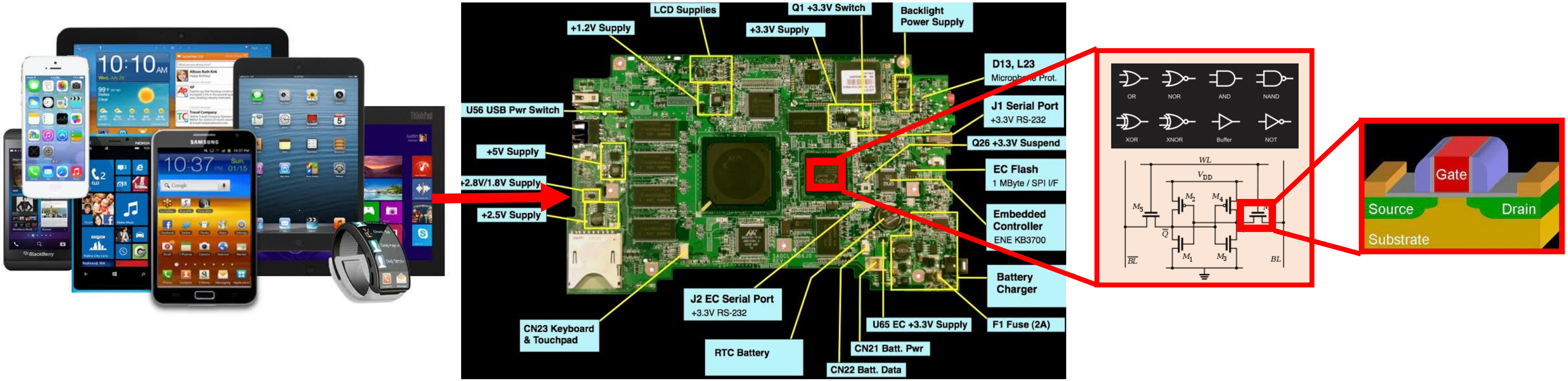
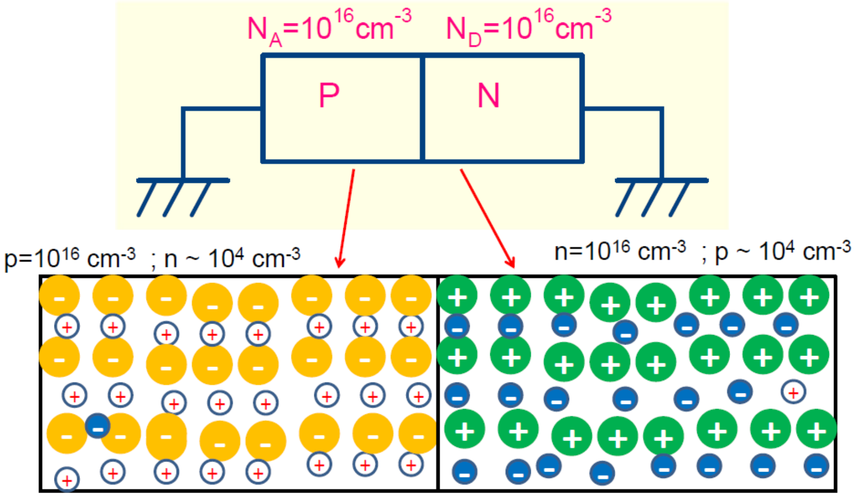


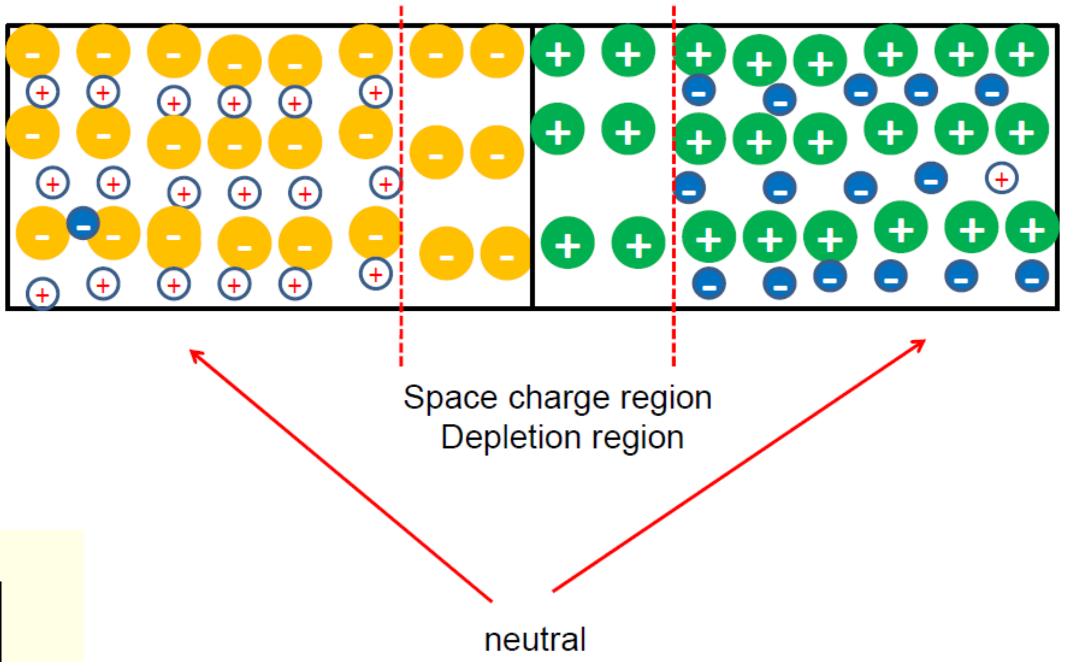
ESC201: Introduction to Electronics

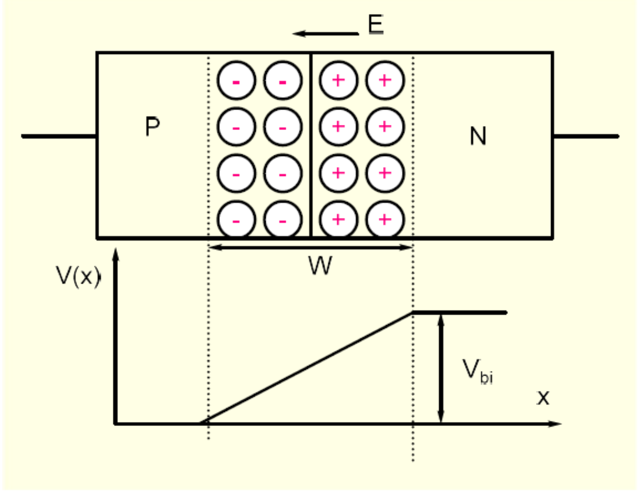
Module 4: Non-Linear Elements

Dr. Shubham Sahay,
Assistant Professor,
Department of Electrical Engineering,
IIT Kanpur

Recap







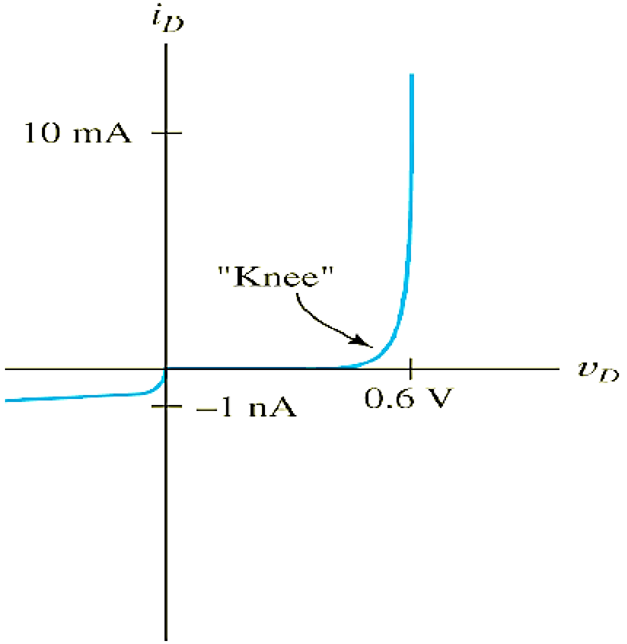
$$V_{bi} = \frac{kT}{q}\ln\left[\frac{N_A N_D}{n_i^2}\right]$$

$N_A = N_D = 10^{16}$ cm^{-3}, $T = 300°K$

$V_{bi} = 0.86$ V

I-V Characteristics- Nonlinear Behavior

Let us ignore breakdown region, assuming that our circuit does not generate large negative voltages



applied voltage $= v_D$

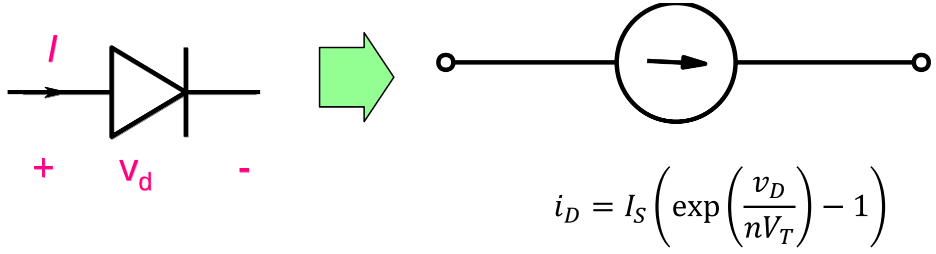
diode current:

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

I_S : Reverse saturation current

n: ideality factor (= 1 for ideal diodes)

$$V_T = \frac{kT}{q} \approx 26mV \text{ at } T = 300K$$



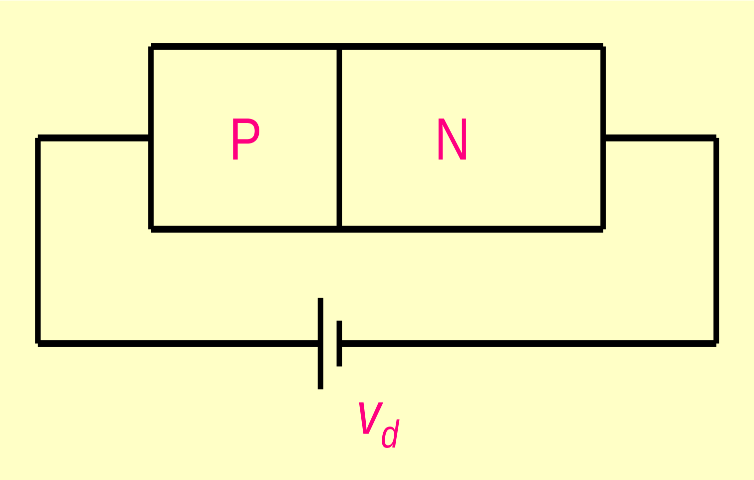
How to analyze circuits containing diodes?

Forward Bias

$$I_D = I_S\left(\exp\left(\frac{v_D}{V_T}\right) - 1\right)$$

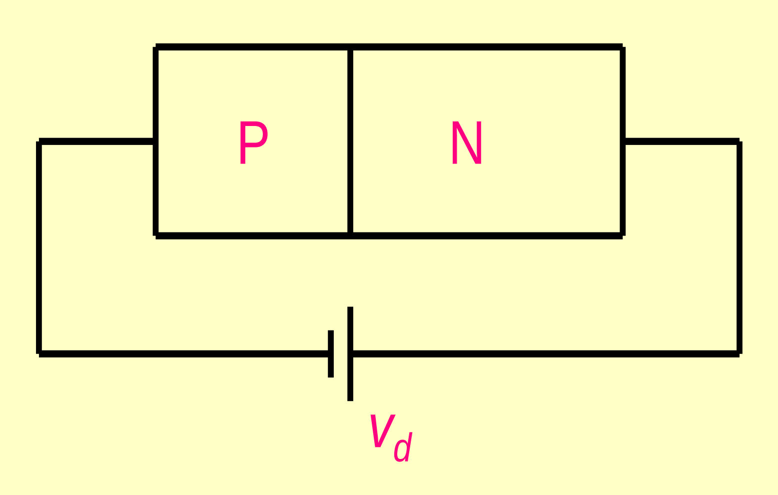
$$v_d >> V_T = 26mV$$

$$i_D \approx I_S \times \exp\left(\frac{v_d}{V_T}\right)$$



Reverse Bias

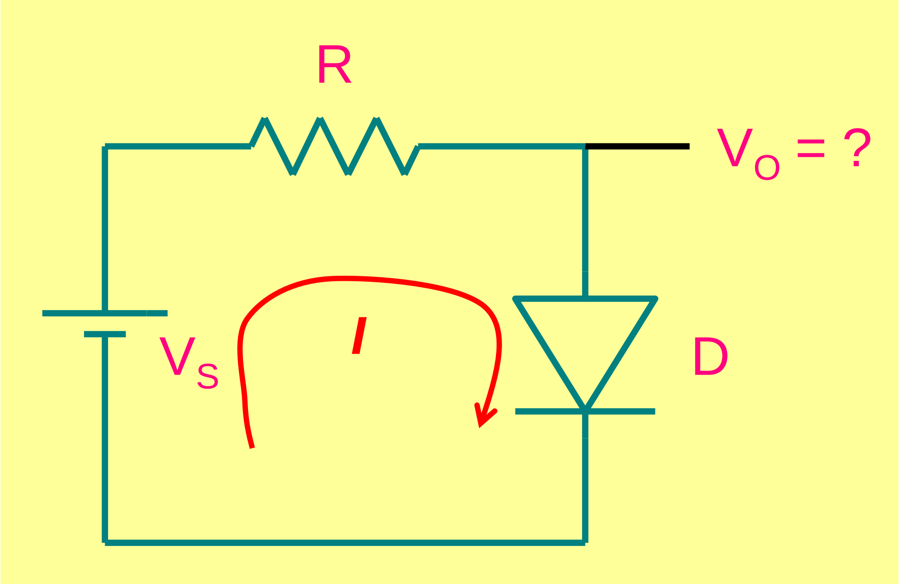
$$I_D = I_S\left(\exp\left(\frac{v_D}{V_T}\right) - 1\right)$$



$$v_d = -v_R \qquad |v_R| >> V_T$$

$$i_D = I_S\left(\exp\left(-\frac{v_R}{V_T}\right) - 1\right) \approx -I_S$$

Analysis



$$V_S = IR + V_D$$

$$I = I_S\left(\exp\left(\frac{V_D}{V_T}\right) - 1\right)$$

2 equations, 2 variables

Numerical methods, graphical method, etc.

