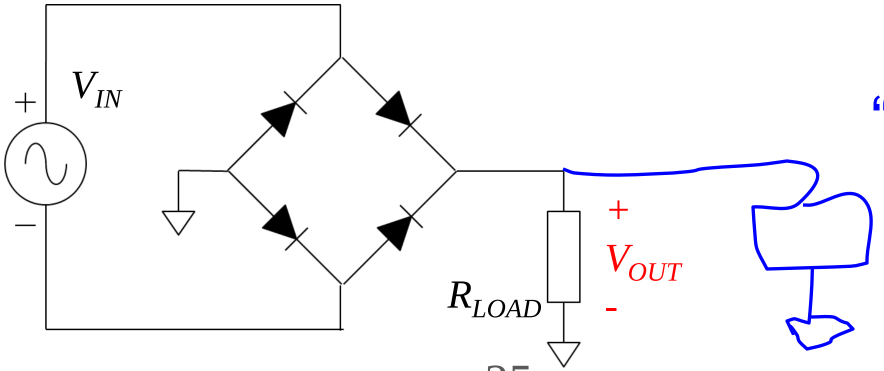




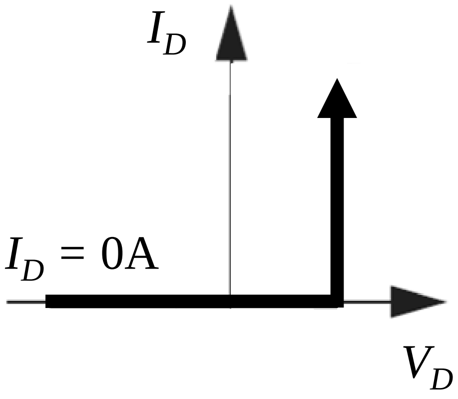


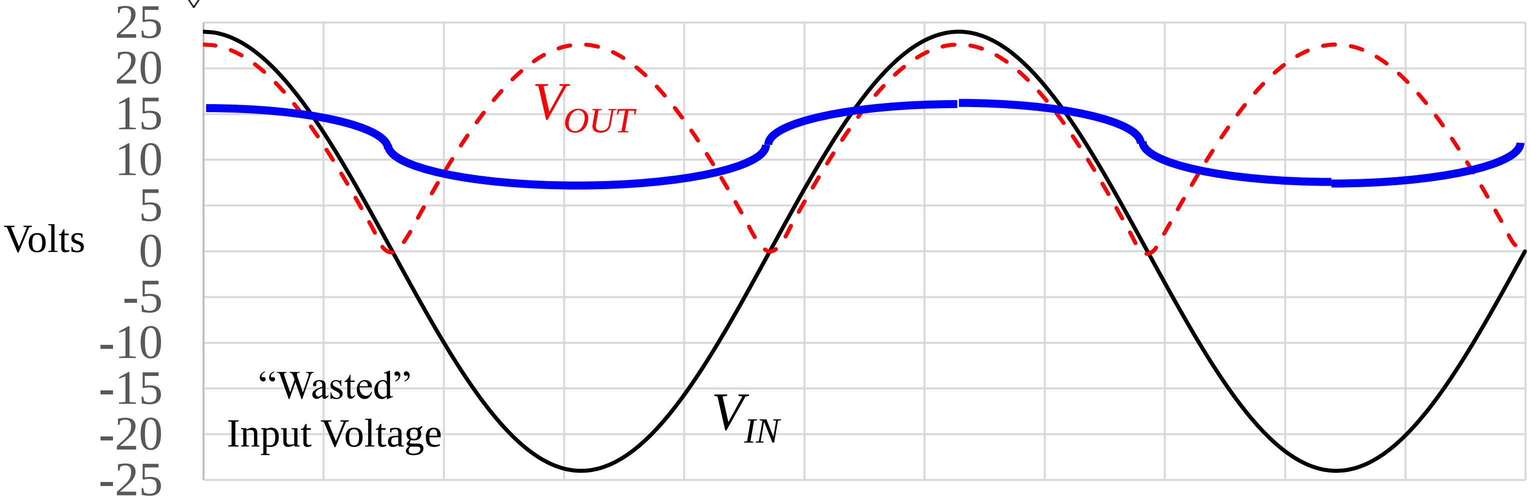


Diode Full-Wave Rectifier

