ESc201 : Introduction to Electronics

Diodes

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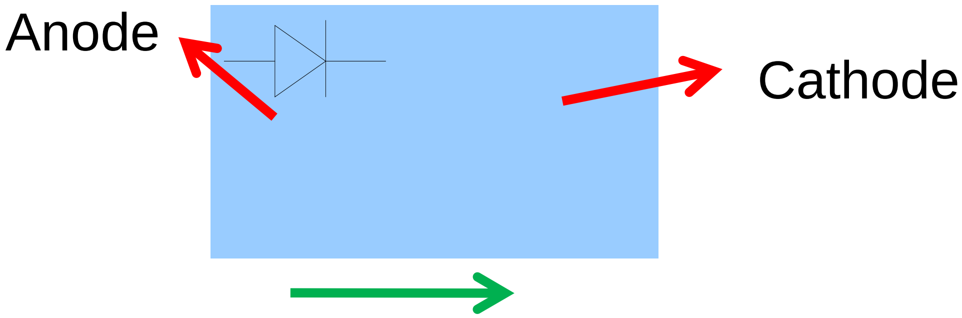
Diode



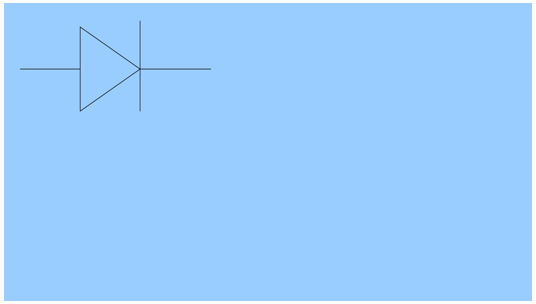
- Like resistors and capacitors, diodes are two terminal devices
  - The 2 terminals are called Anode and Cathode

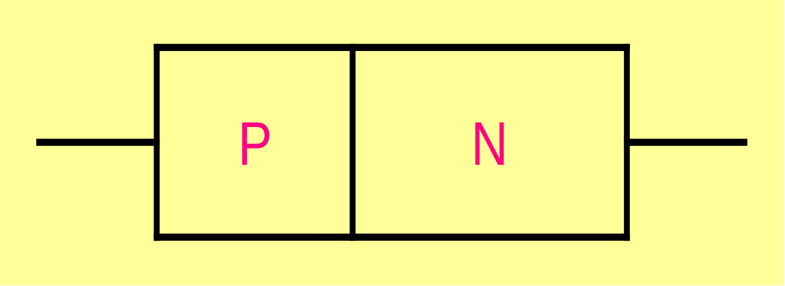
- It conducts current in one direction only (from anode to cathode)

Diodes are nonlinear, two terminal, passive electrical devices

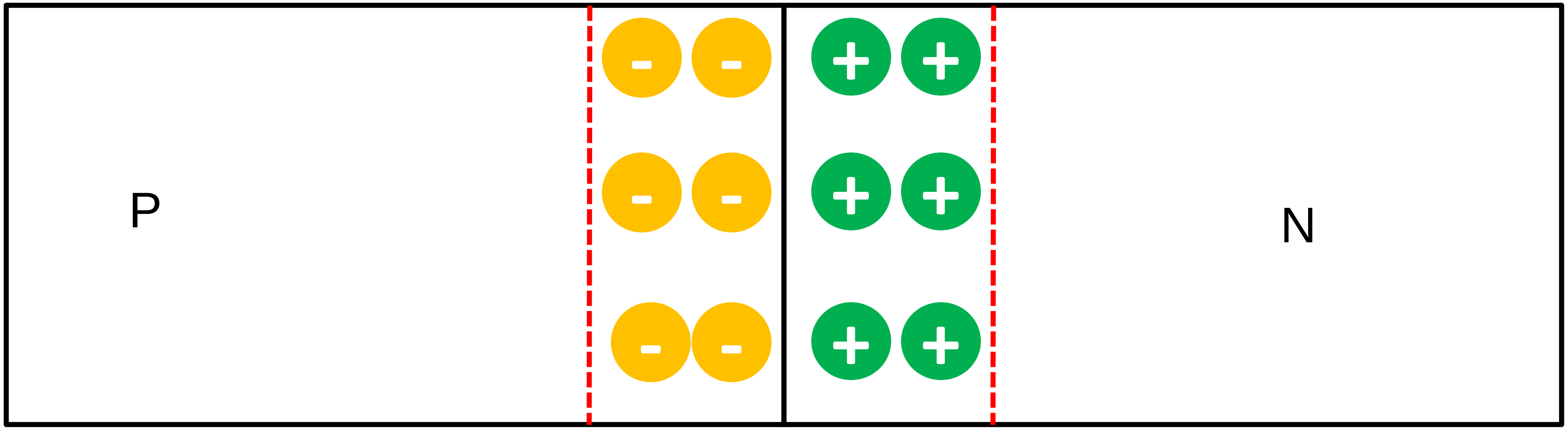
Diodes only consume power

PN Junction Diode



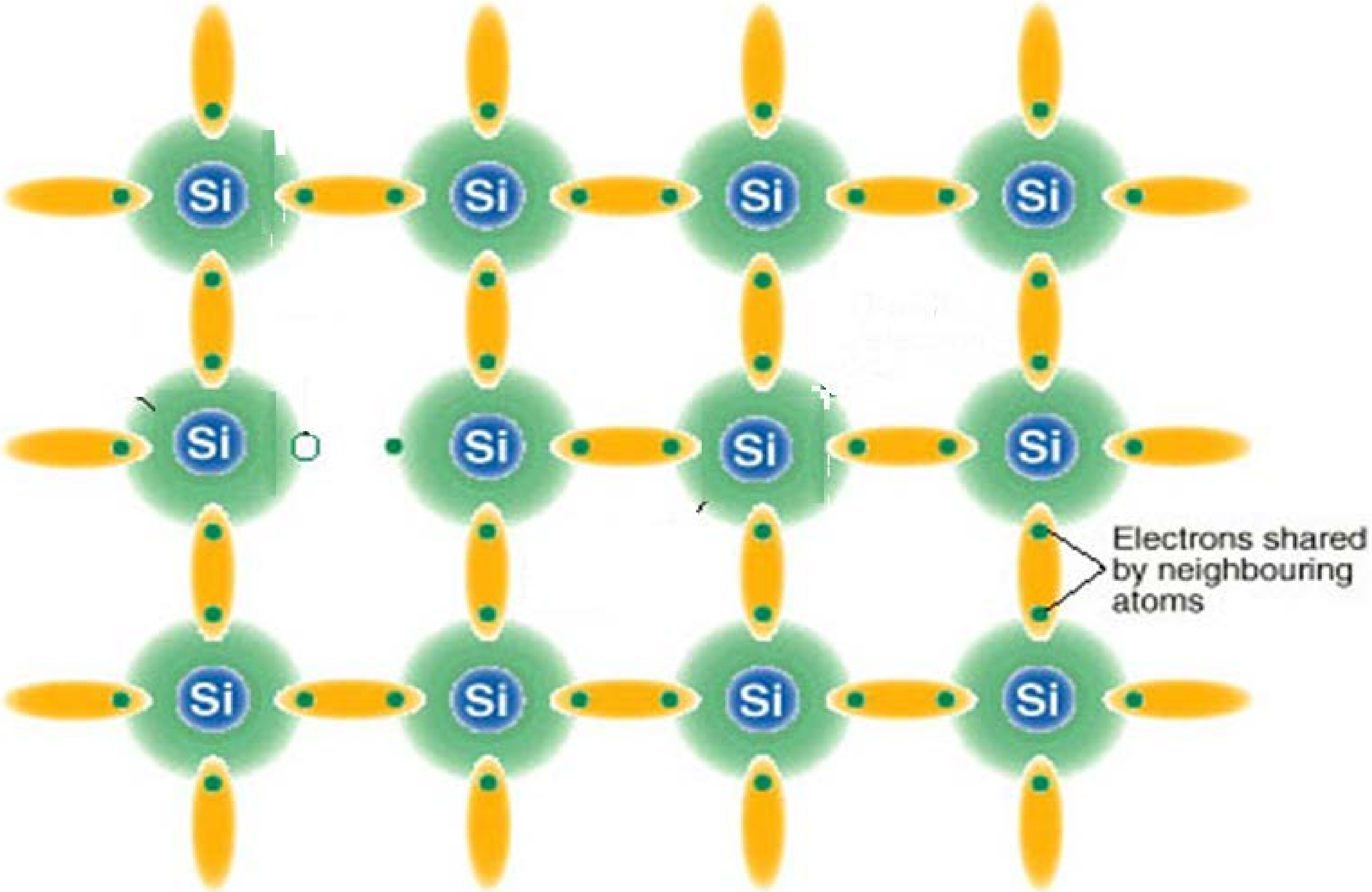


Inside a PN junction at equilibrium (zero applied voltage), there is built-in voltage with N region being positive and P-region negative.



The built-in voltage (also called potential barrier) prevents electrons and holes to give rise to current.

Simplified Picture



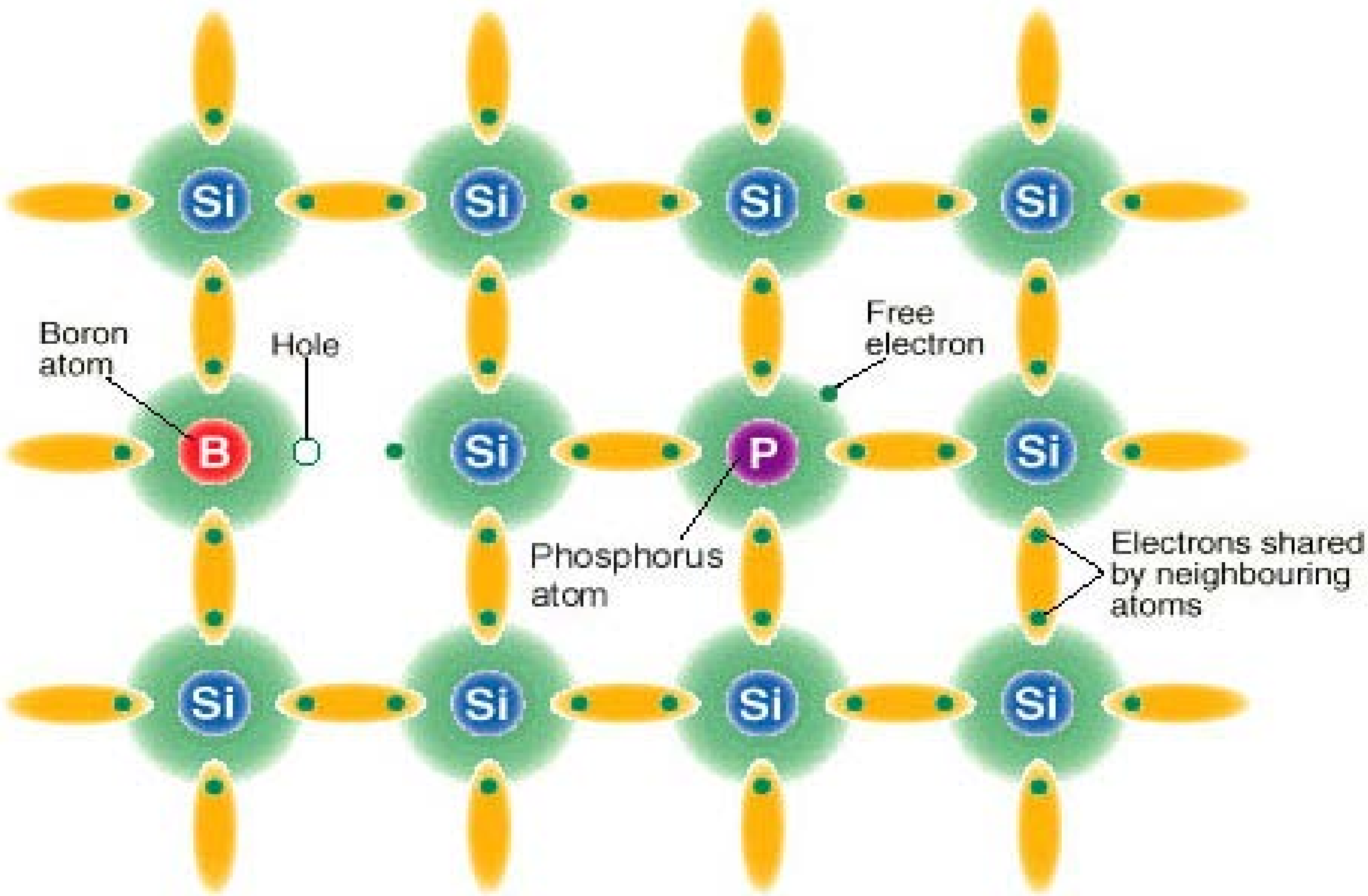
Extrinsic Semiconductors

Adding small amounts of suitable impurity atom can drastically alter number of electrons and holes in a semiconductor !