- 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.

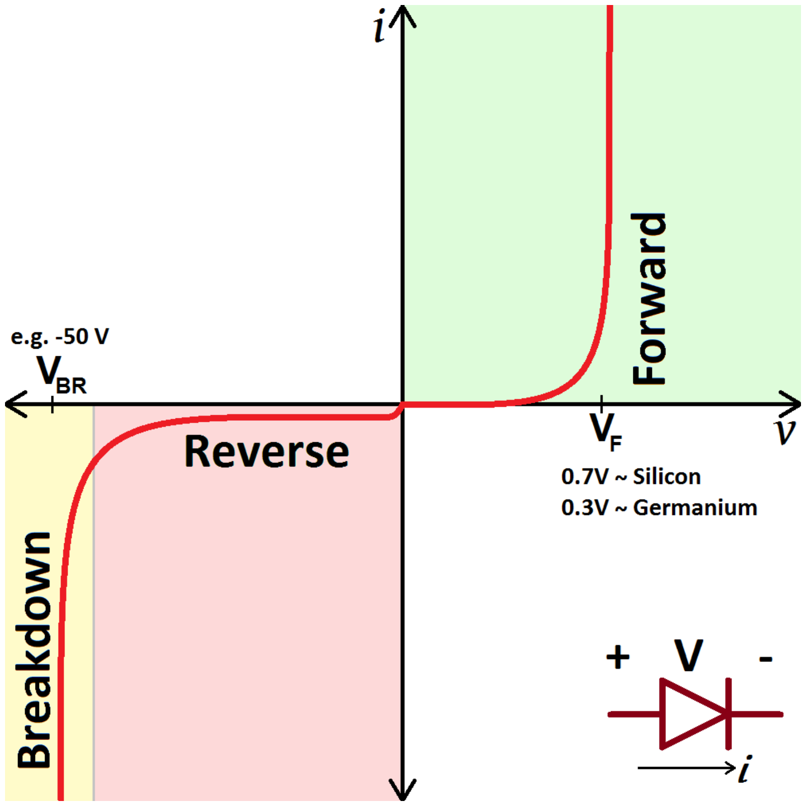
Need SIMPLER and LINEAR Device Models

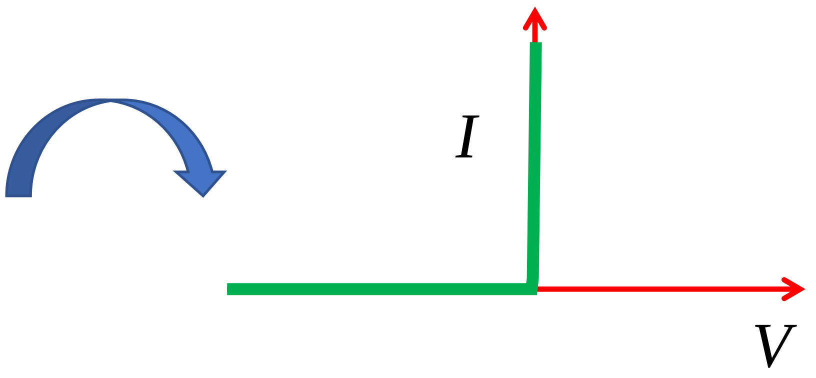
Piecewise Linear Approximation

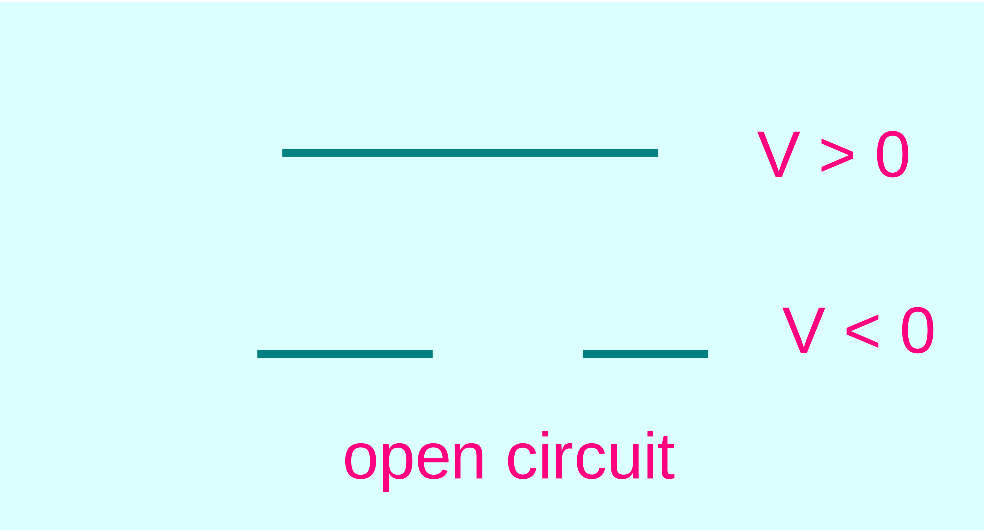
- Diode is clearly a non-linear device
- We can however approximate its behavior with that of a piecewise linear system
- IV graph is made by joining two or more straight lines