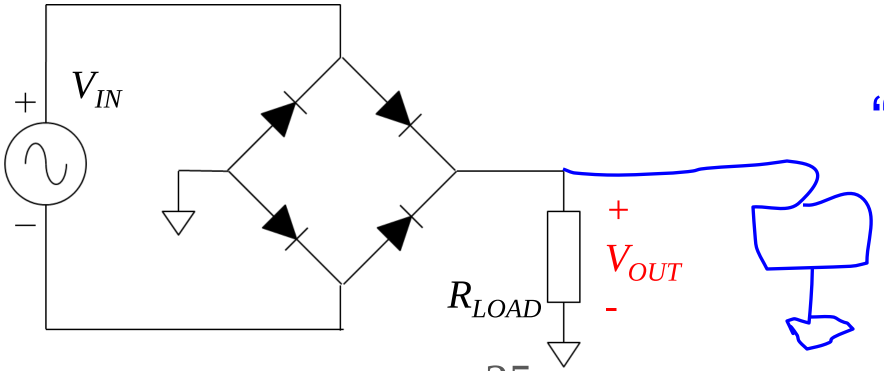


"Averager"
Charge
Storage





Diode Full-Wave Rectifier



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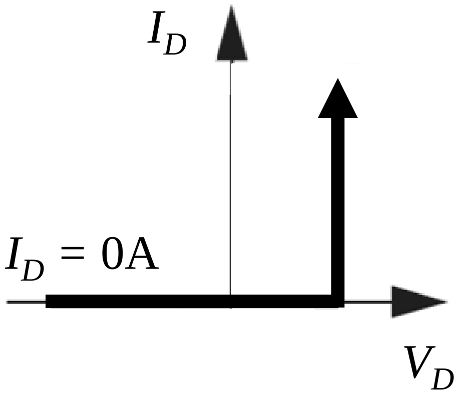
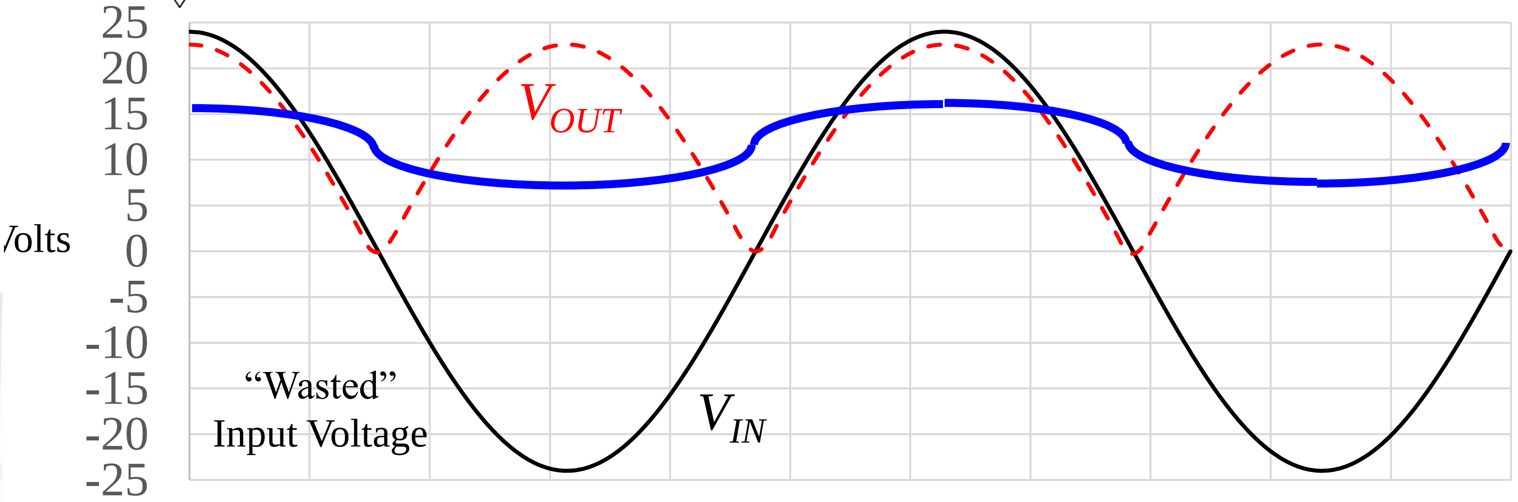
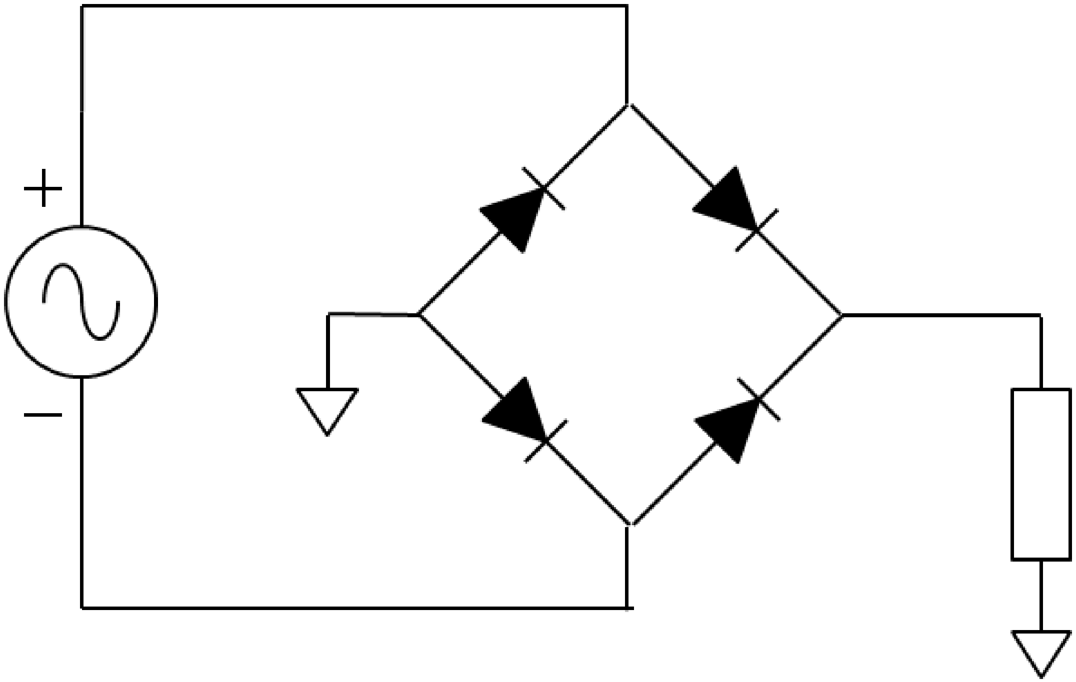
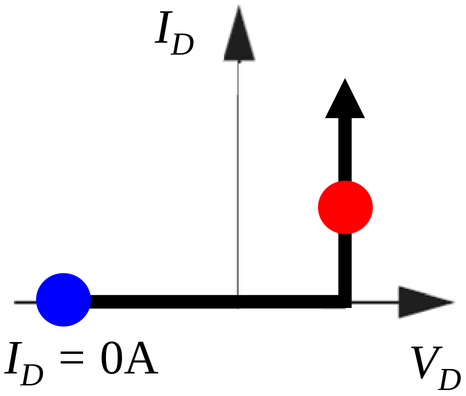