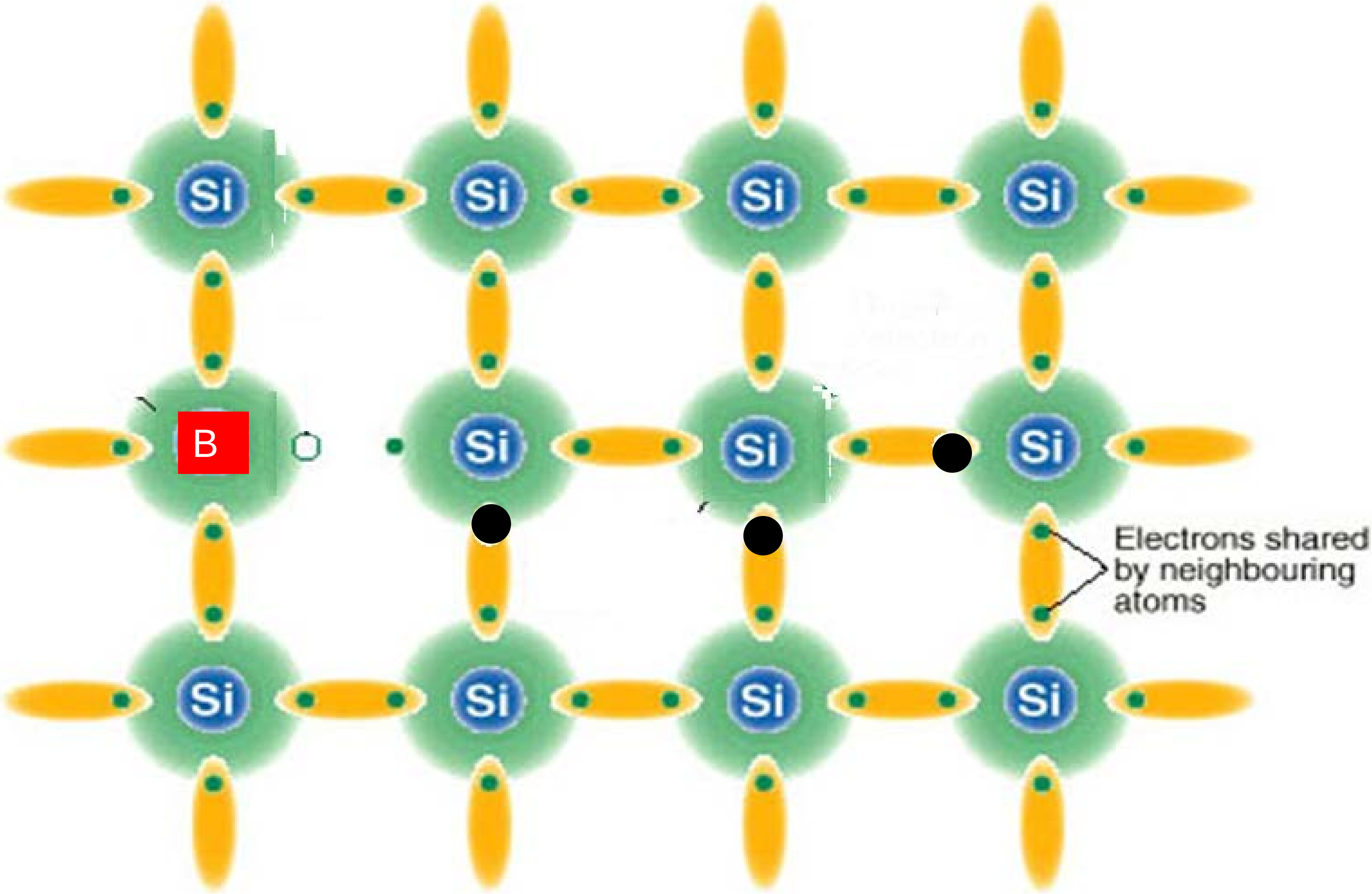
	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII	VII	VII	IB	IB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110								

Addition of a group V element impurity to Silicon should increase electrons while addition of group III element impurity should increase number of holes

Doping



Si
Boron atom
Hole
B
P
Free electron
Phosphorus atom
Electrons shared by neighbouring atoms


Si
B
Electrons shared by neighbouring atoms

N and P-type Semiconductors

N-type : n > p

A Semiconductor such as Silicon doped with a donor impurity such as Phosphorous or Arsenic from group V of periodic table. The donor impurity donates an electron to conduction band thereby increasing their concentration

P-type : p > n

A Semiconductor such as Silicon doped with a Acceptor impurity such as Boron from group III of periodic table. The acceptor impurity increases number of holes in valence band.

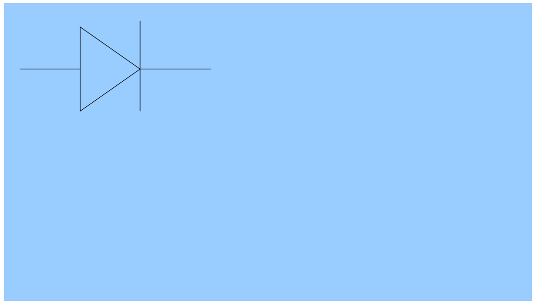
No. of silicon atoms per unit volume $\square\ 4 \times 10^{22}\, cm^{-3}$

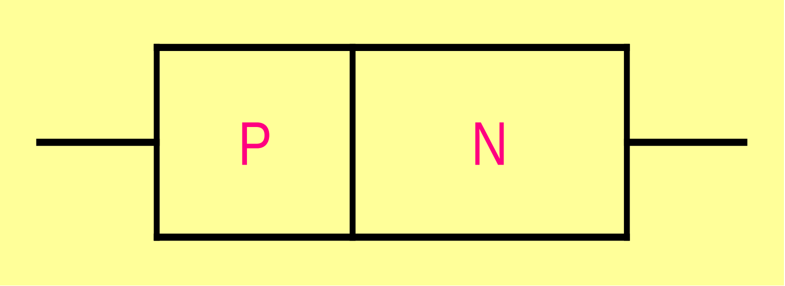
Impurity concentration : $N_A = 10^{17}\, cm^{-3}$

1 in 400,000 Silicon atoms is replaced by Boron

Very small amounts of impurity atoms can cause a drastic change in electrical property of a semiconductor.

PN Junction Diode





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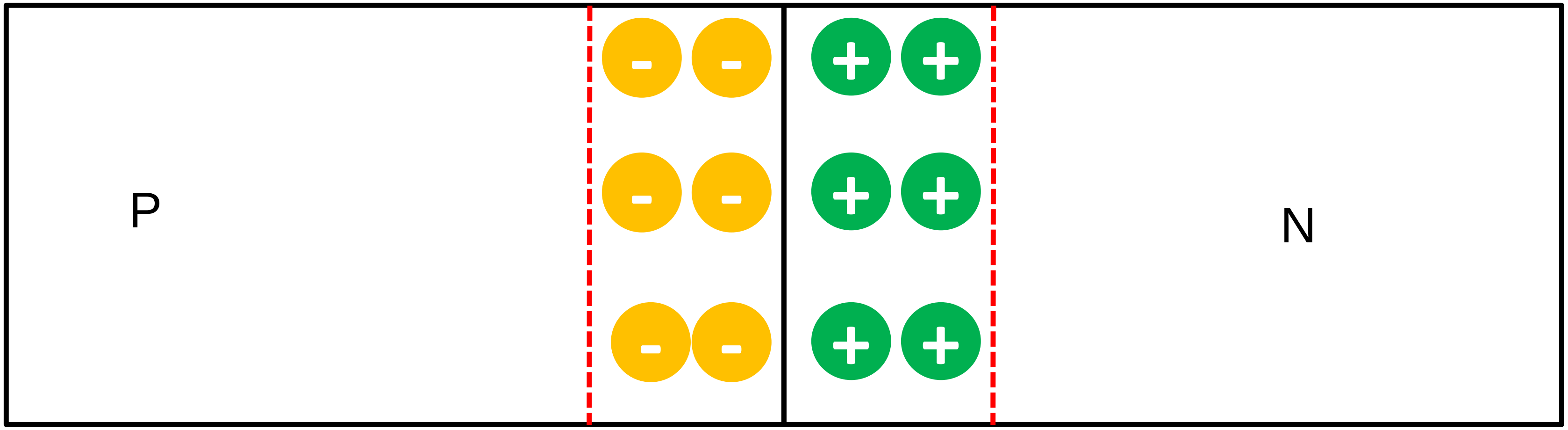
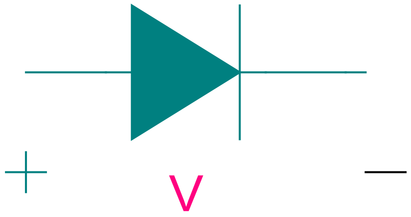
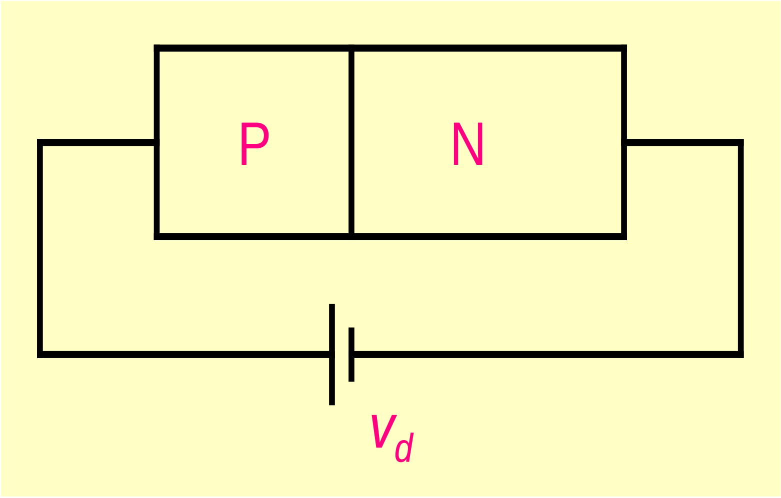


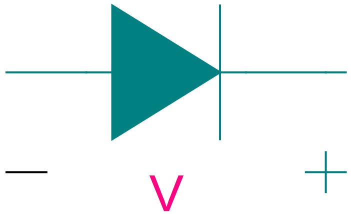
The built-in voltage (also called potential barrier) prevents electrons and holes to give rise to current.