Model A: Ideal

- Simplest possible approximation: acts as an ideal valve
- ignore breakdown

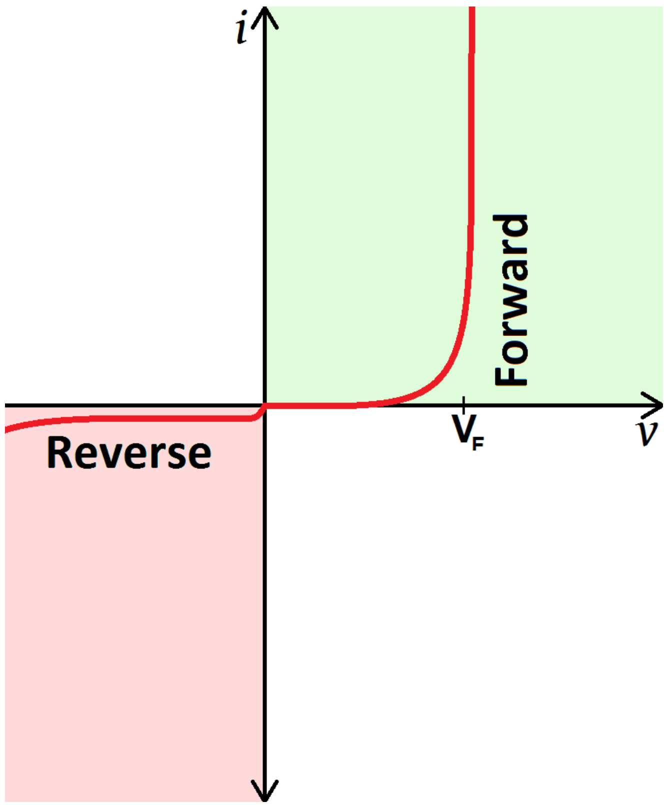


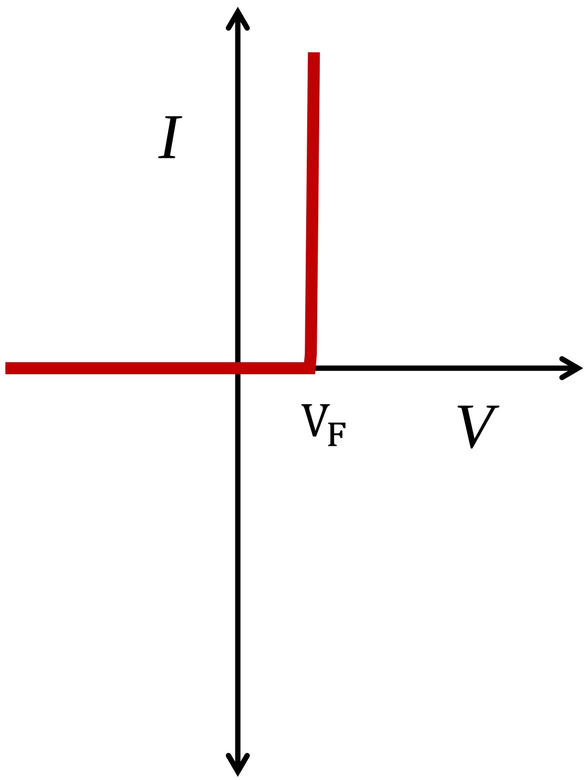


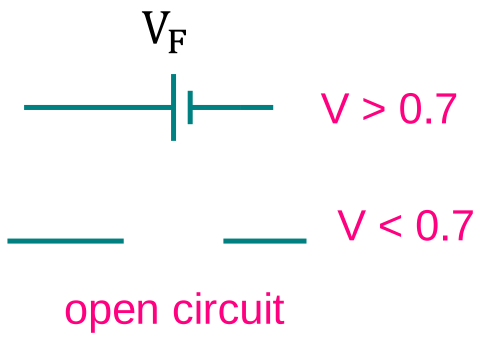


Model B: Constant Voltage Drop

- Simplest possible approximation: acts as an ideal valve with a drop in voltage

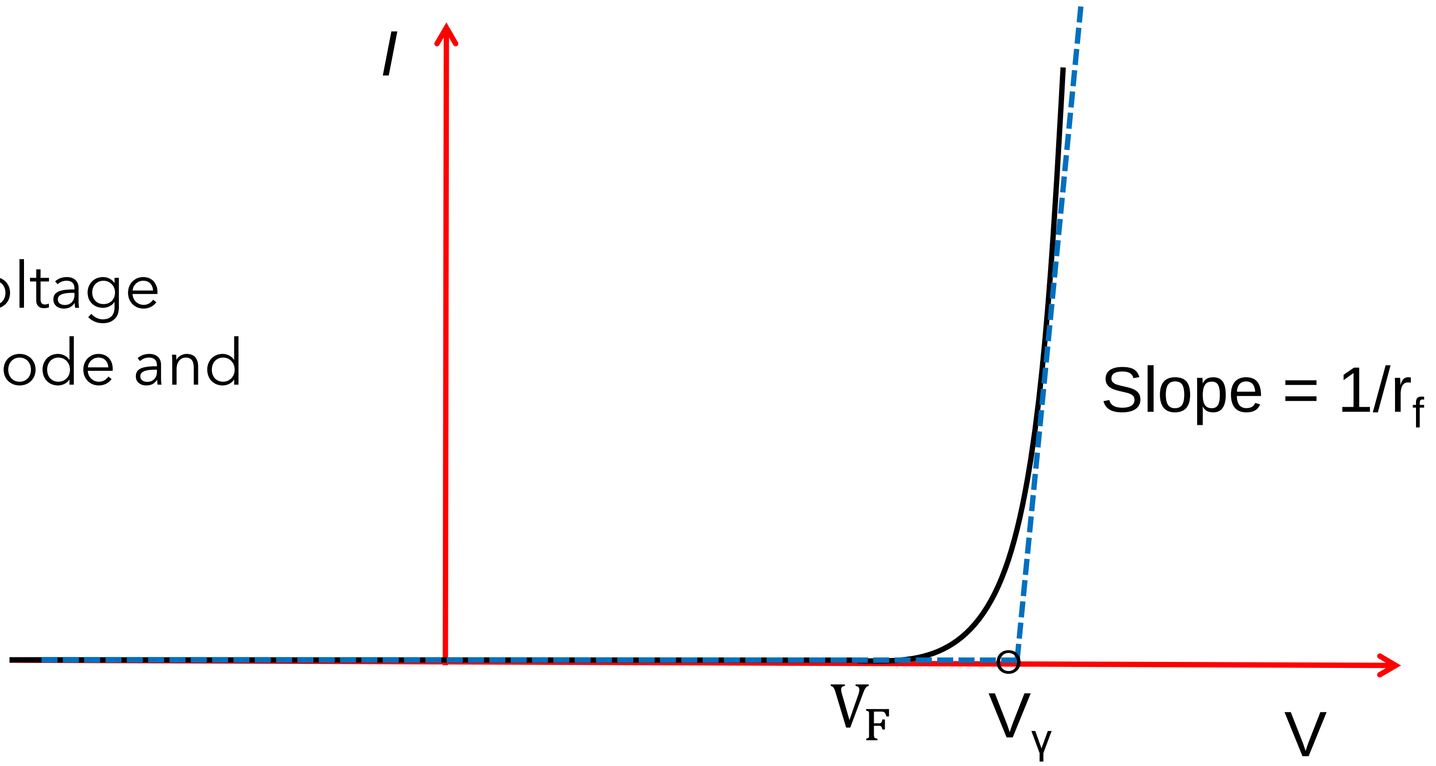






Model C: Piecewise Linear

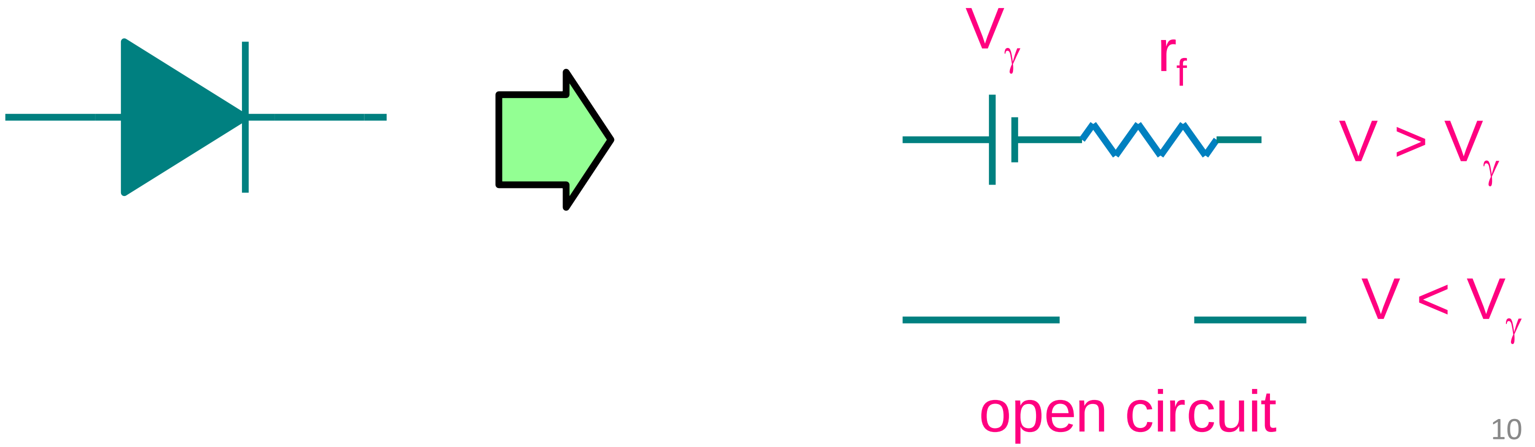
$$V = V_\gamma + I\, r_f$$



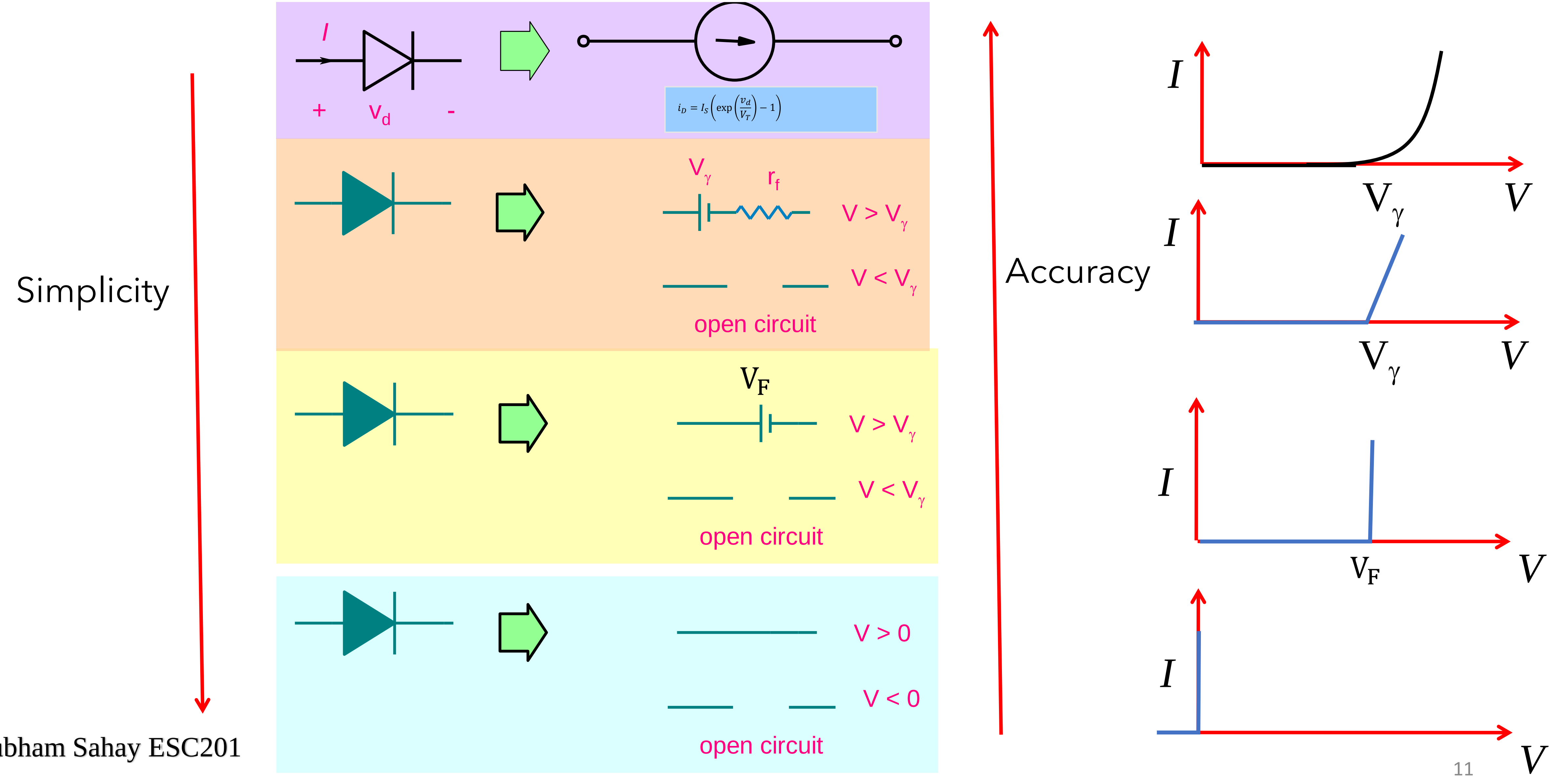
V_γ is called cut-in or turn-n voltage and depends on nature of diode and range of current considered

For example:

V_γ = 0.7V and r_f ~10Ω

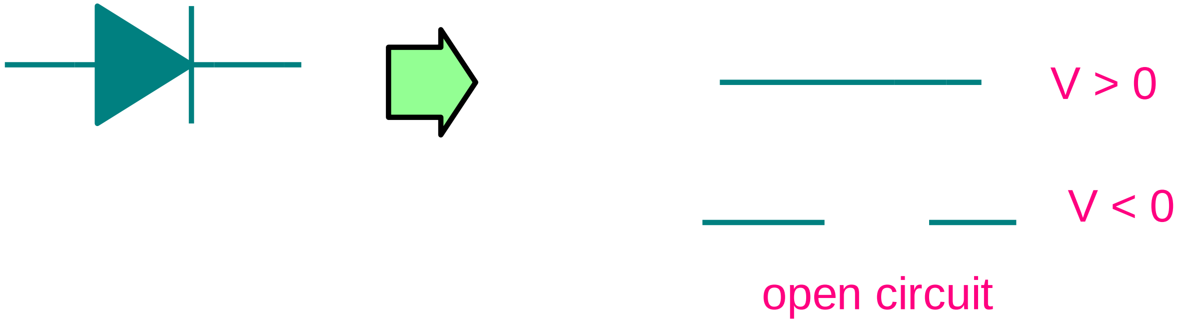


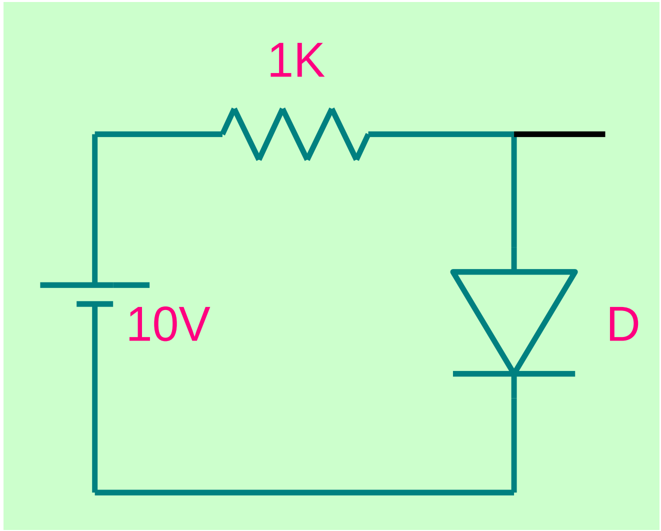
Summary: approximations

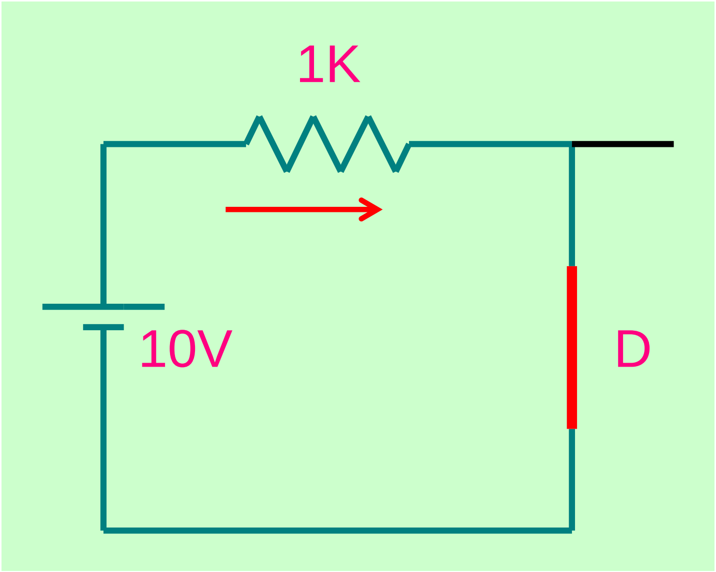


Example 1

Analysis using ideal diode model



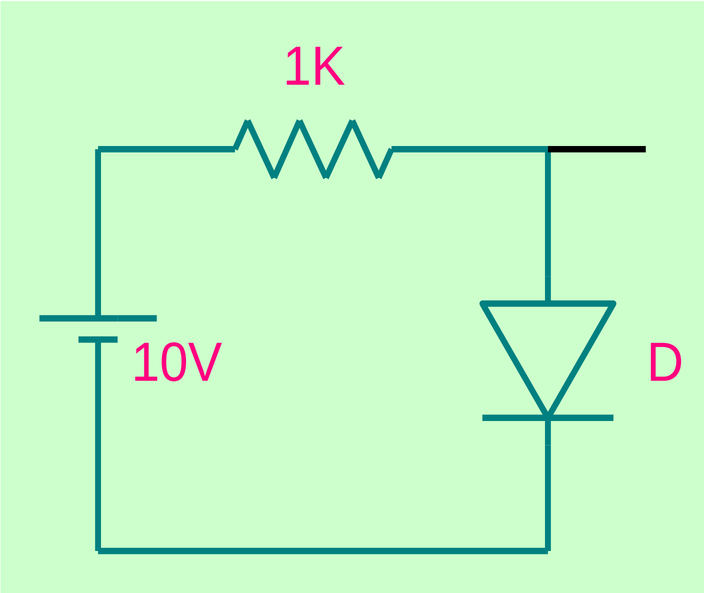


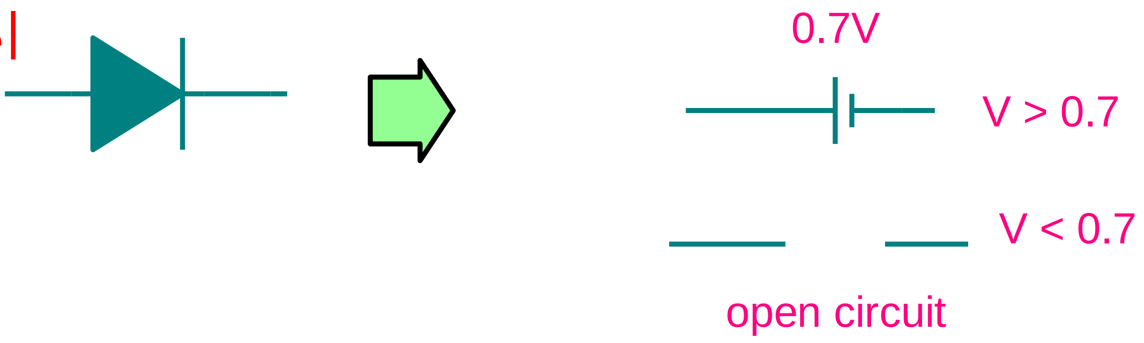


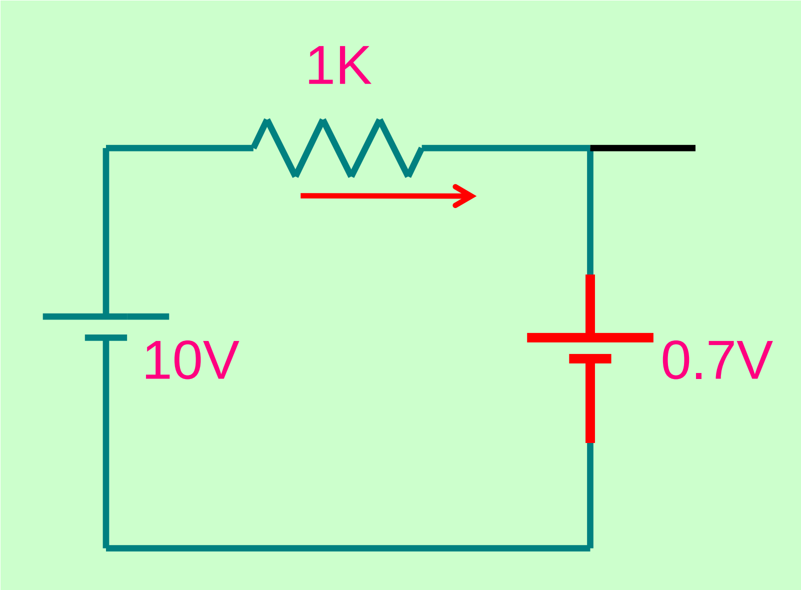
$$I = \frac{10}{1k} = 10mA$$

Example

Analysis with a constant voltage diode model



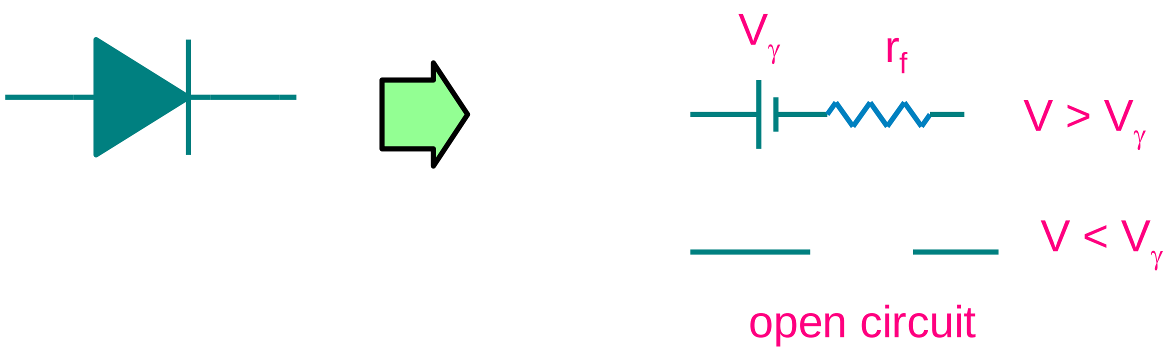


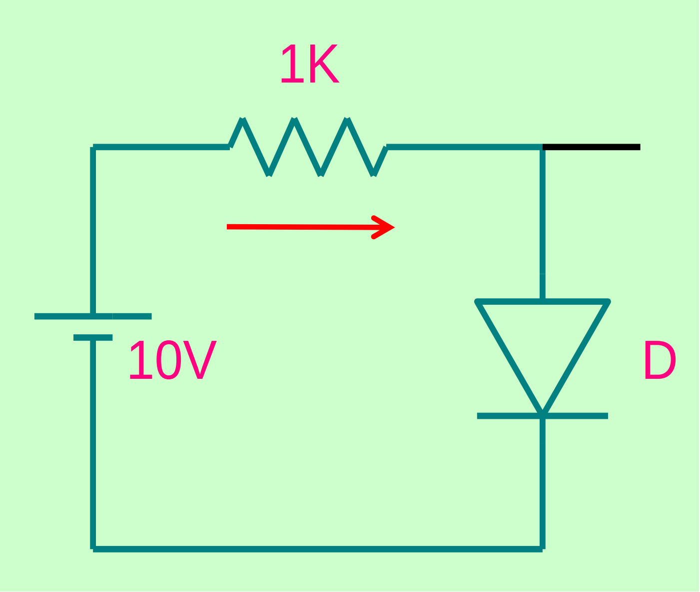


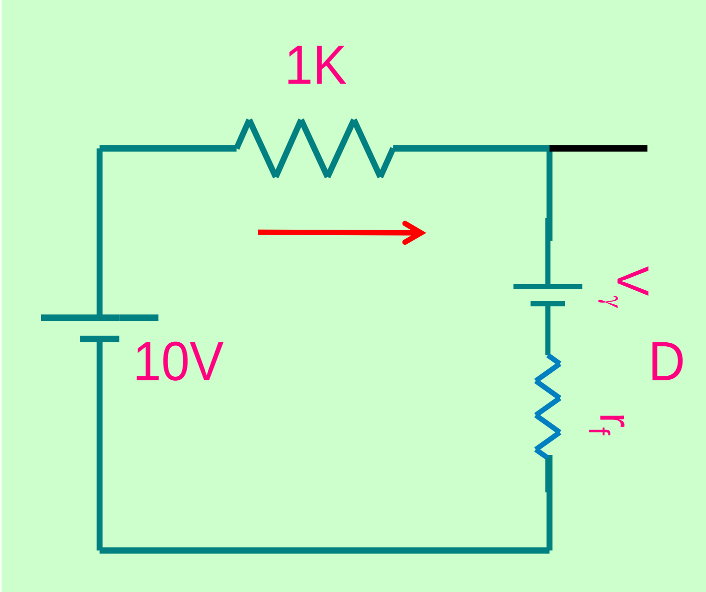
$$I = \frac{10 - 0.7}{1k} = 9.3mA$$

Example

Analysis with a constant voltage plus resistor diode model







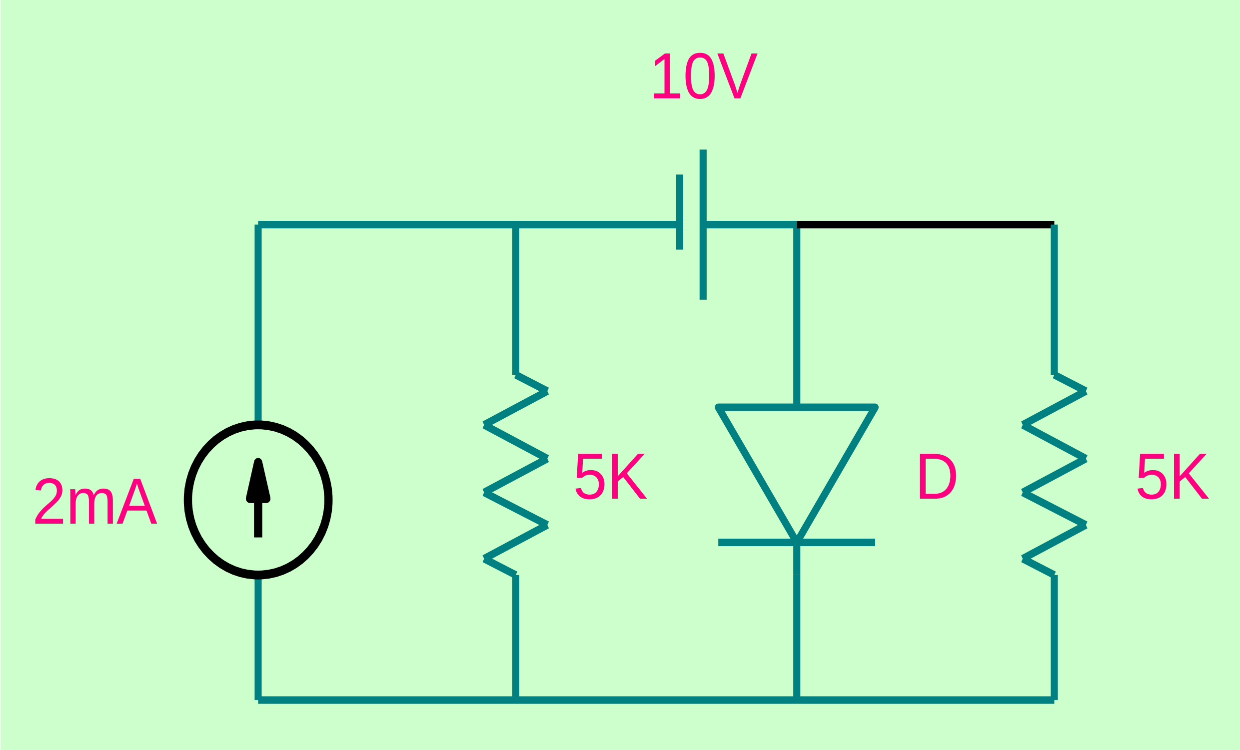
$$I = \frac{10 - 0.7}{1000 + 10} = 9.208mA$$

Analysis: 'assumed' states

- How to know in which state diode is?
  - Easier if the voltage is known.
  - Otherwise
  - Analyze circuit assuming diode is forward biased
    - Check assumption ($I > 0$?)
  - Analyze circuit assuming diode is reverse biased
    - Check assumption ($V < 0$?)
  - Select the consistent one.
- What if 2 diodes: 4 possible circuits, only 1 will be valid
- N diodes => 2^N circuits, only one will be valid

Example 2

Find the current through the 5k resistor 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!!