Diode Full-Wave Rectifier

- Two diodes conduct, two diodes act as open circuits





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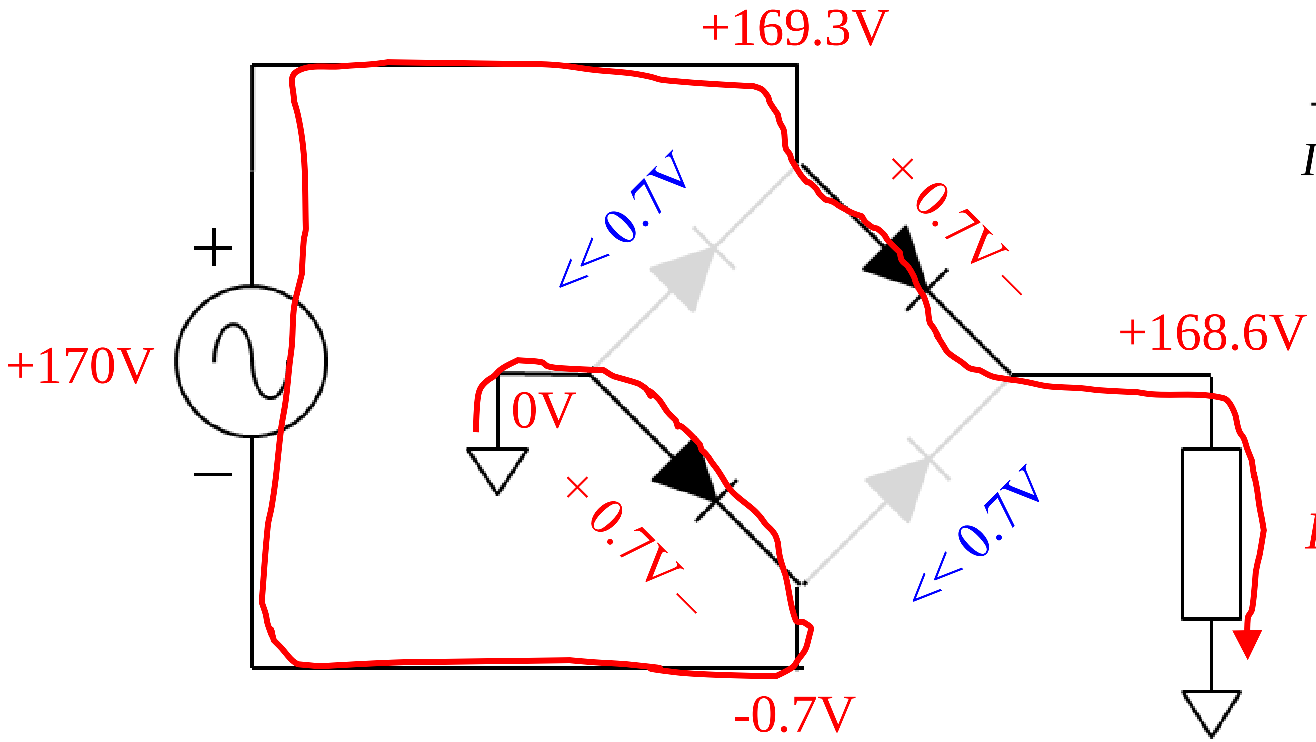