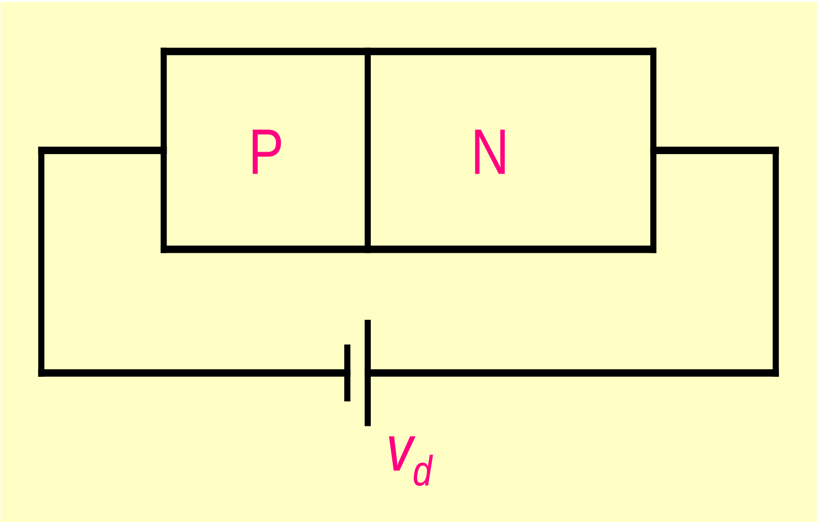
Forward and Reverse Bias



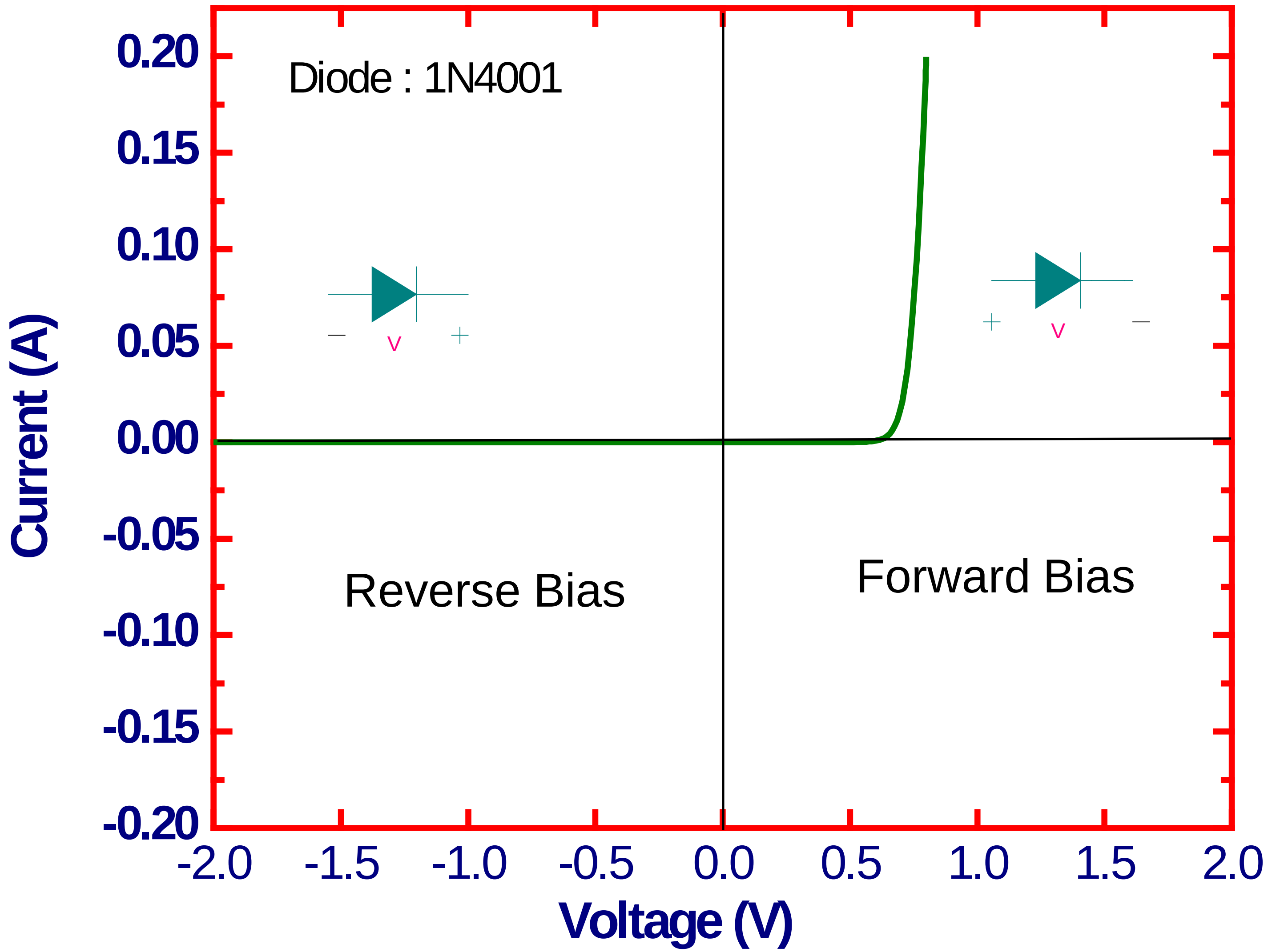


Forward Bias: P is biased at a higher voltage compared to N. It lowers the built-in potential and allows current to flow.



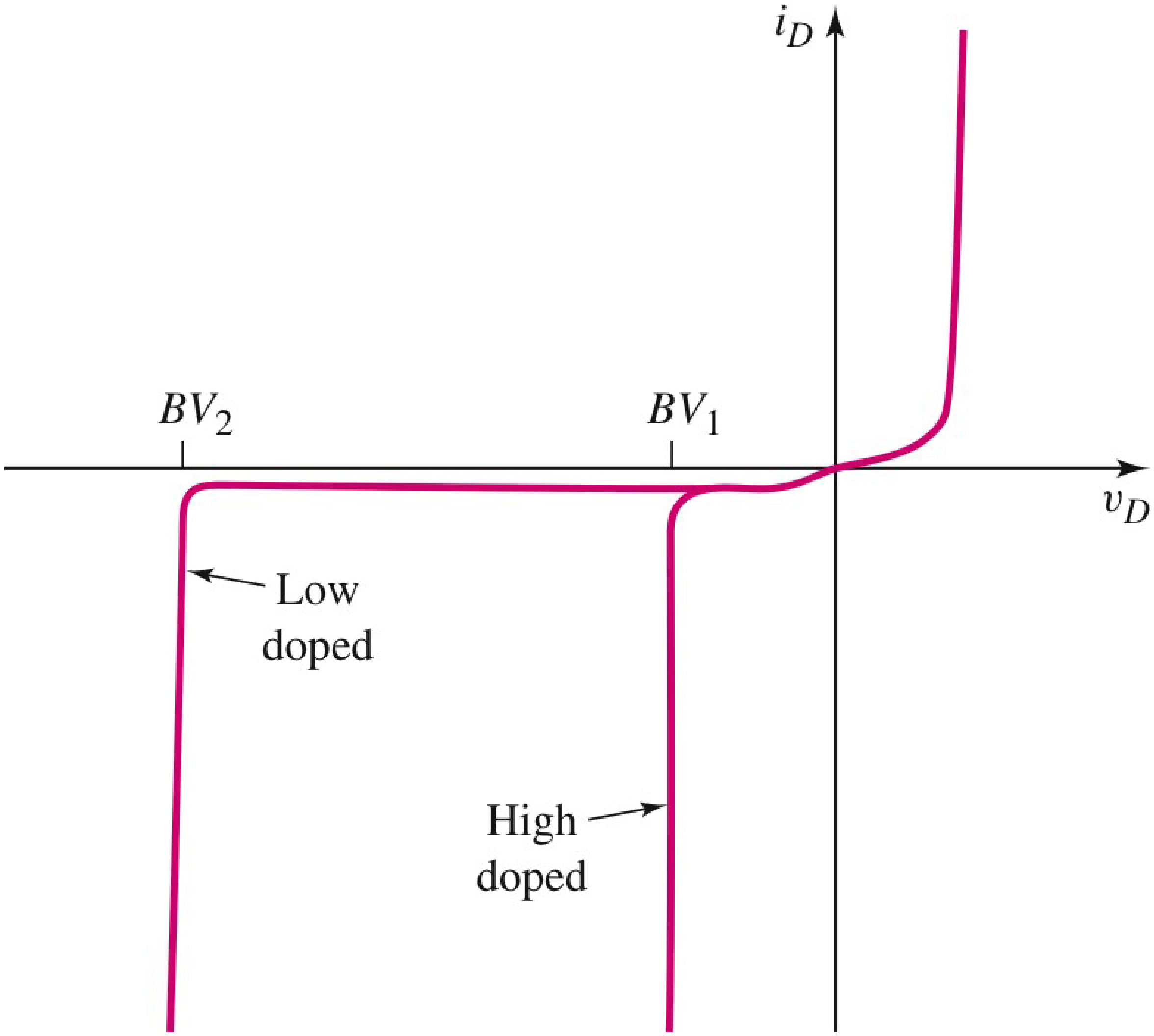


Reverse Bias: N is biased at a higher voltage compared to P. This increases built-in potential and very little current flows.

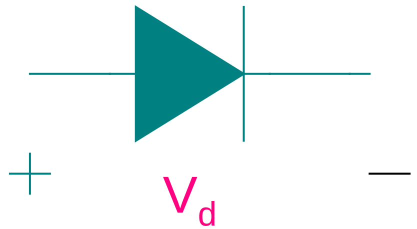


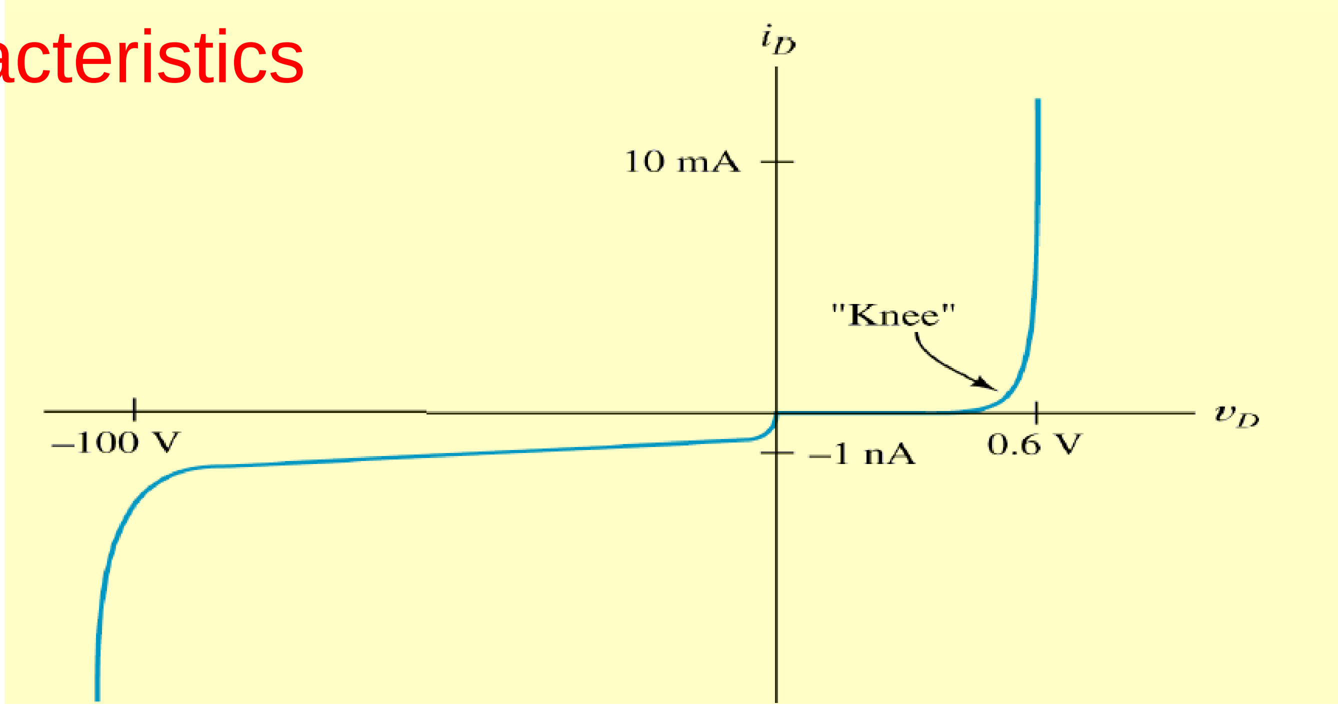
The p-n junction only conducts significant current in the forward-bias region.

Breakdown



Diode : I-V Characteristics





$$i_D = I_S \times \{\exp(\frac{v_d}{nV_T}) - 1\}$$

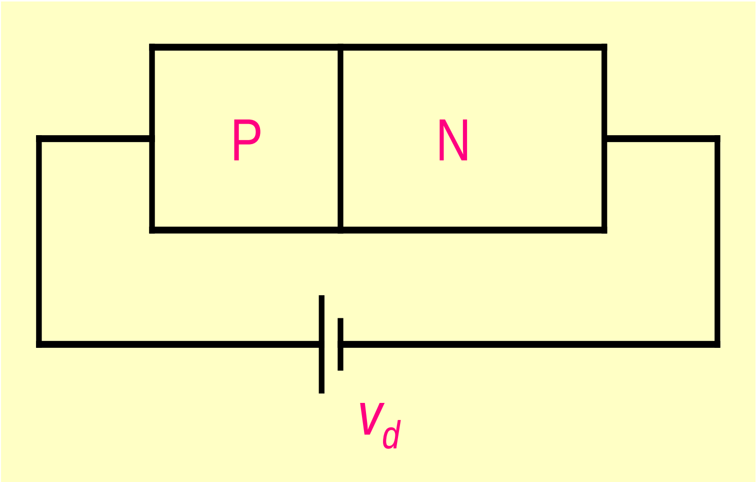
I_s : Reverse Saturation Current

i_d:diode current; v_d: applied voltage

$$V_T = kT/q \cong 26mV \text{ at } T = 300K$$

n is called ideality factor and is equal to 1 for ideal diodes

Forward Bias

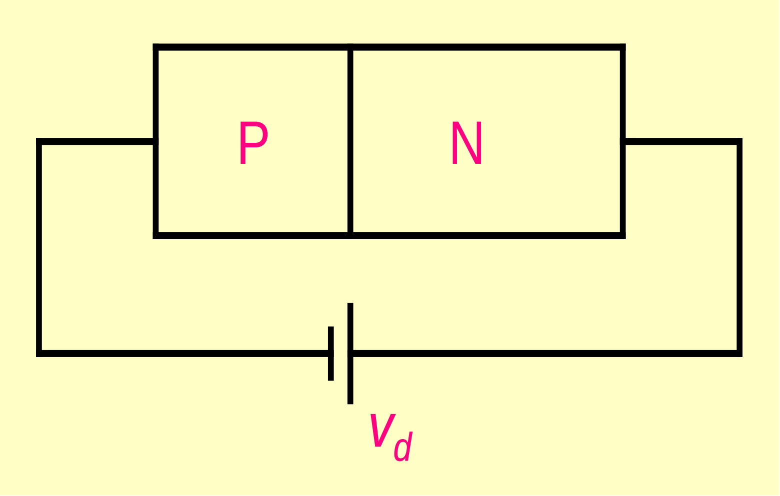


$$v_d >> V_T = 26mV$$

$$i_D = I_S \times \{\exp(\frac{v_d}{V_T}) - 1\}$$

$$i_D \cong I_S \times \exp(\frac{v_d}{V_T})$$

Reverse Bias



$$i_D = I_S \times \{\exp(\frac{v_d}{V_T}) - 1\}$$

$$v_d = -v_R$$

$$i_D = I_S \times \{\exp(-\frac{v_R}{V_T}) - 1\} \cong -I_S$$

$$|v_R| >> V_T$$

Example

At a temperature of 300 K, the diode current is i_D=0.1mA for v_D = 0.6 V. Let n = 1 and V_T = 26mV. Find the saturation current I_s. Then compute the diode current when v_D = 0.65V and at 0.7 V.