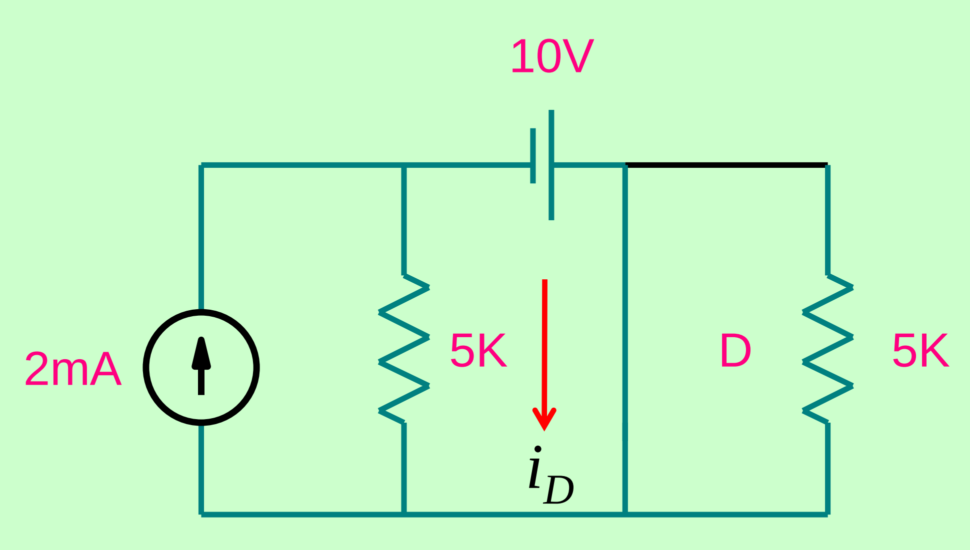
Example 2

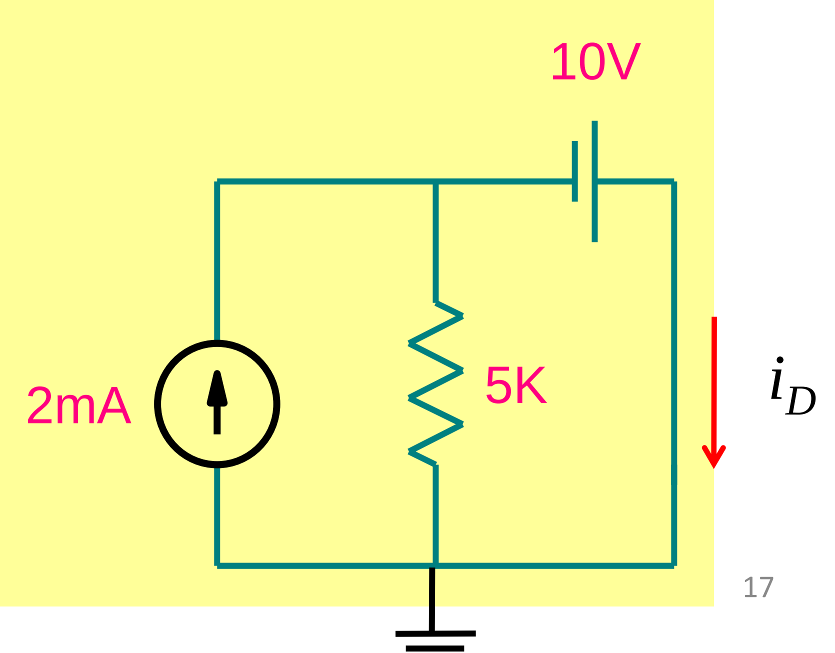
Assume forward bias

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

$$i_D = 4mA$$

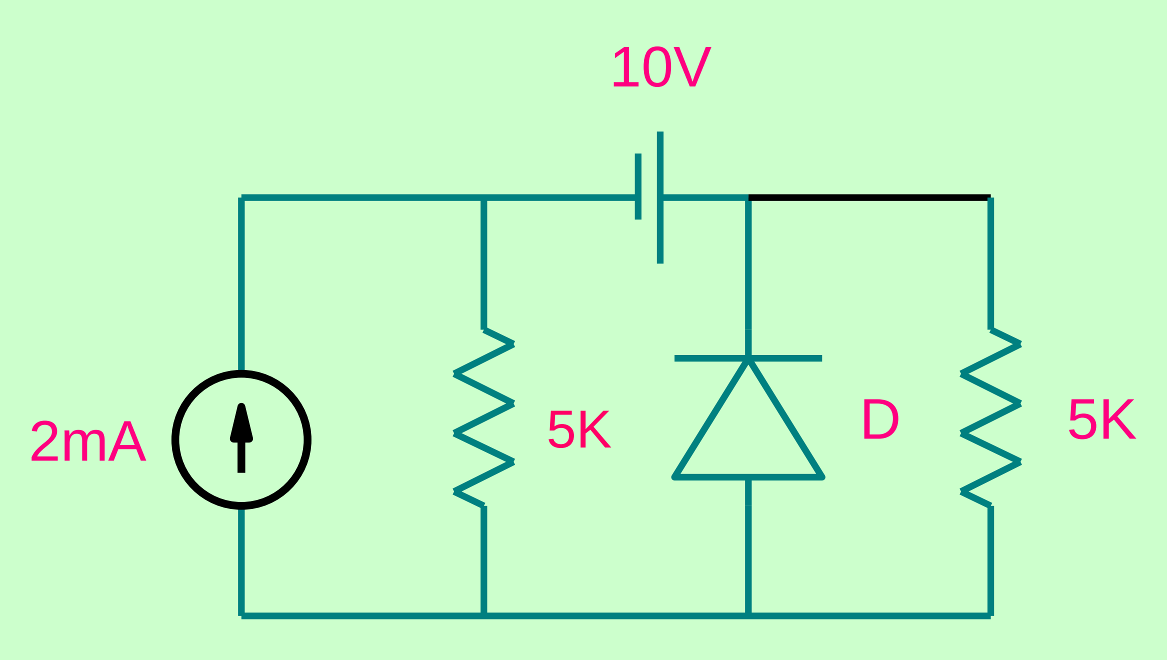
Current is positive, so our assumption is correct