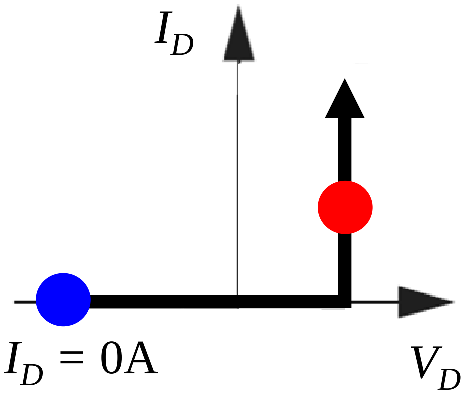

Diode Full-Wave Rectifier

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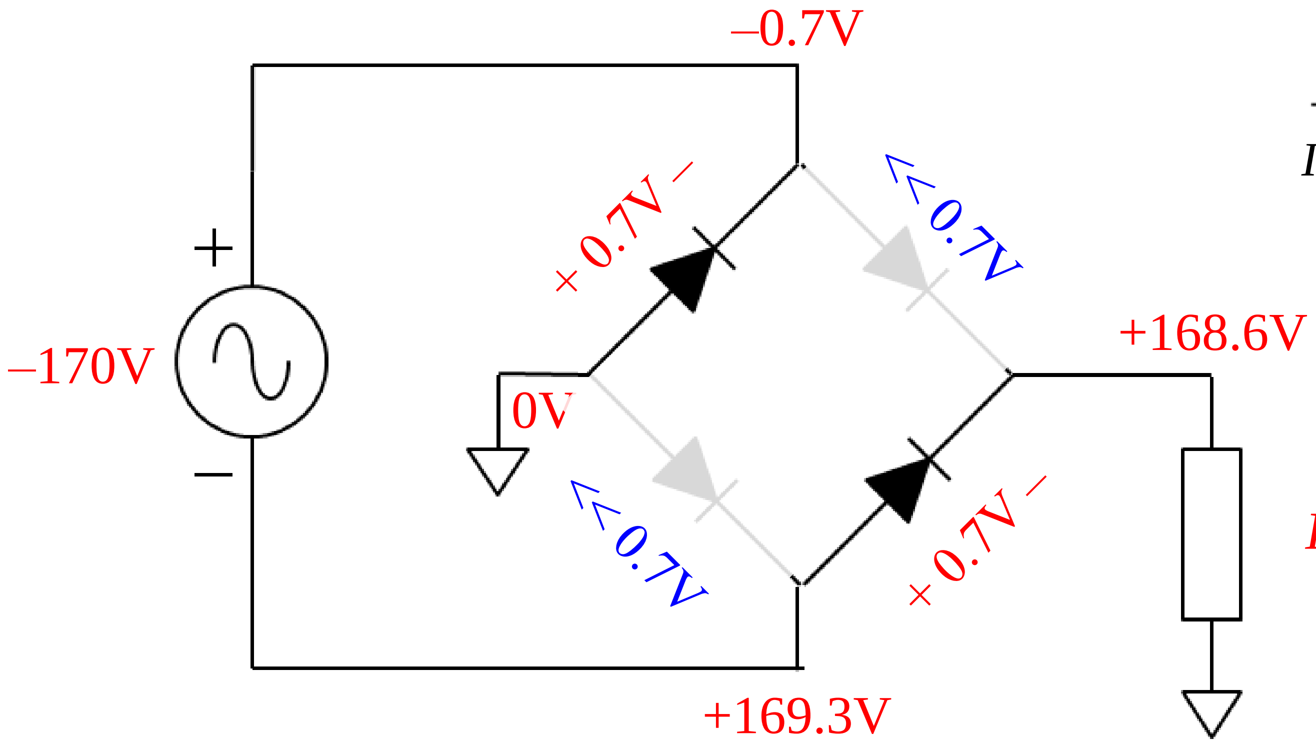

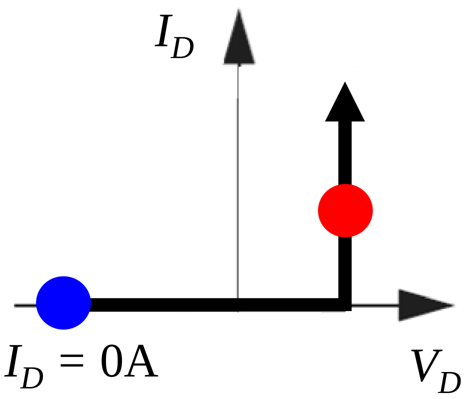

What Do You Need to Do Next?

1. Take the **Lecture 4 Quiz** on canvas!

2. Check out Piazza and Gradescope