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

$$I_s = \frac{i_D}{\exp(v_D / nV_T) - 1}$$

$$= \frac{10^{-4}}{\exp(0.600 / 0.026) - 1}$$

$$= 9.502 \times 10^{-15} \ A$$

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

Then for $v_D = 0.650$ V, we have:

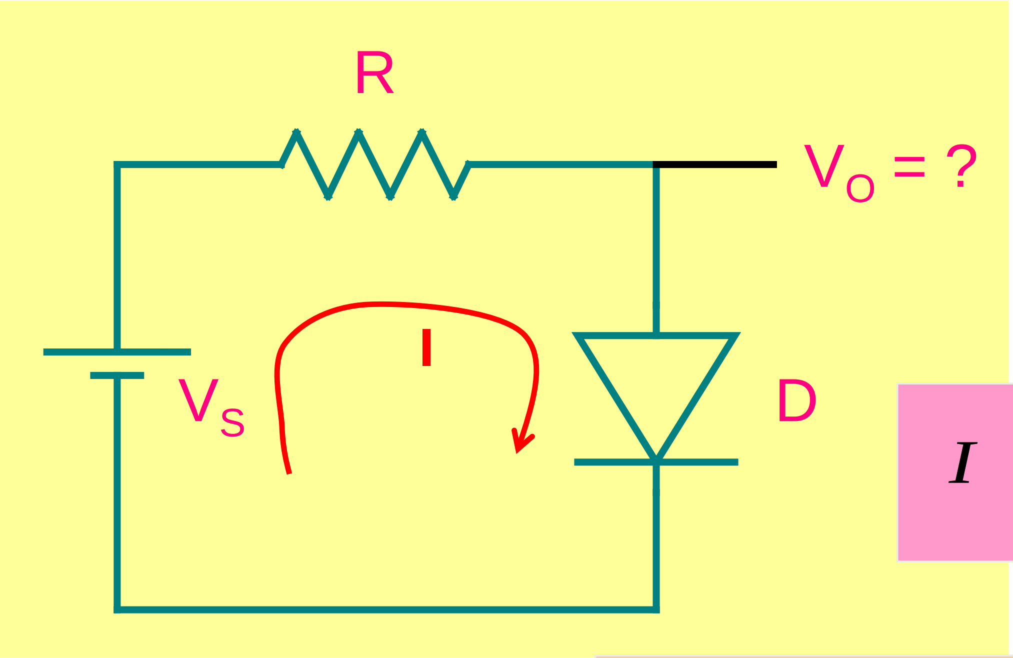
$$i_D = I_s\left[\exp(v_D / nV_T) - 1\right] = 9.502\times10^{-15}\times\left[\exp(0.650/0.026) - 1\right]$$
$$= 0.6841 \text{ mA}$$

Similarly for $v_D = 0.700$ V,

$$i_D = 4.681 \text{ mA}$$

Notice the difference
in current
for 0.05 difference in v_D

Analysis using non-linear diode model is not easy



$$V_S = I \times R + V_O \quad (1)$$

$$I = I_S \times \{\exp(\frac{V_O}{nV_T}) - 1\} \quad (2)$$

$$\Rightarrow \quad V_O = nV_T \times \ln(\frac{I}{I_S} + 1) \quad (3)$$

$$\Rightarrow \quad V_S = IR + nV_T \times \ln(\frac{I}{I_S} + 1) \quad (4)$$

Iterative Method:

$$V_S = IR + V_O \quad (1)$$

$$V_O = nV_T \times \ln(\frac{\mathrm{I}}{\mathrm{I_S}} + 1) \quad (3)$$

Assume

$$V_O = 0.6\mathrm{V}$$

Calculate

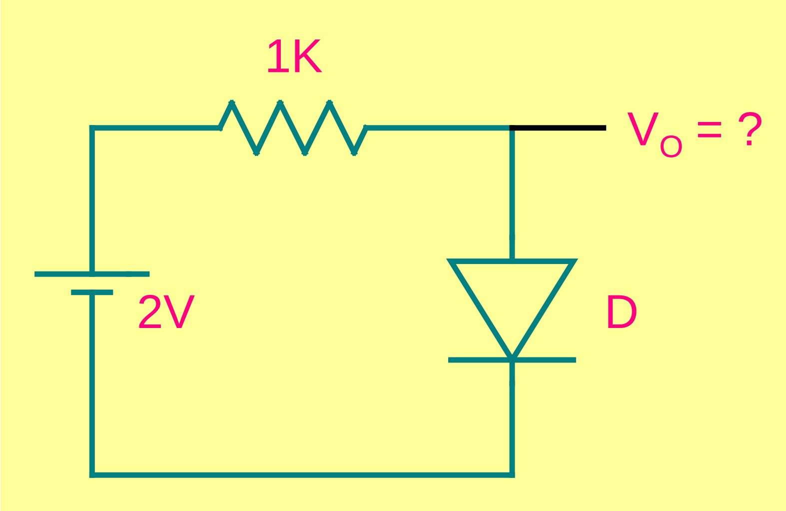
$$I = \frac{V_S - V_O}{R}$$

Re-calculate

$$V_O = nV_T \times \ln(\mathrm{I}/\mathrm{I_S} + 1)$$

Convergence:

$$\frac{\Delta I}{I} \leq \varepsilon$$



$$i_D = I_S \times \{\exp(\frac{V}{V_T}) - 1\}$$

$$I_S = 2 \times 10^{-15} A$$

$$V_T = kT/q \cong 26mV$$

at T = 300K

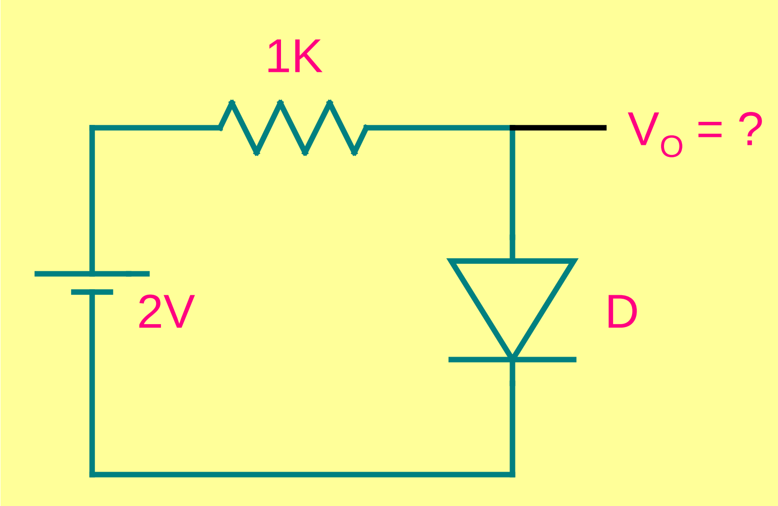
Assume V_O

$$I = \frac{V_S - V_O}{R}$$

$$V_O = nV_T \times \ln(I/I_S + 1)$$

$V_O = 0.5$	$V_O = 0.711$	$V_O = 0.707$
$I = 1.5 \times 10^{-3}$	$I = 1.289 \times 10^{-3}$	$I = 1.293 \times 10^{-3}$
$V_O = 0.711$	$V_O = 0.707$	$V_O = 0.707$

CONVERGENCE



$$i_D = I_S \times \{\exp(\frac{V}{V_T}) - 1\}$$
$$I_S = 2 \times 10^{-15} A$$
$$V_T = kT/q \cong 26mV \quad \text{at T} = 300\text{K}$$

Assume V_O

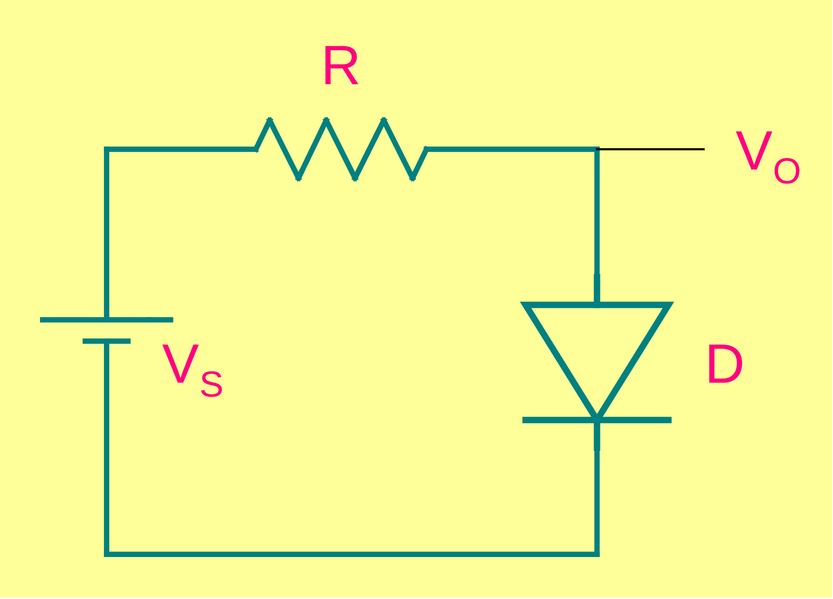
$$I = \frac{V_S - V_O}{R}$$

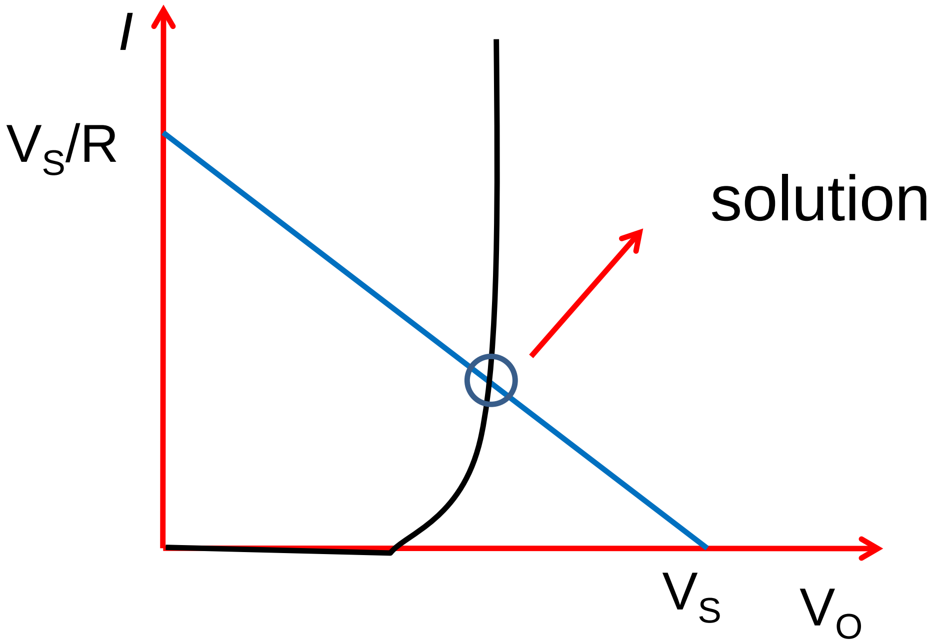
$$V_O = nV_T \times \ln(I/I_S + 1)$$

$V_O = 1.0$	$V_O = 0.7$	$V_O = 0.707$
$I = 1.0 \times 10^{-3}$	$I = 1.3 \times 10^{-3}$	$I = 1.293 \times 10^{-3}$
$V_O = 0.7$	$V_O = 0.707$	$V_O = 0.707$