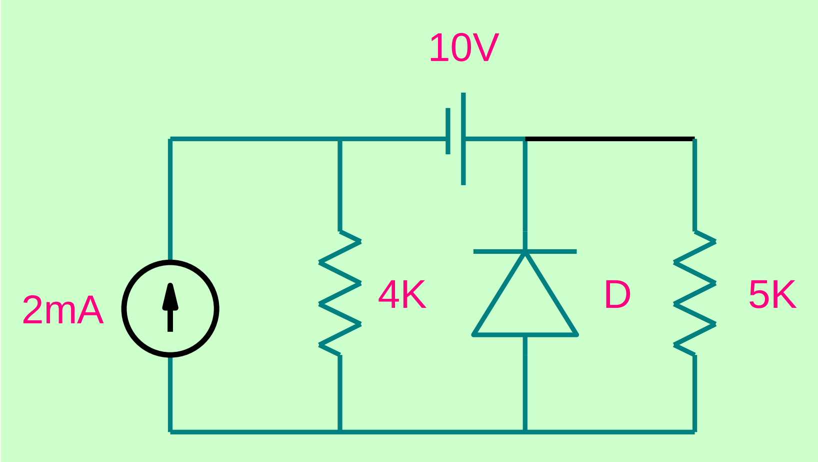


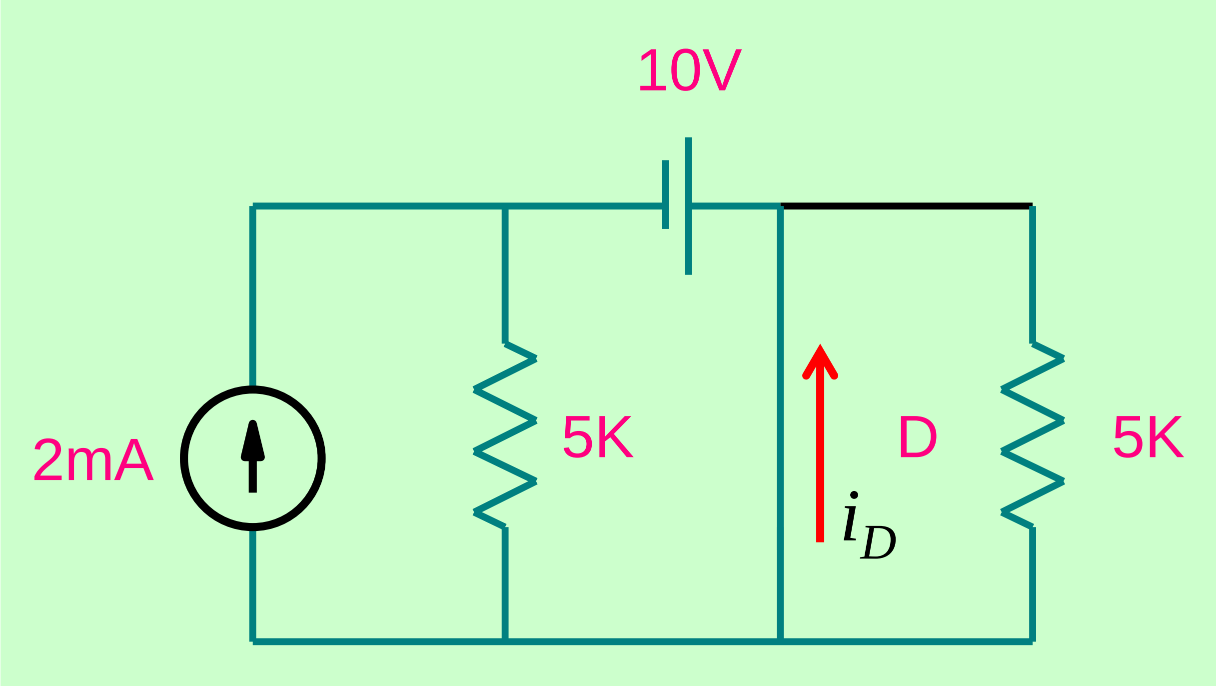
Example 3

Find the current through the 5k resistor using ideal diode model



Example 3





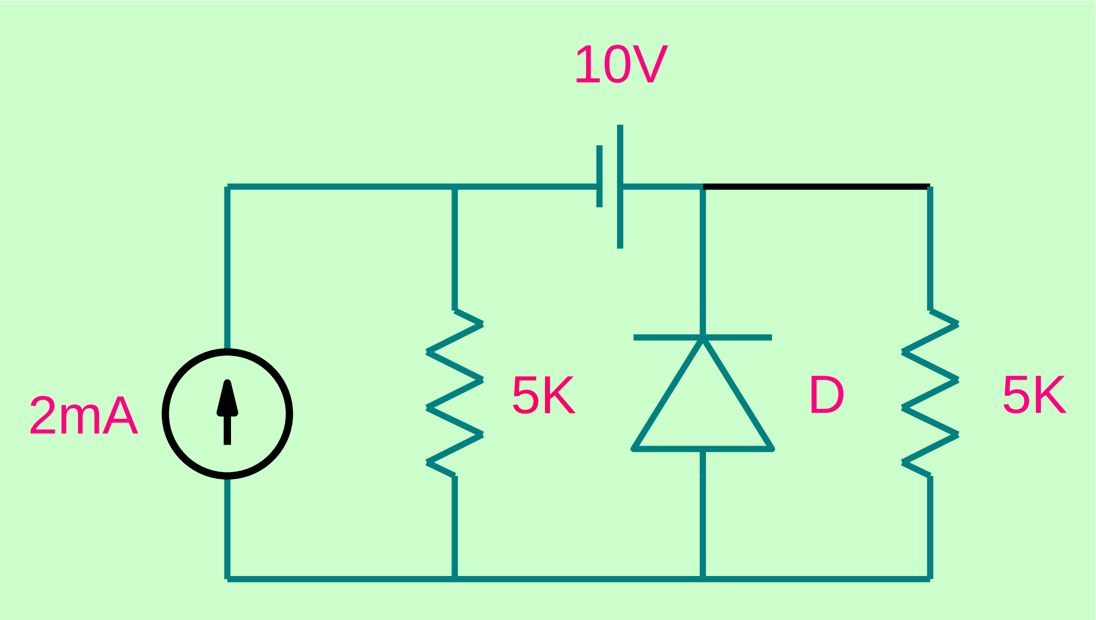
Assume forward bias

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

$$i_D = -4 \quad mA$$

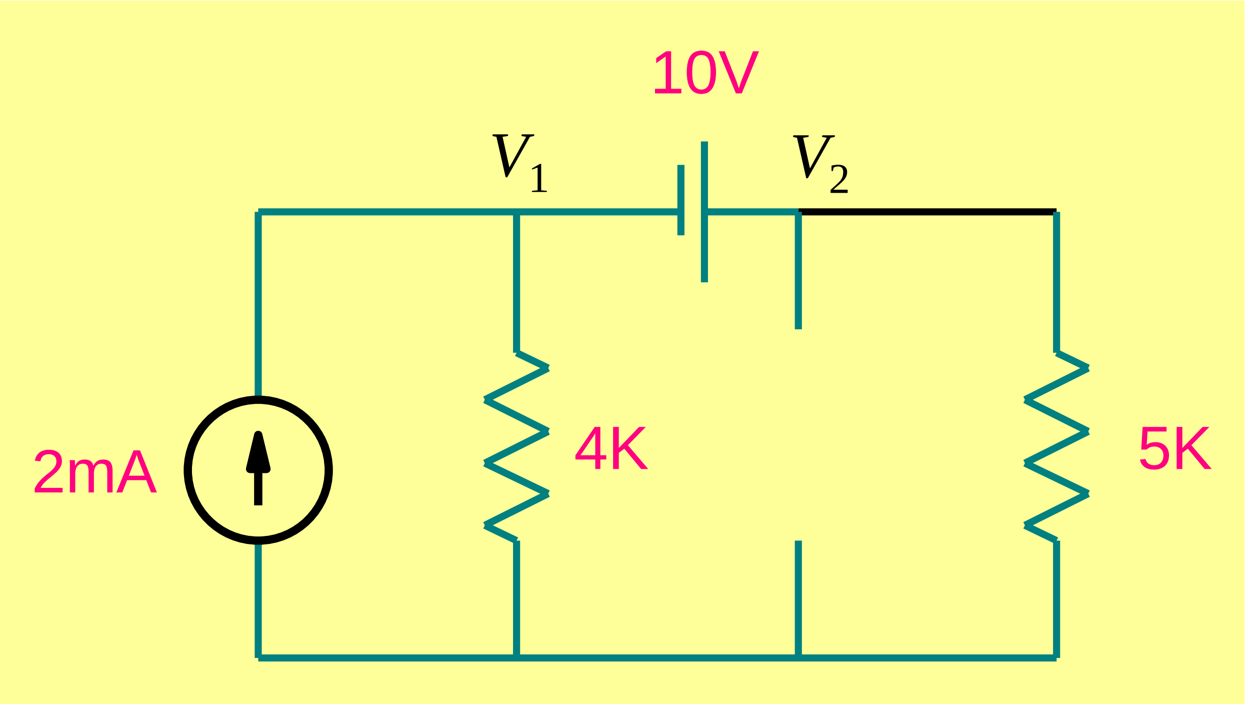
Therefore, our assumption is incorrect

Example



Assume reverse bias

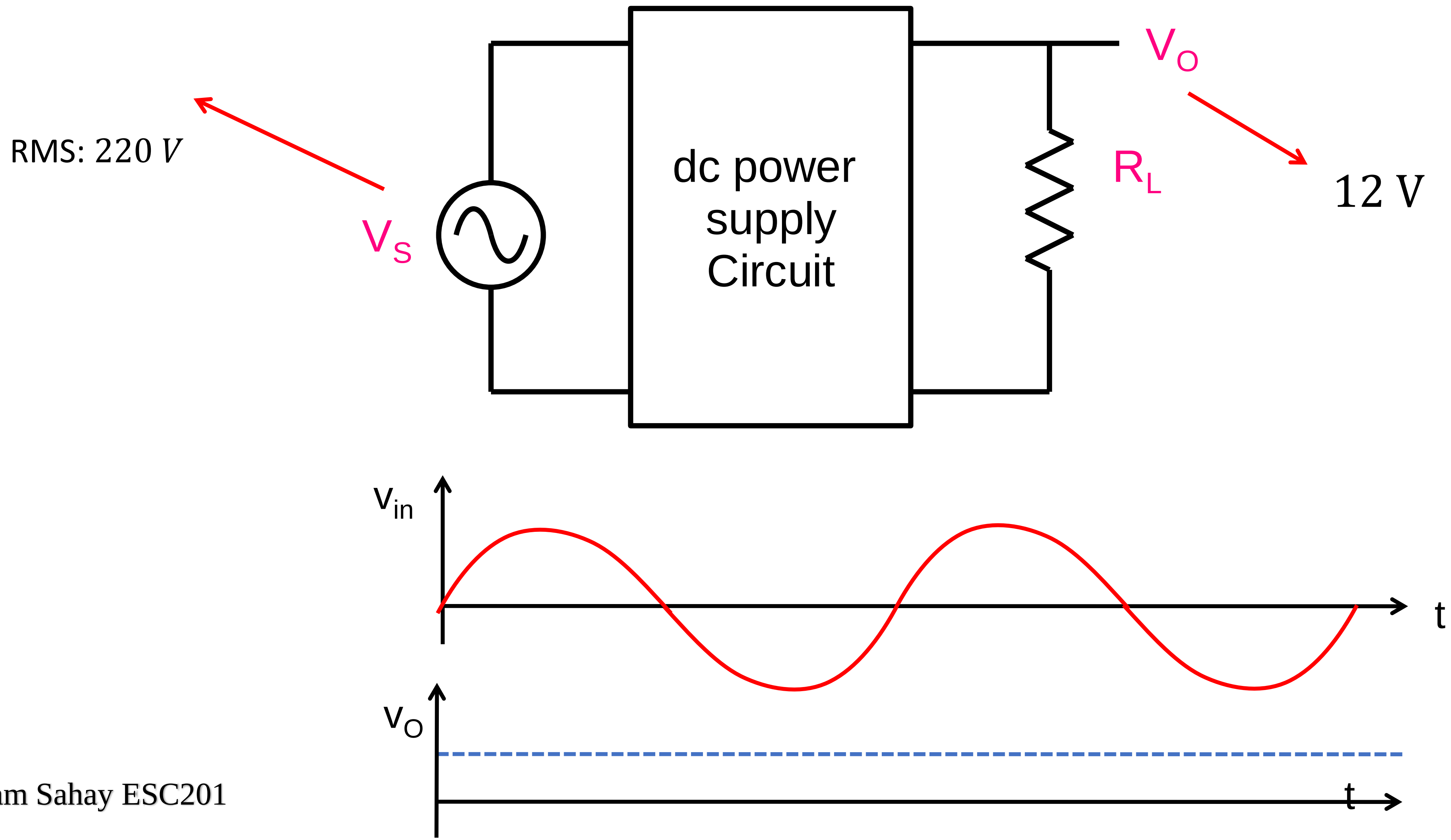
$$-2mA + \frac{V_1}{5k} + \frac{V_1 + 10}{5k} = 0$$
$$V_1 = 0$$
$$V_2 = 10V$$



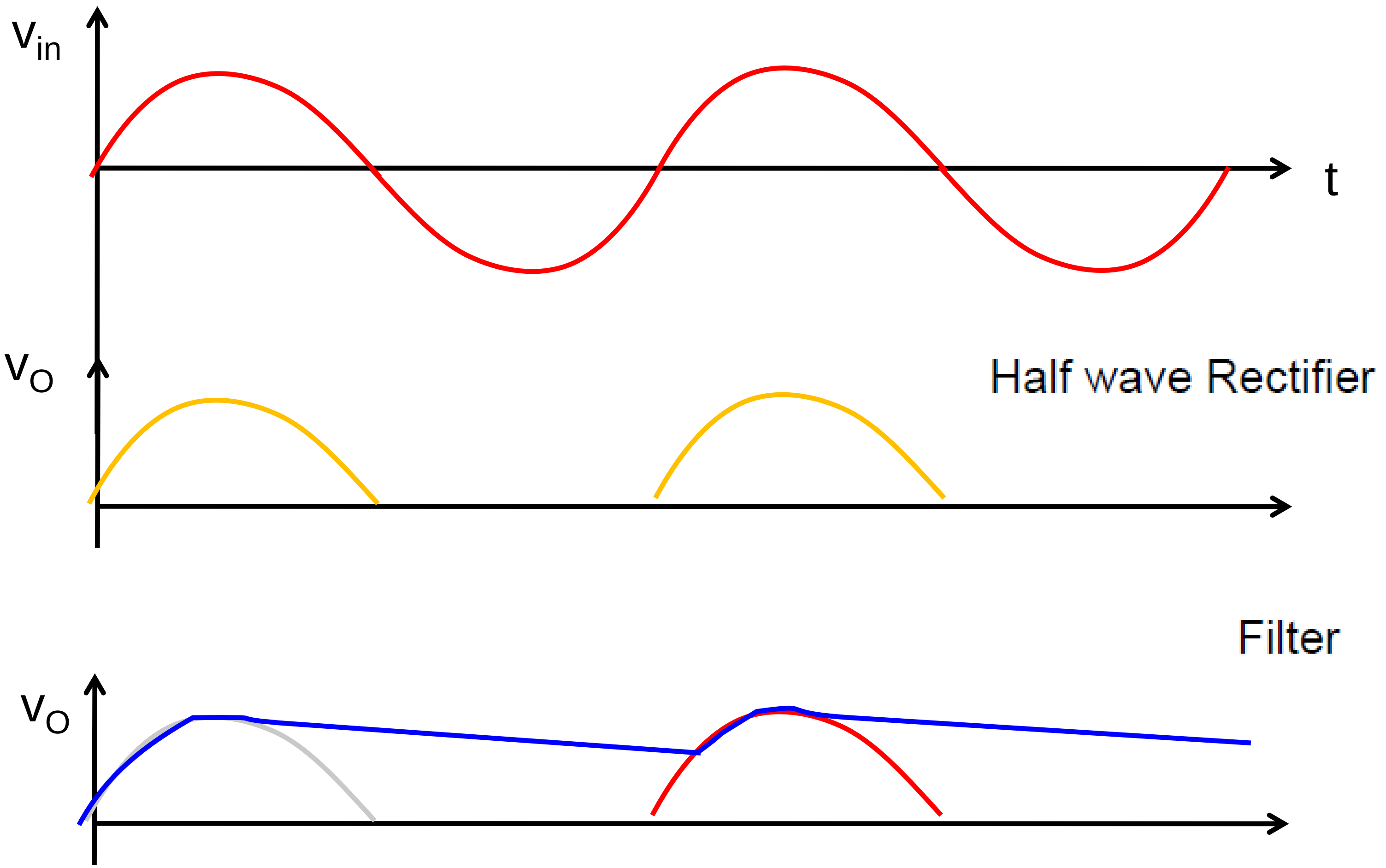
Therefore, our assumption is correct,

$I_{5K} = 2A$

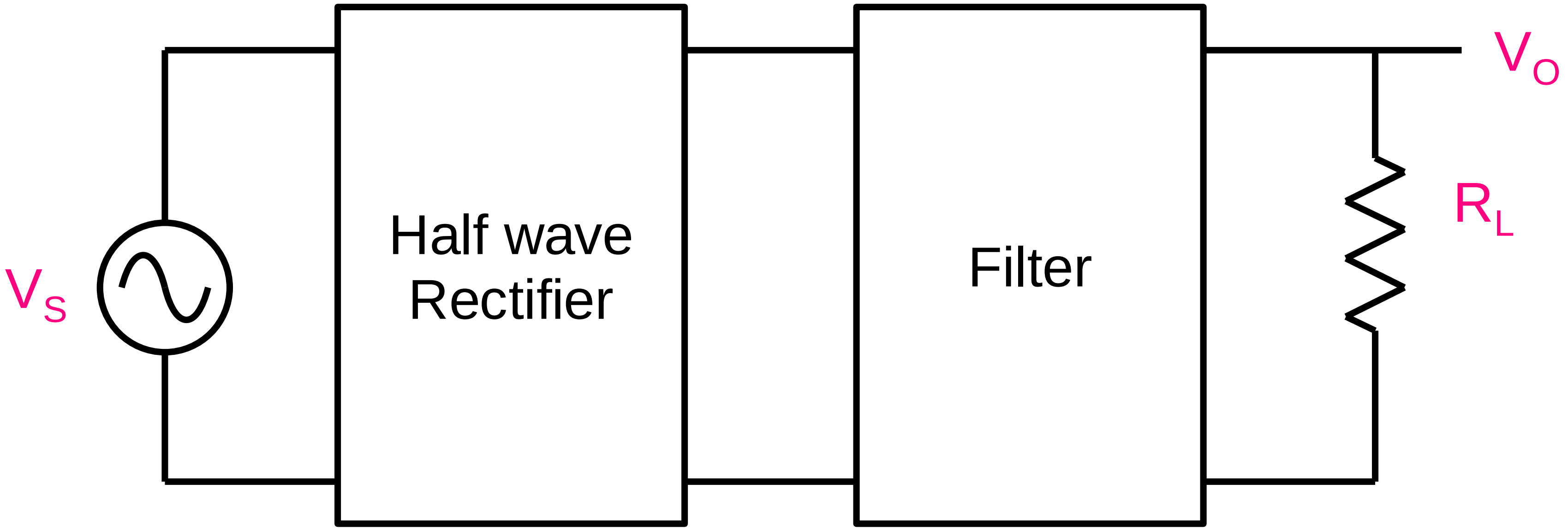
DC power supply



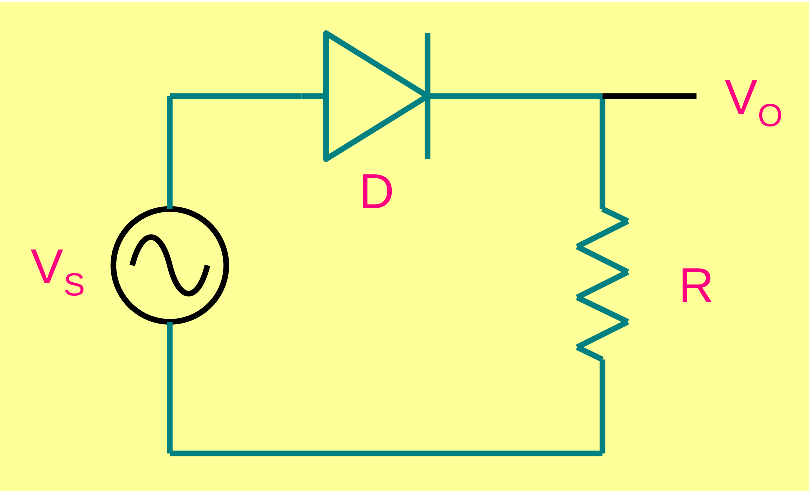
Strategy 1

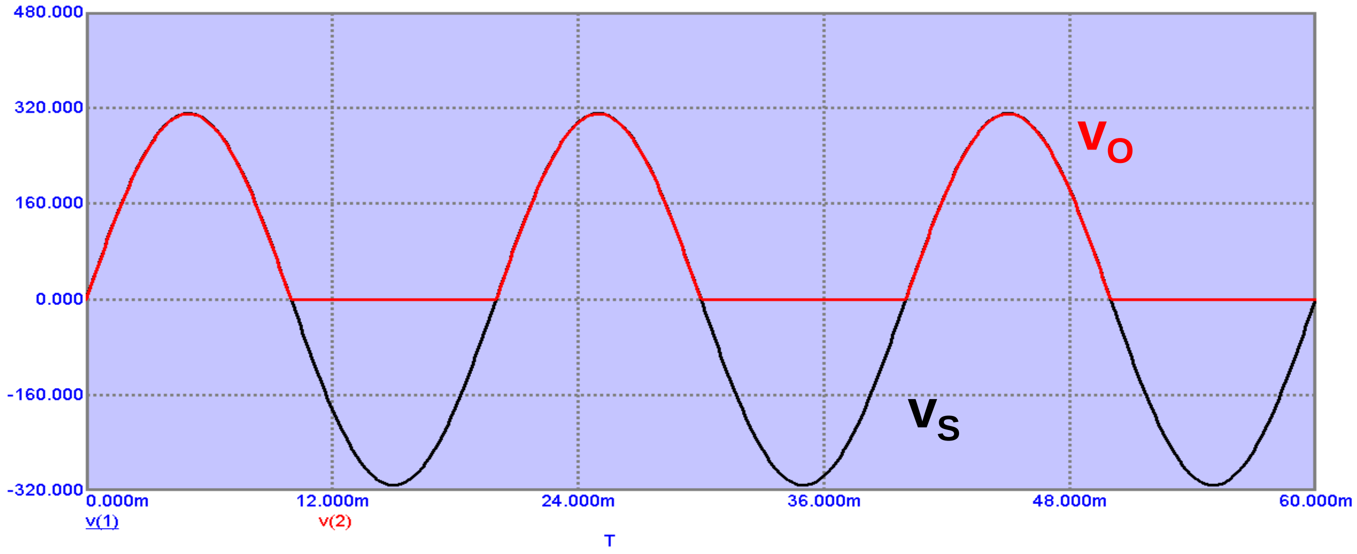


Power supply: block diagram



Half-wave rectifier





RMS: $220\ V$

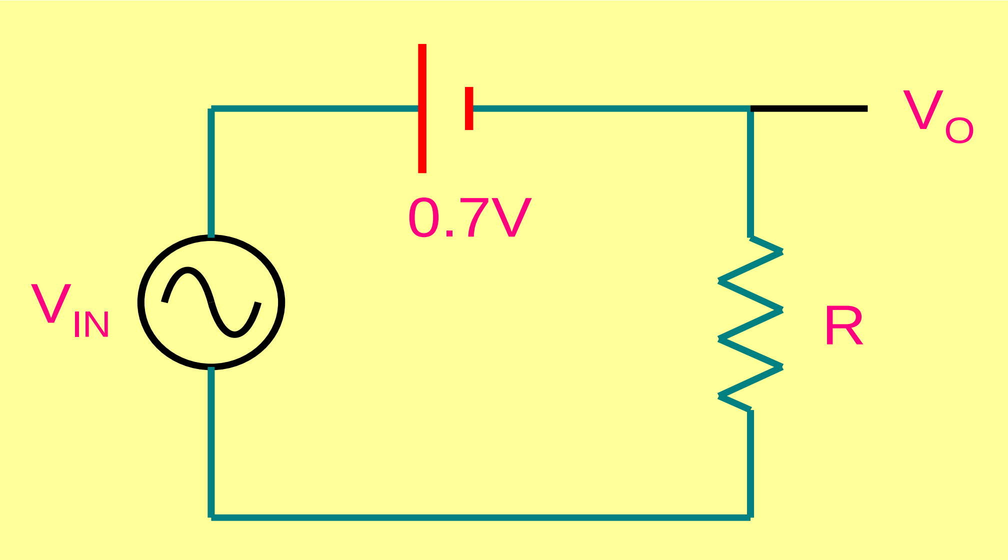
→

Peak value: 311.13

Peak value: $311.1 - 0.7 = 310.4\ V$

Voltage too high!