CONVERGENCE to the same Result

Graphical Method: Method of Load Line





$$V_S = I \times R + V_O$$

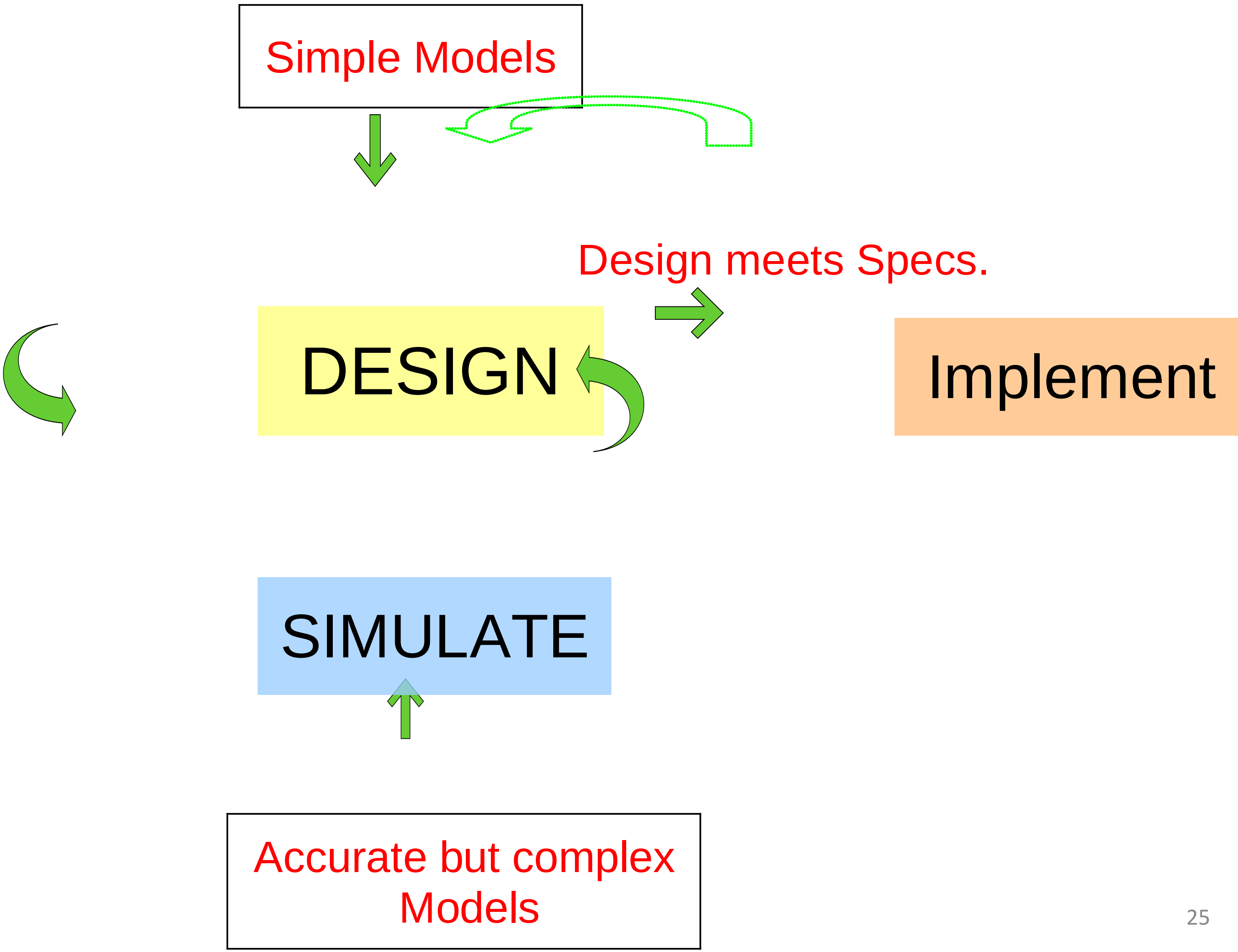
$$\Rightarrow \quad I = \frac{V_S - V_O}{R}$$

$$I = I_S \times \{\exp(\frac{V_O}{nV_T}) - 1\}$$

How about something that is

simple & easy to work with

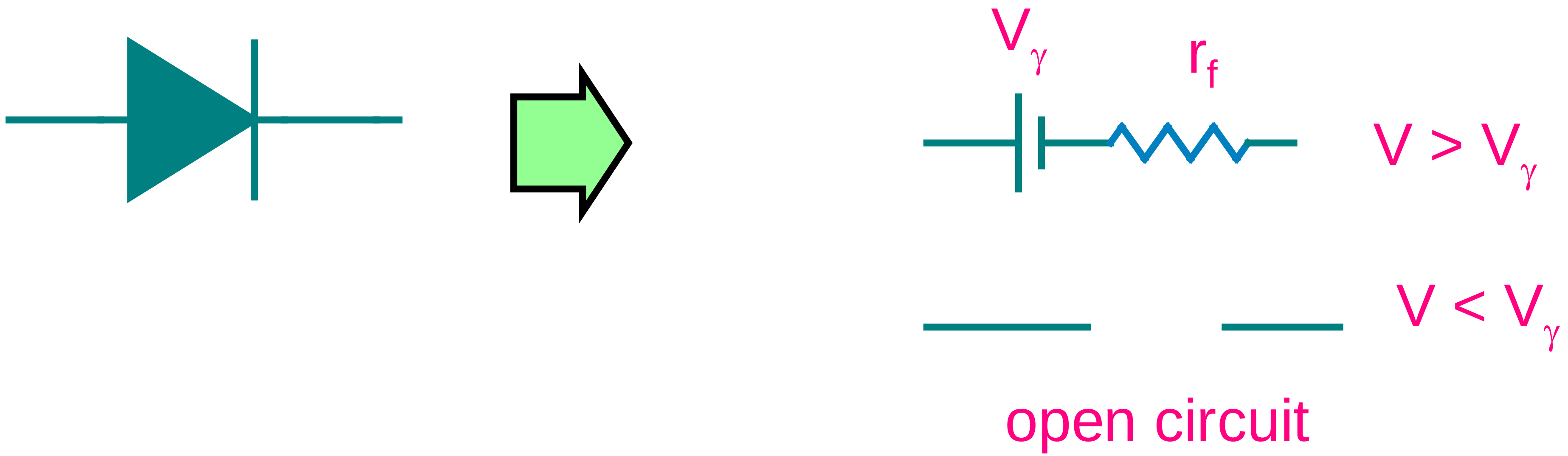
Role of simple model in design cycle



•Analysis using a non-linear diode model is relatively difficult and time consuming.

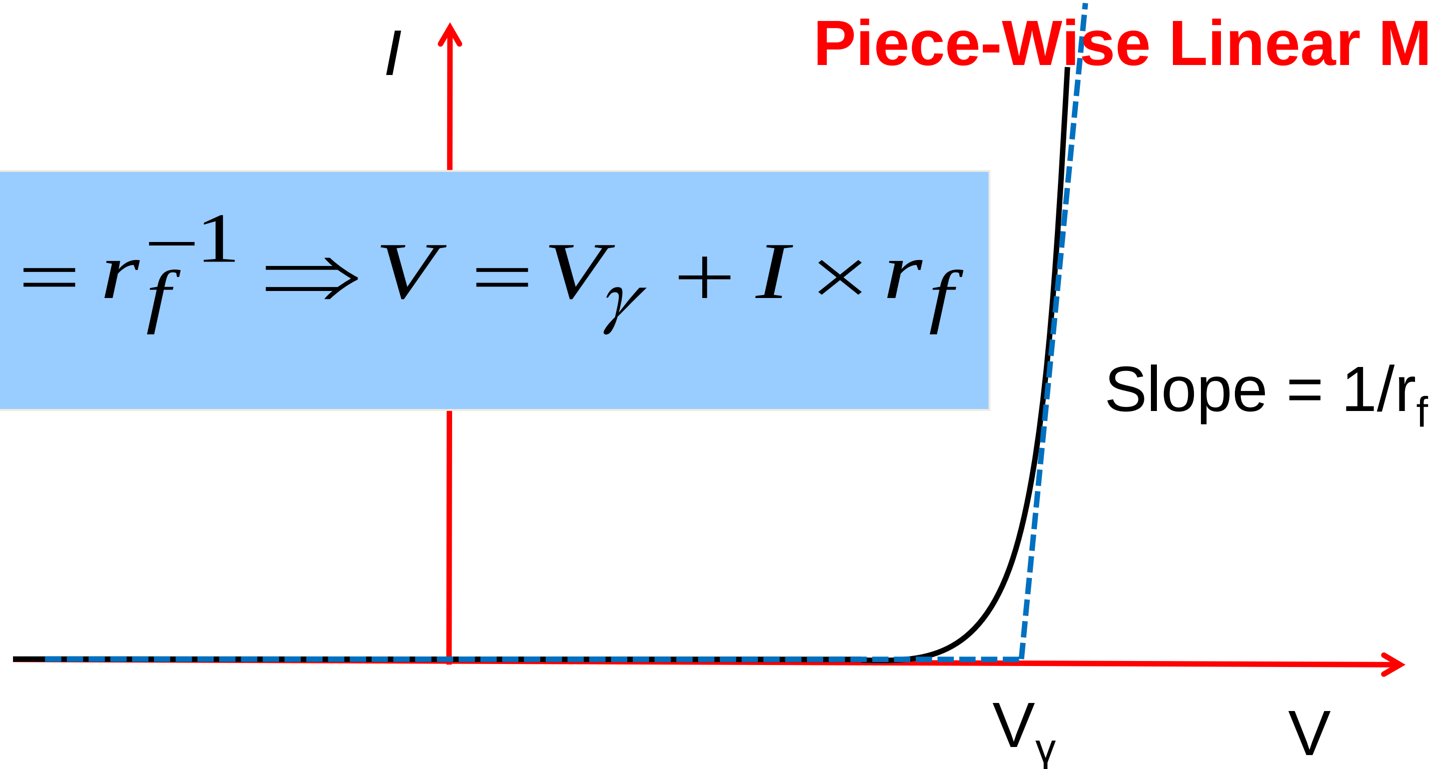
•It also does not give a symbolic expression that can provide insight and help in the design of the circuit.

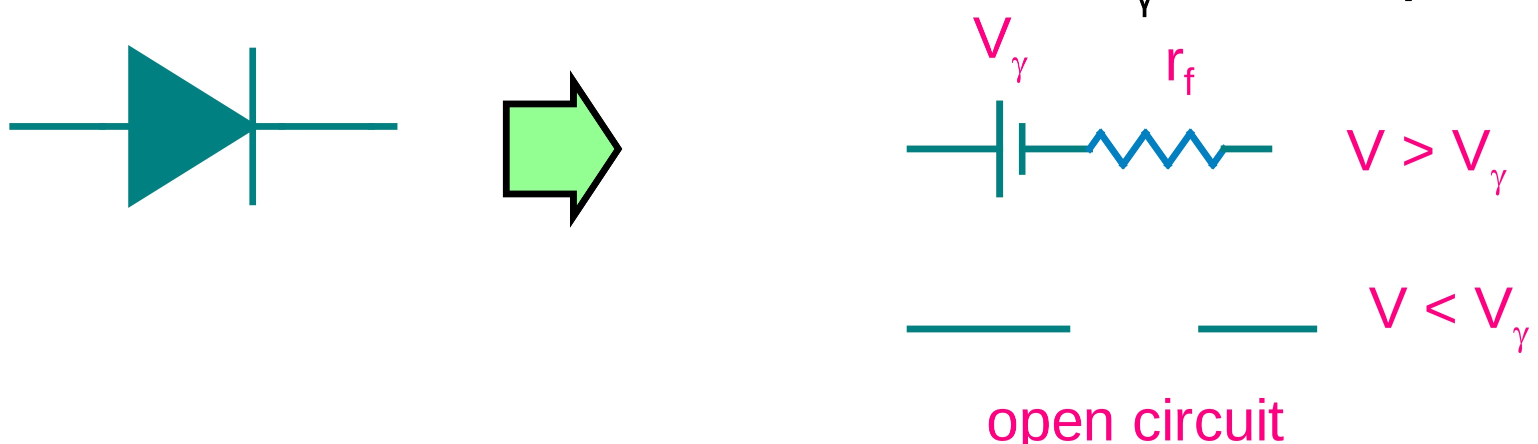
Need SIMPLER and LINEAR Device Models



Piece-Wise Linear Model

$$\frac{I-0}{V-V_\gamma} = r_f^{-1} \Rightarrow V = V_\gamma + I \times r_f$$

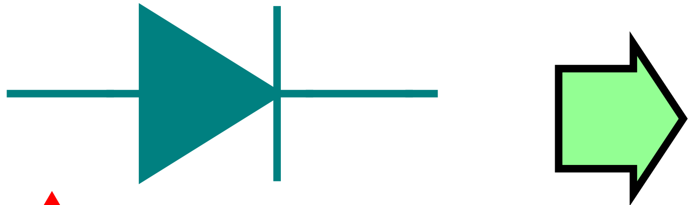


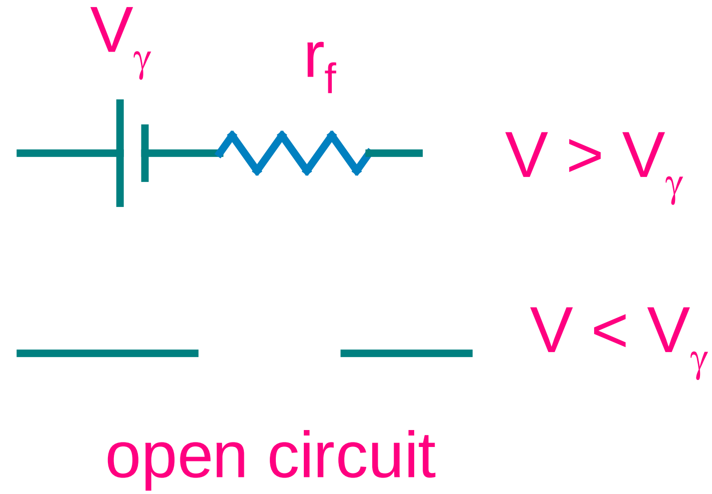


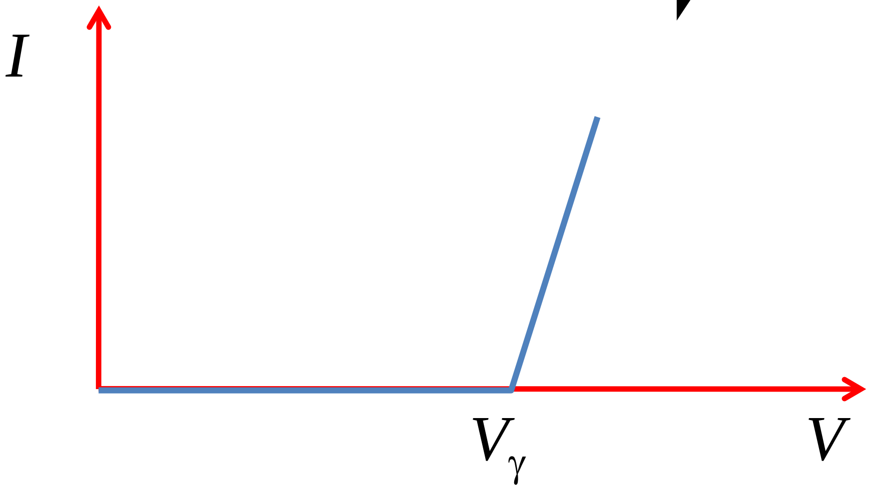
V_γ is called cut-in or turn-on voltage and depends on nature of diode and range of current considered

For most of our analysis, we will take $V_\gamma = 0.7$V and $r_f \sim 10\Omega$

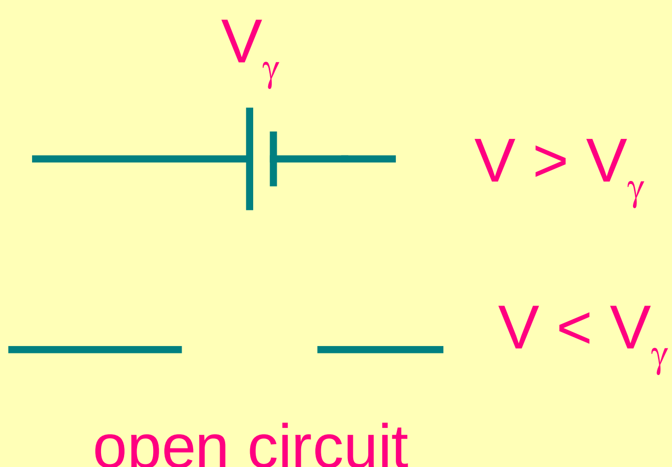
Even Simpler Diode Models

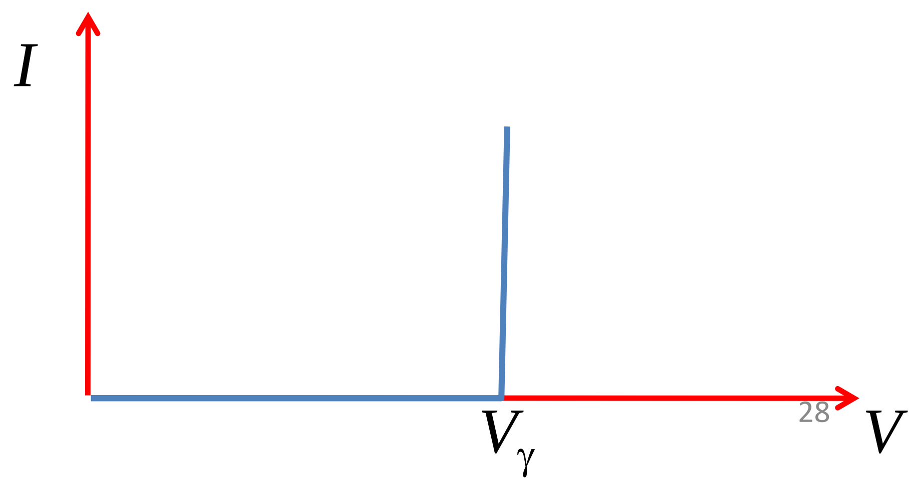






Constant voltage drop model





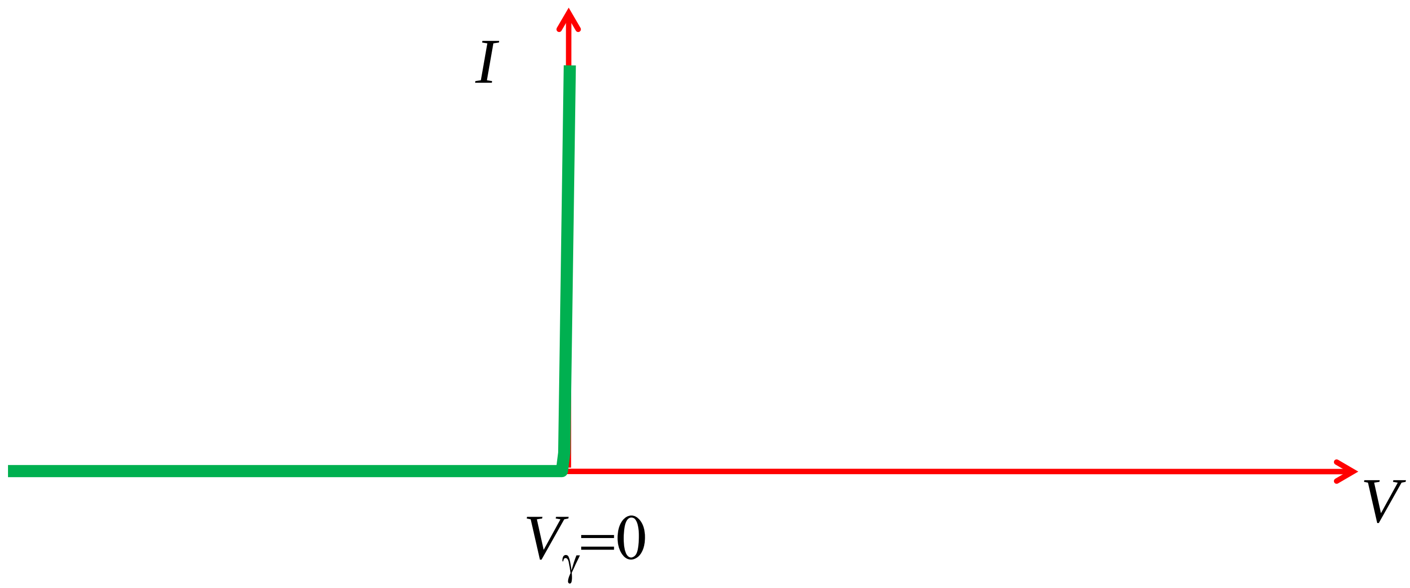
Even Simpler Diode Models

Ideal diode model

V > 0

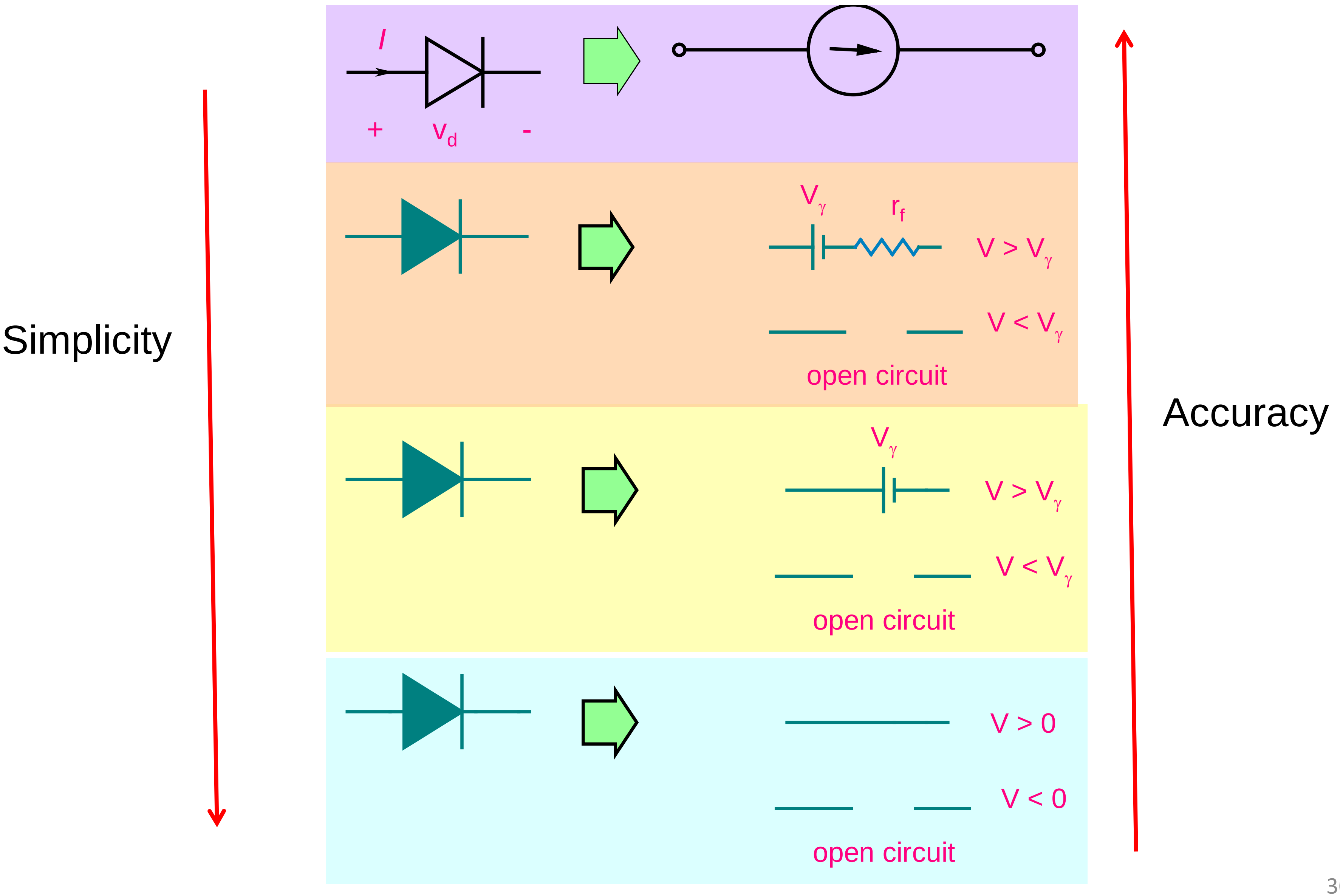
V < 0

open circuit

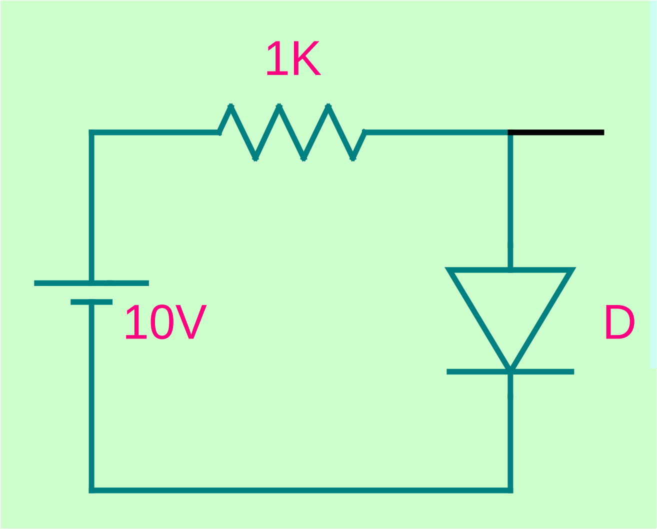


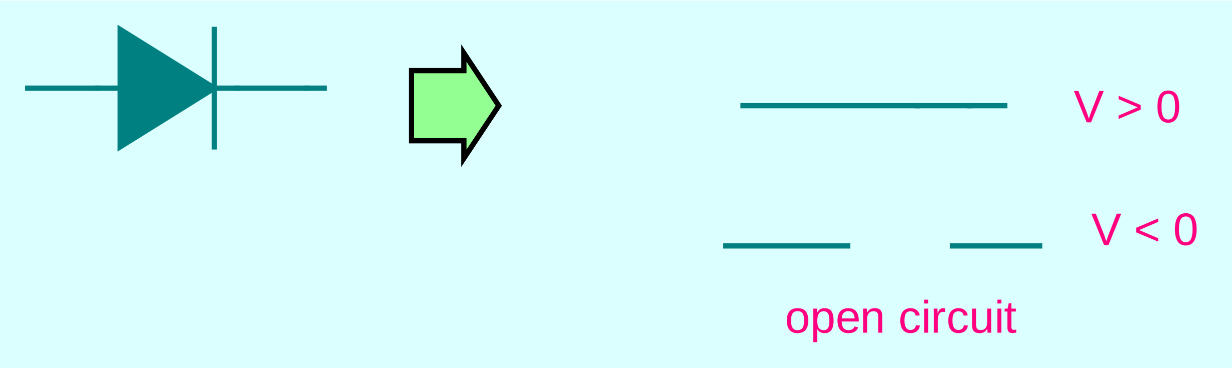
Diode Models

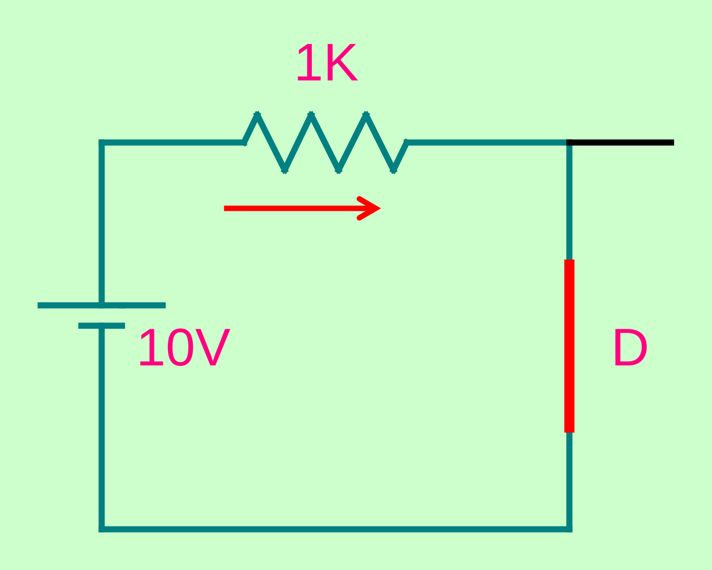
$$i_D = I_S \times \{\exp(\frac{V_d}{V_T}) - 1\}$$