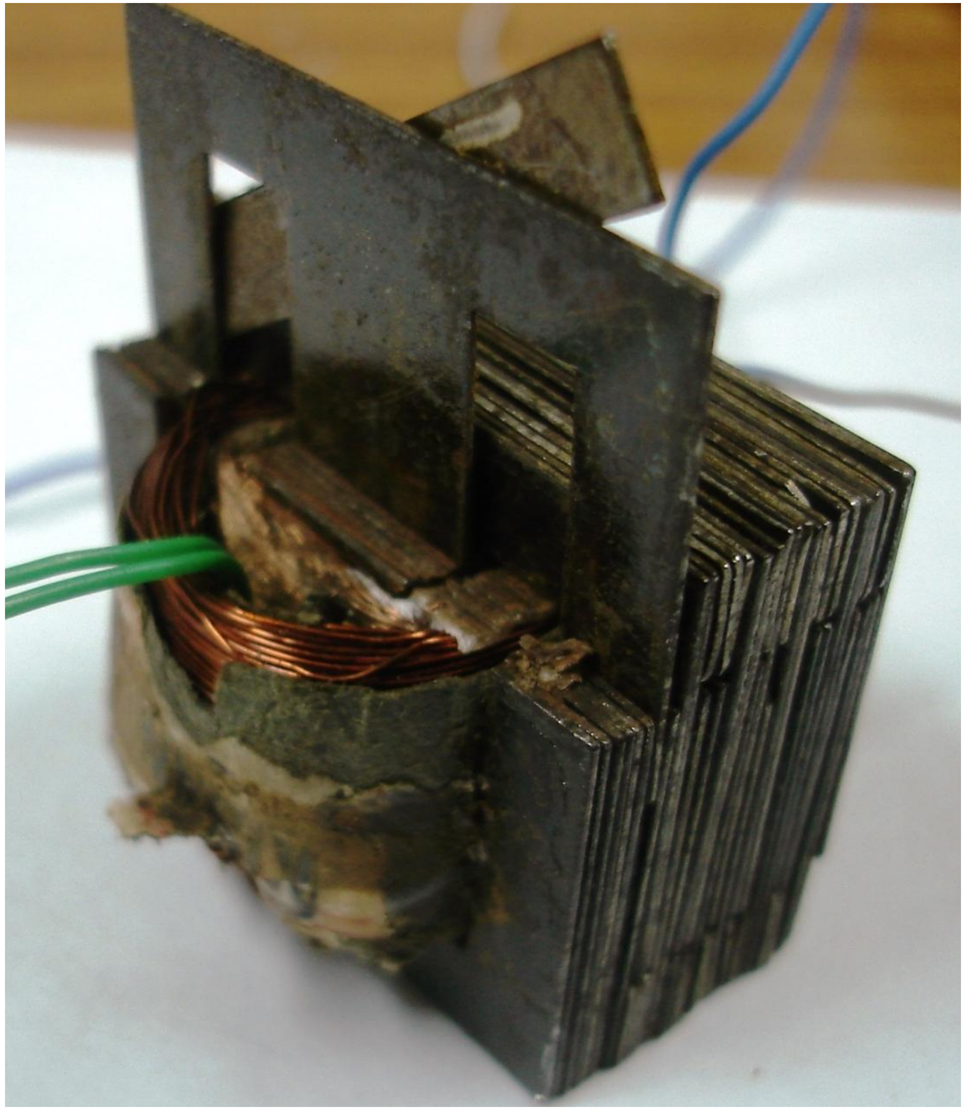
Half-wave rectifier

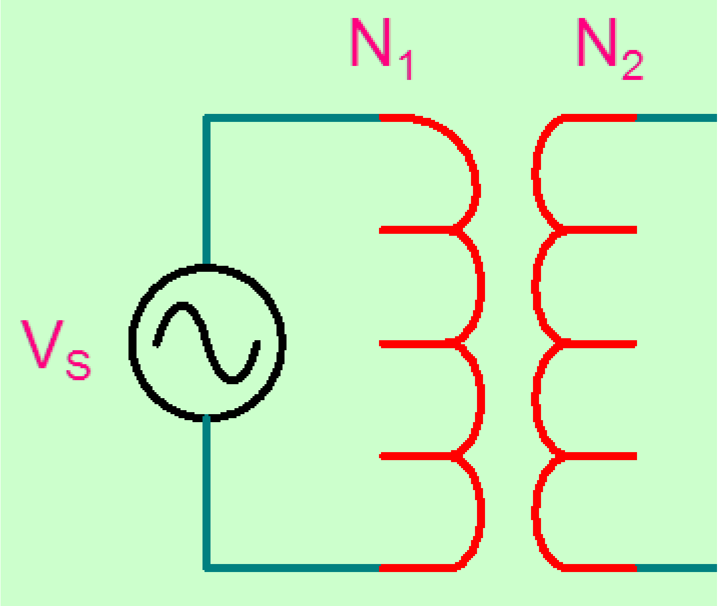


$$V_S = 220V \times \sqrt{2}$$
$$= 311.127V \;\; peak\, value$$

For V_O to be 12V,
the input V_{IN} should be ~12.7V

Step-down transformer

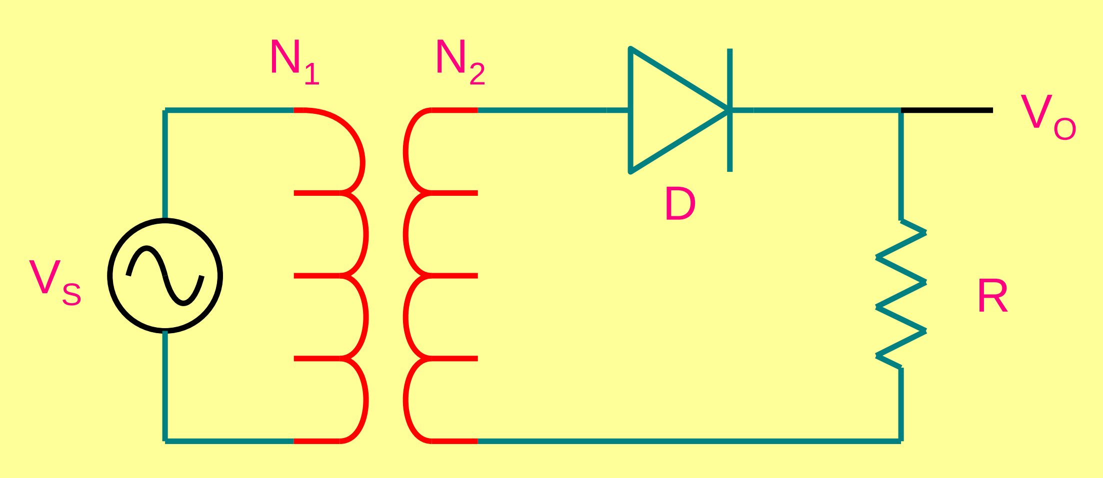


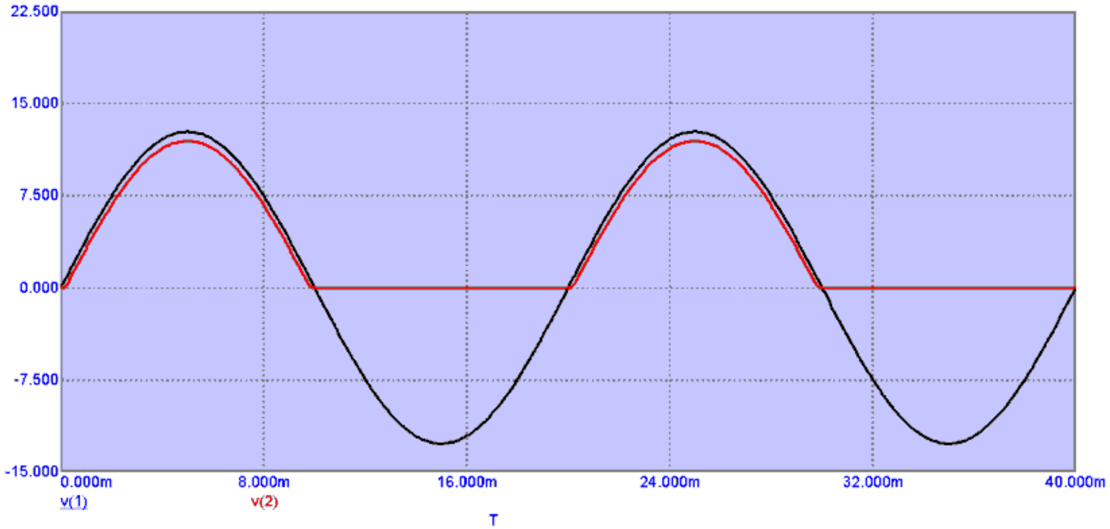


$$\frac{N_1}{N_2} = \frac{311}{12.7} = 24.5$$

$$\frac{V_S}{V_{IN}} = \frac{N_1}{N_2}$$

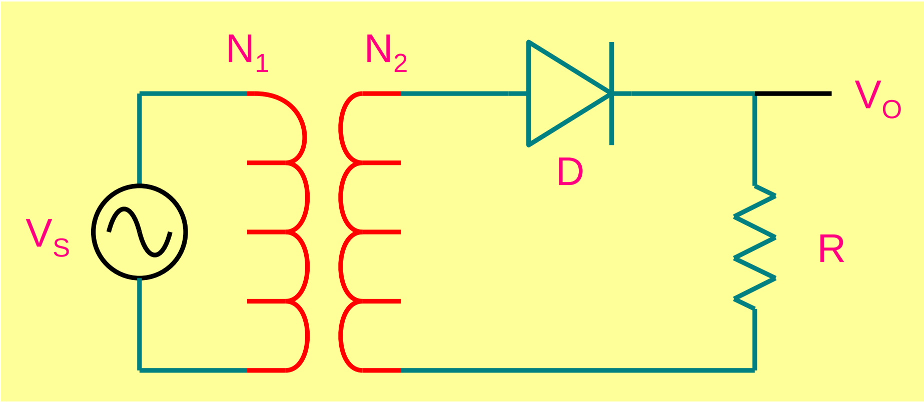
Step 1

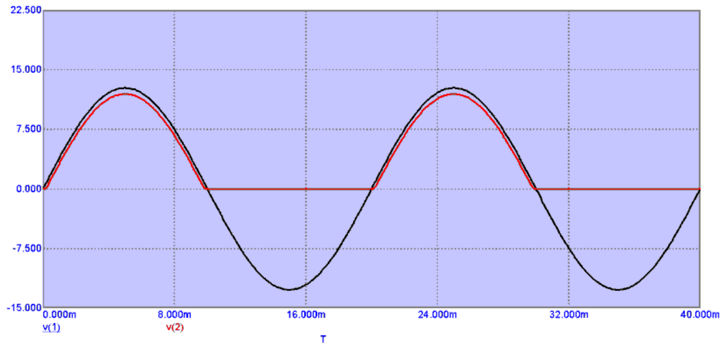




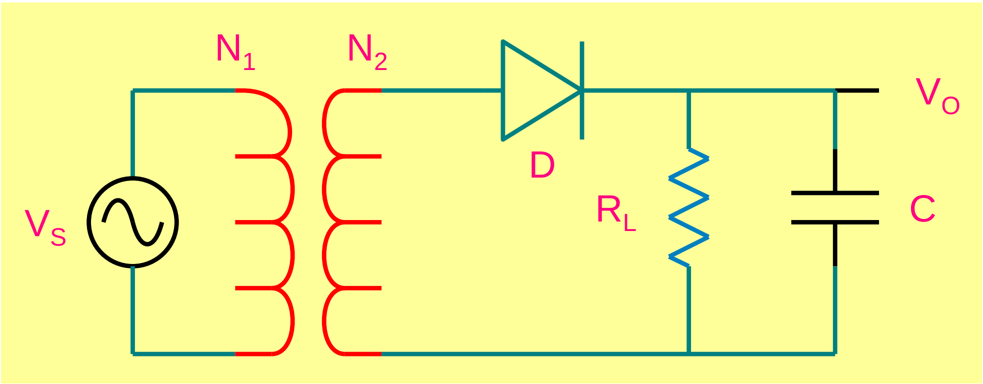
Want to hold that voltage during negative half cycle