Analysis using ideal diode model

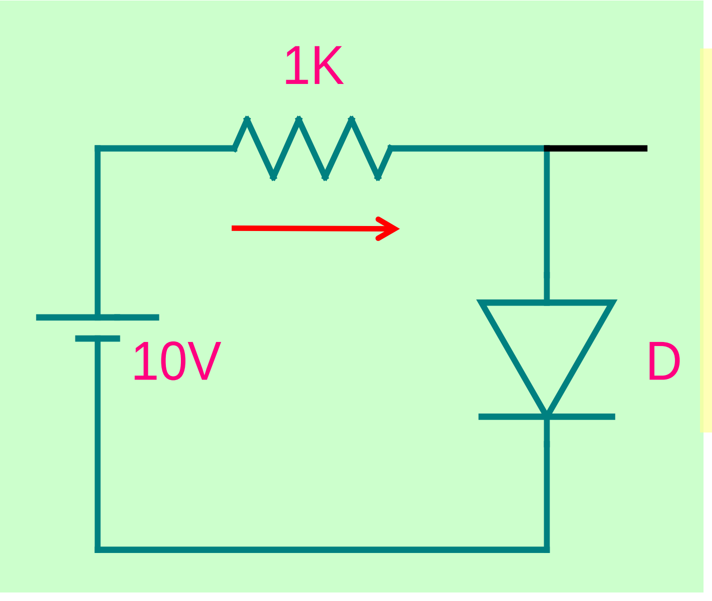


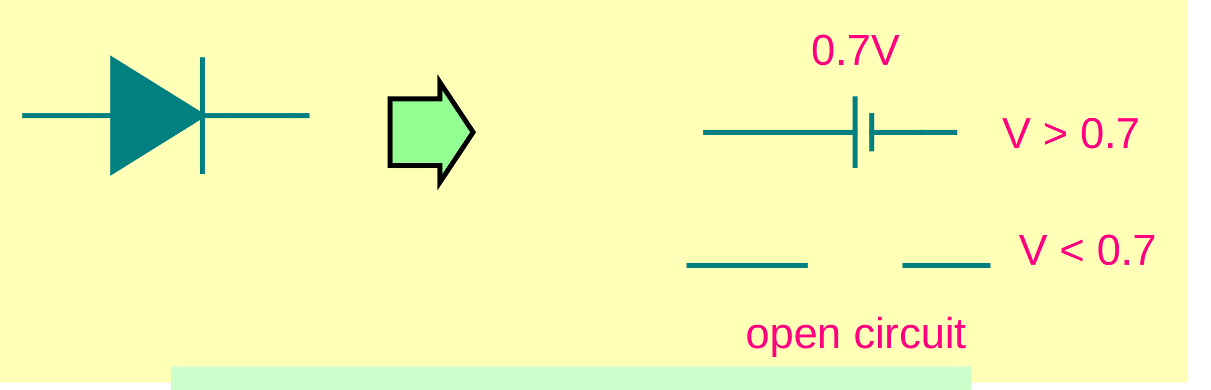


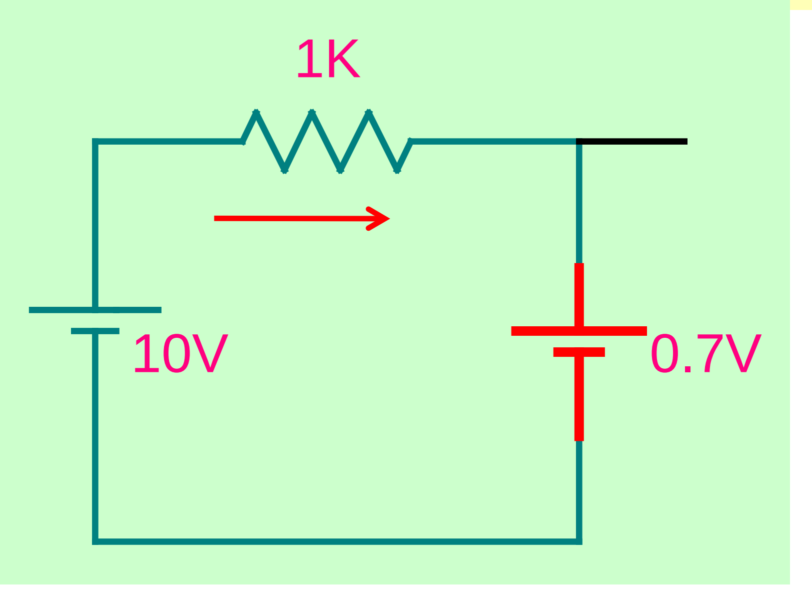


$$I = \frac{10}{1k} = 10mA$$

Analysis with a constant voltage diode model

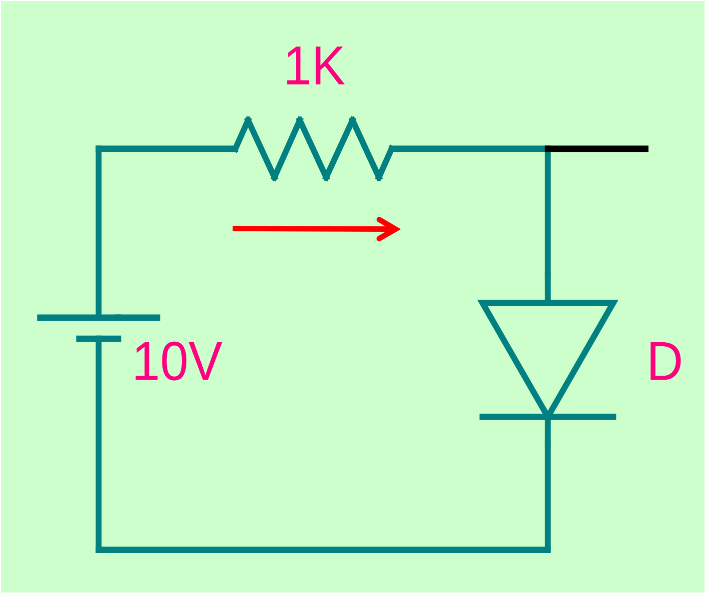


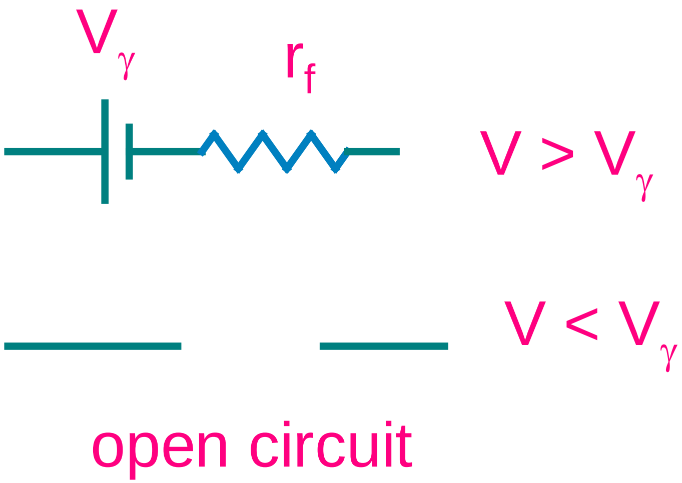




$$I = \frac{10 - 0.7}{1k} = 9.3mA$$

Analysis with a constant voltage plus resistor diode model

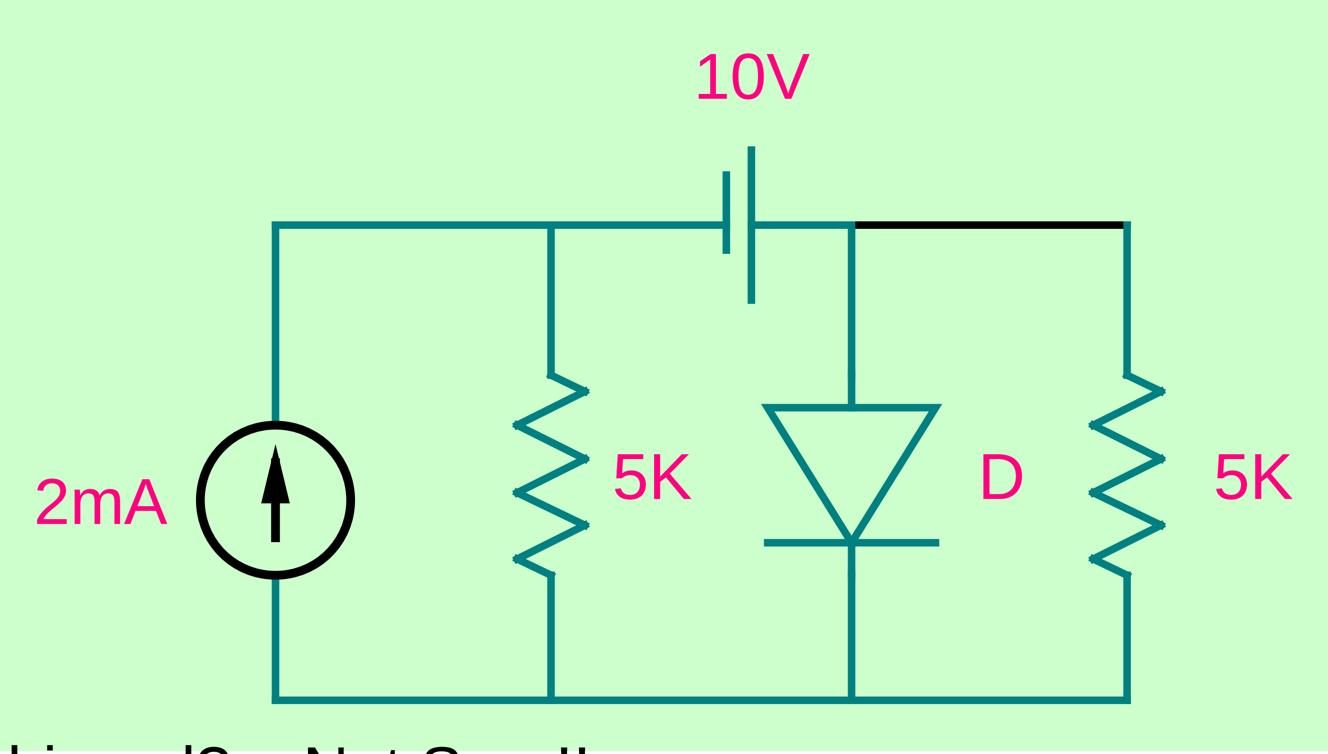




$$I = \frac{10 - 0.7}{1000 + 10} = 9.208mA$$

Example

Find the current through the diode using ideal diode model



Is the diode forward biased? – Not Sure!!

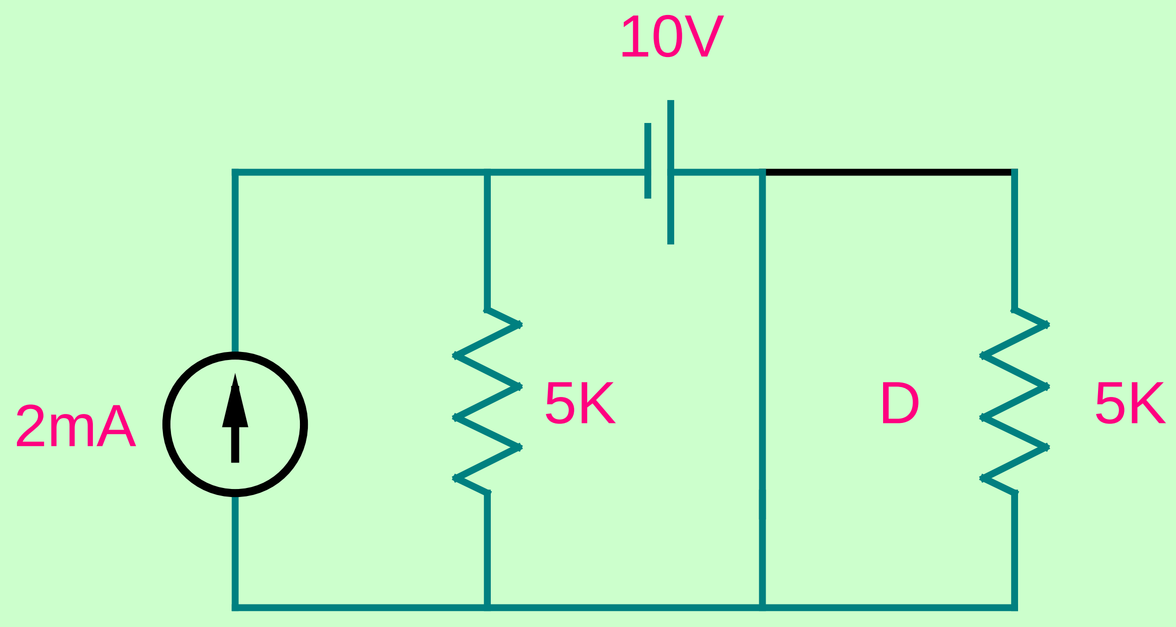
Assume that it is forward biased ☺

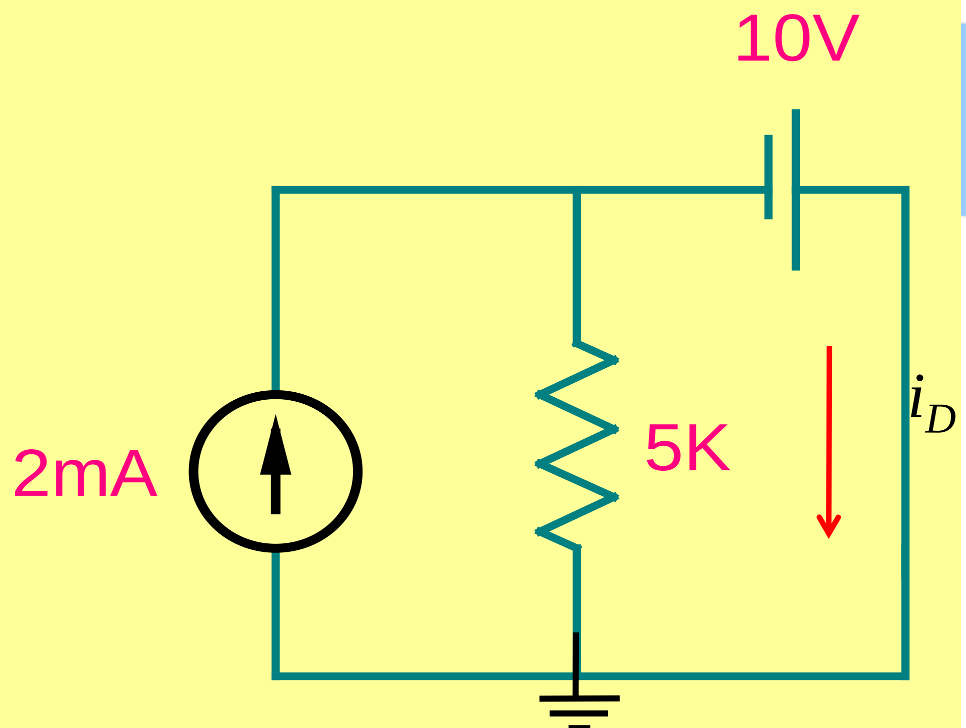
Carry out analysis and then check if current through the diode is in **appropriate** direction.

If not, diode is reverse biased and we carry out the analysis again!!

Example

Assume forward bias



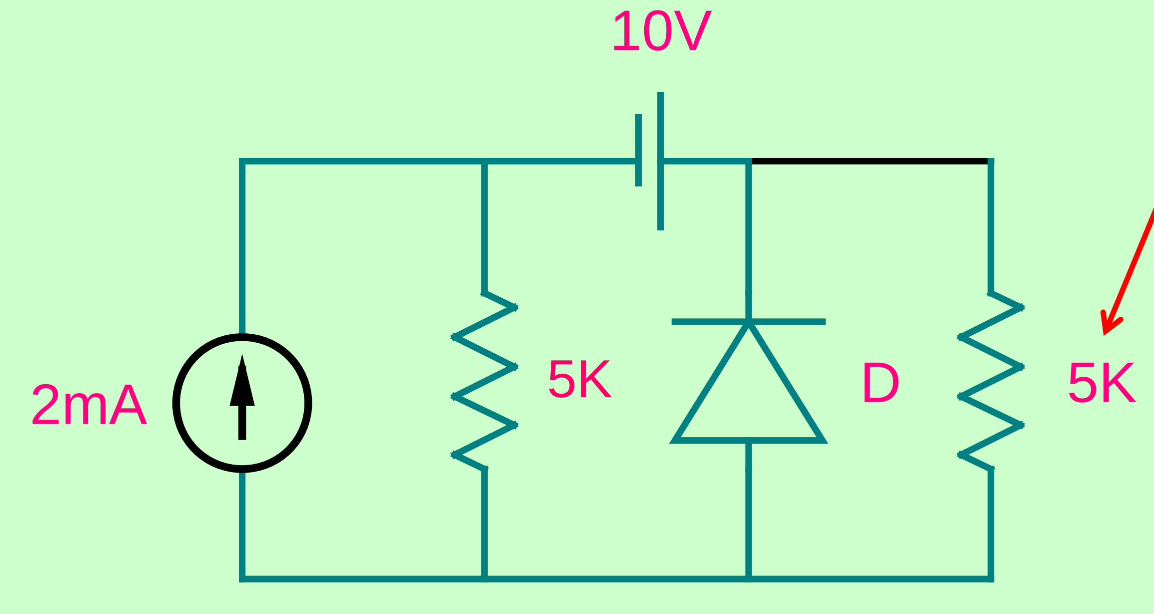


$$-2mA + \frac{-10}{5K} + i_D = 0$$

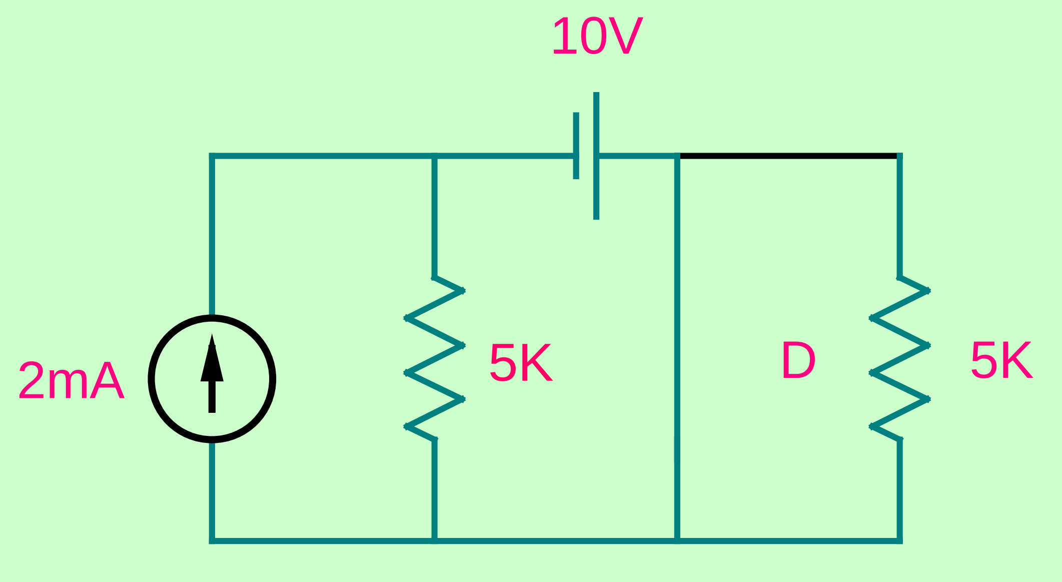
$$i_D = 4mA$$

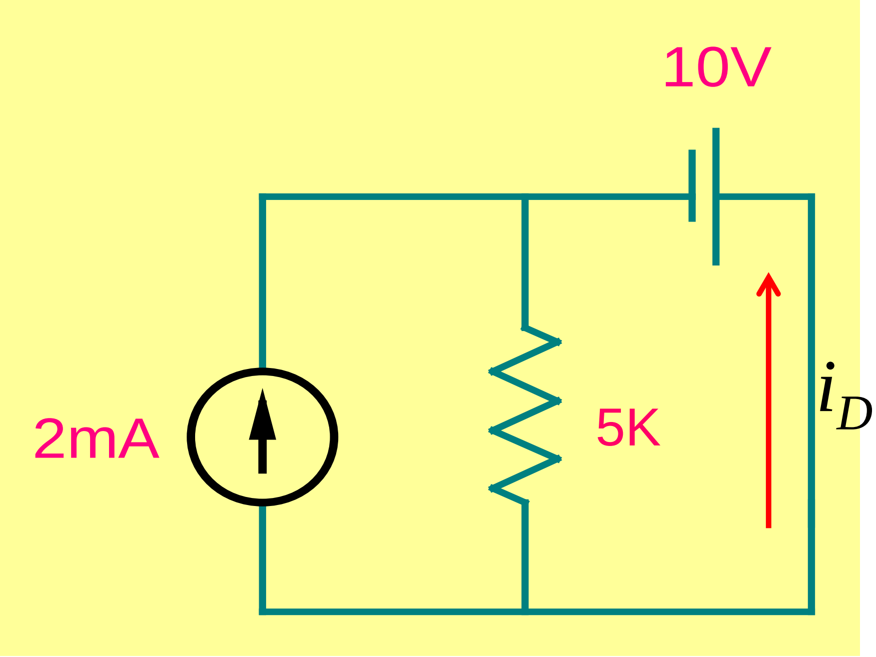
Current is positive, so our assumption is correct

Example Find the current through the 5K resistor using ideal diode model



Assume forward bias



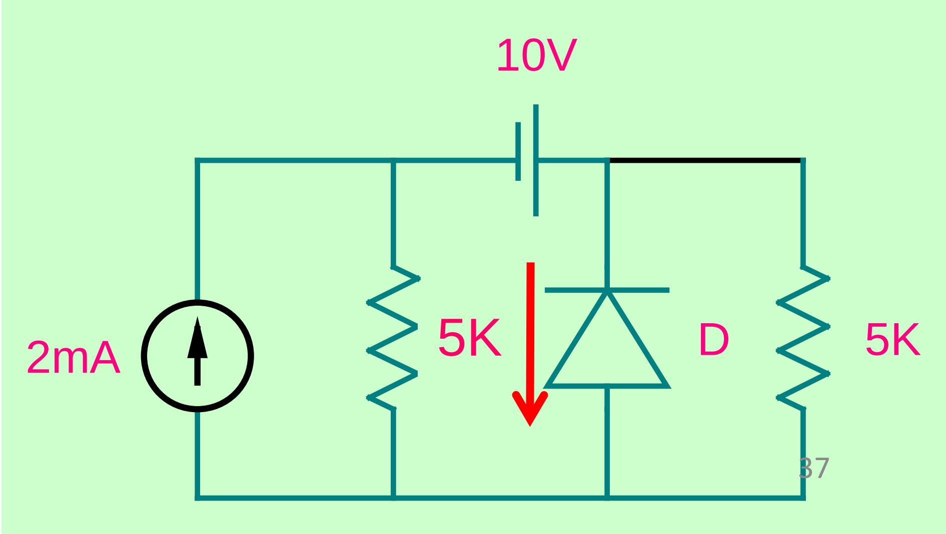


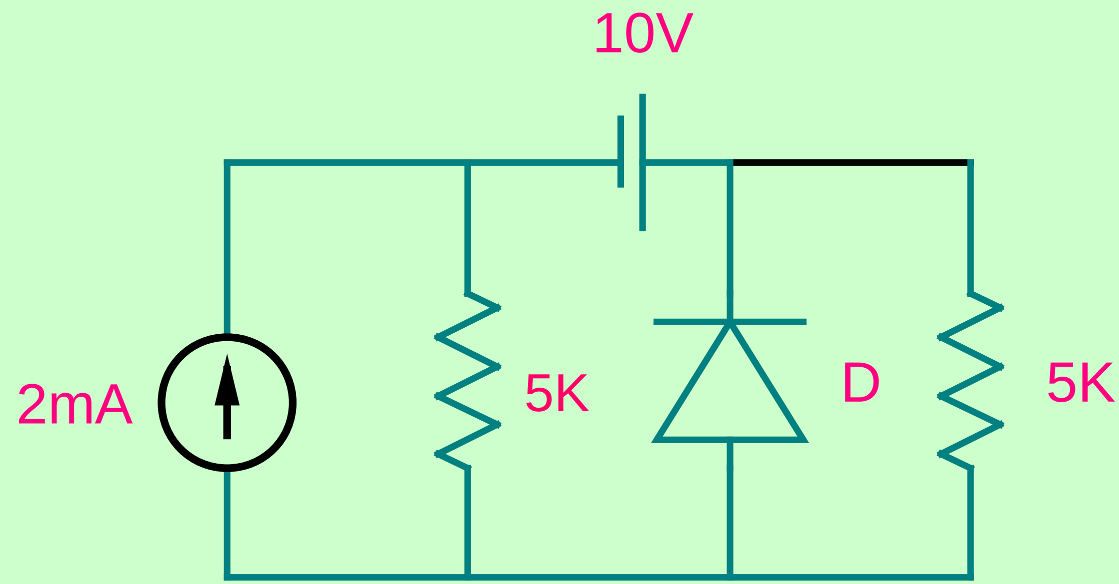
$$-2mA + \frac{-10}{5K} - i_D = 0$$

$$i_D = -4 \quad mA$$

This is not possible.

Therefore, our assumption is incorrect





Assume reverse bias

$$-2mA+\frac{V_1}{5k}+\frac{V_1+10}{5k}=0$$

$$V_1=0$$

$$V_2=10V$$