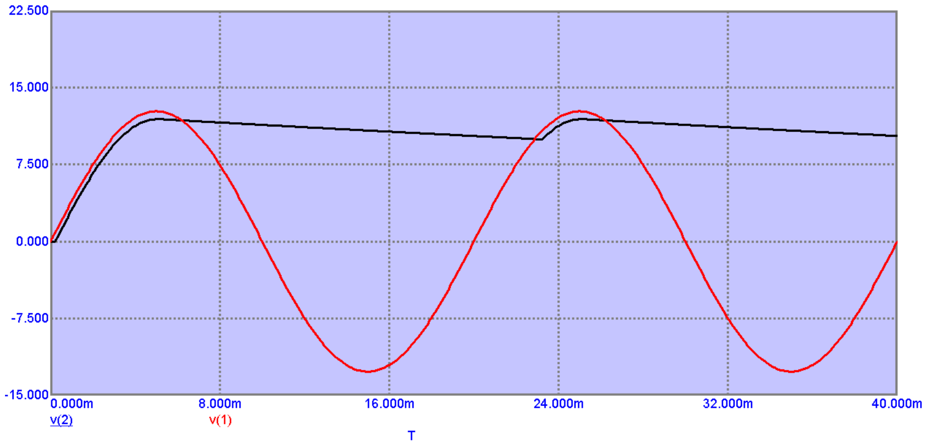
Filtering



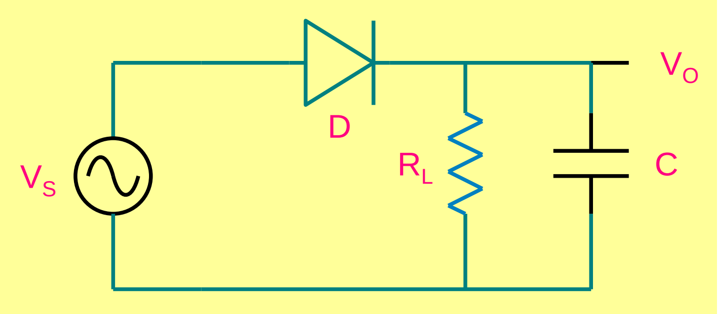


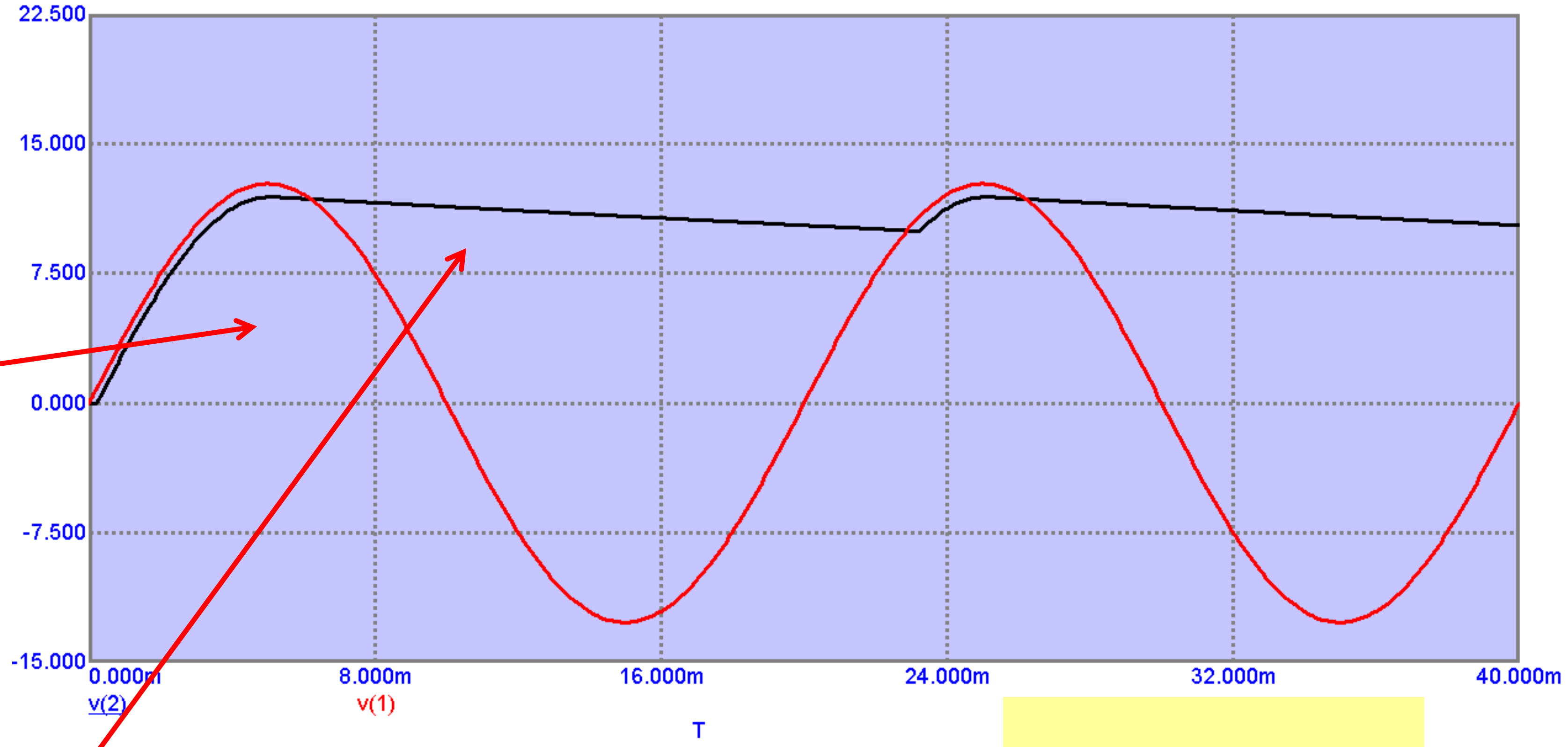
Want to hold that voltage during negative half cycle





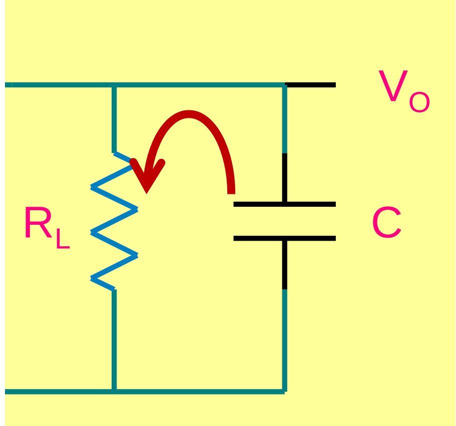
Filtered output





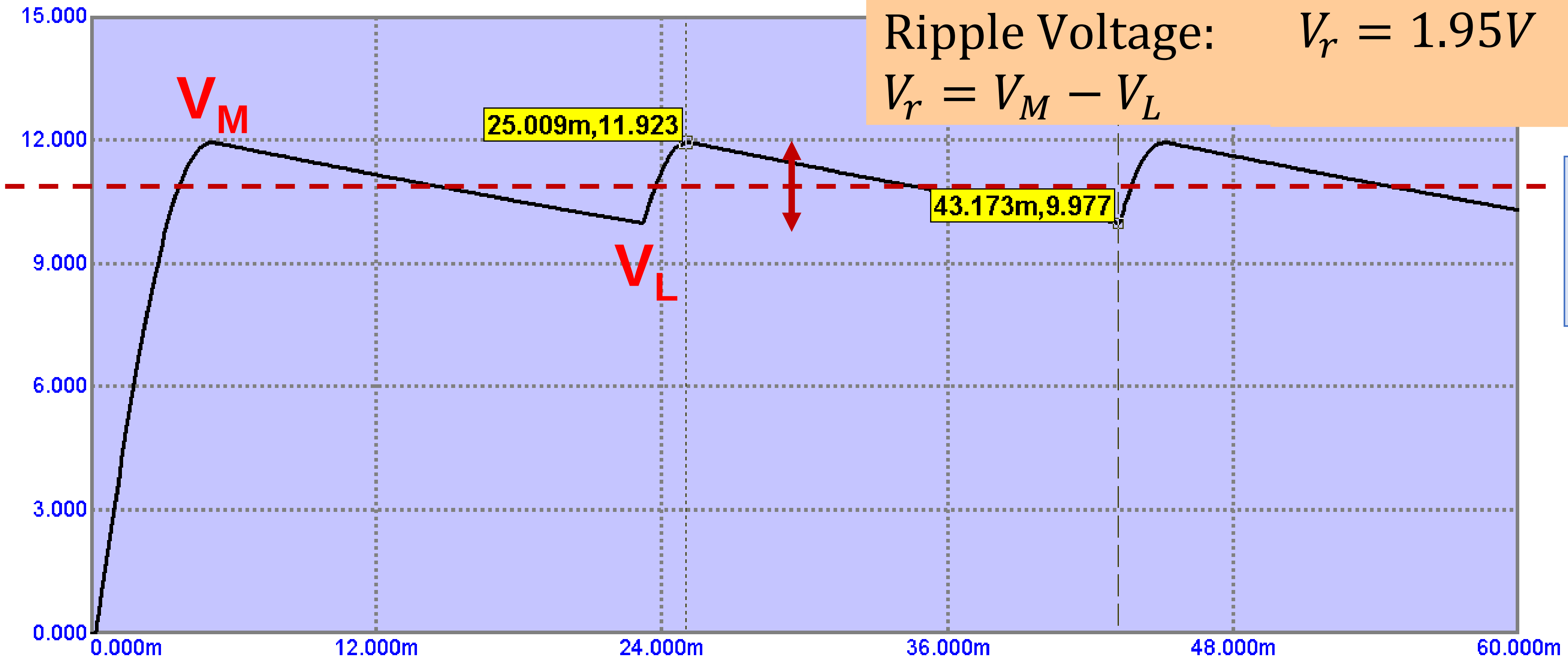
Diode is forward biased

Diode is reverse biased



$R_L C$ should be high.

Output has a ripple



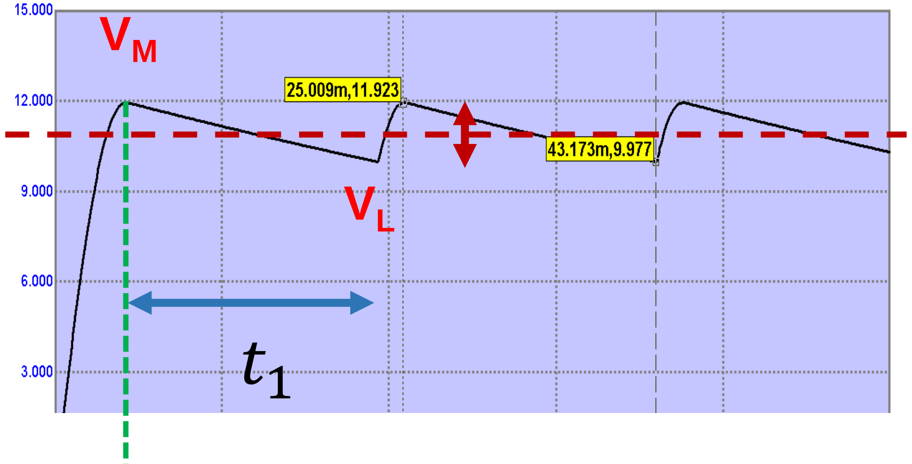
Ripple Voltage: $V_r = 1.95V$

$V_r = V_M - V_L$

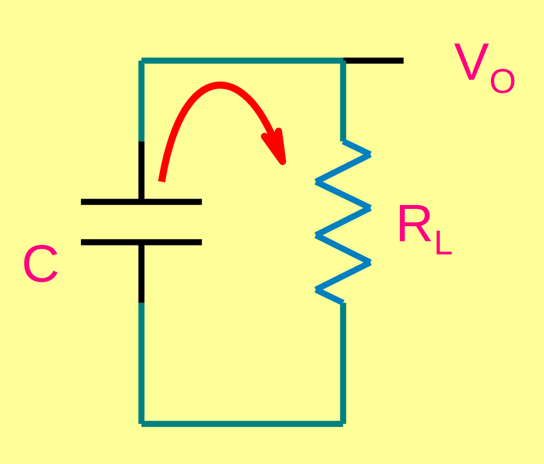
Average Output Voltage :

$$V_O(avg) \cong V_M - \frac{V_R}{2}$$

Approximate ripple calculation



$t = 0$



Ripple Voltage:
$V_r = V_M - V_L$

$$V_r = V_M \times \left(1 - e^{-\frac{t_1}{R_L C}}\right)$$

- Capacitor discharges from V_M to V_L
- Recall: $v_C(t) = v_C(\infty) + \left(v_C(0^+) - v_C(\infty)\right)e^{-\frac{t}{RC}}$

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

- Suppose it discharges for time t_1

$$V_L = V_M \times e^{-\frac{t_1}{R_L C}}$$

Design circuit such that $t_1 \ll R_L C$

$$V_r \cong V_M \times \left\{1 - \left(1 - \frac{t_1}{R_L C}\right)\right\}$$
$$= \frac{V_M t_1}{R_L C}$$

$t_1 \approx T$

$$V_r \approx \frac{V_M T}{R_L C}$$