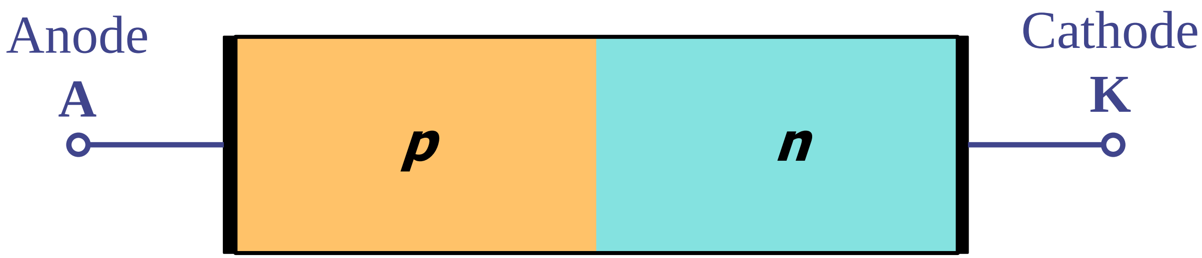
Diodes

Structure. Symbol

Diode - semiconductor device

Physical structure



The ***pn* junction** - an interface between two types of semiconductor materials, *p*-type and *n*-type.

In the outer shells of the electrically neutral atoms:

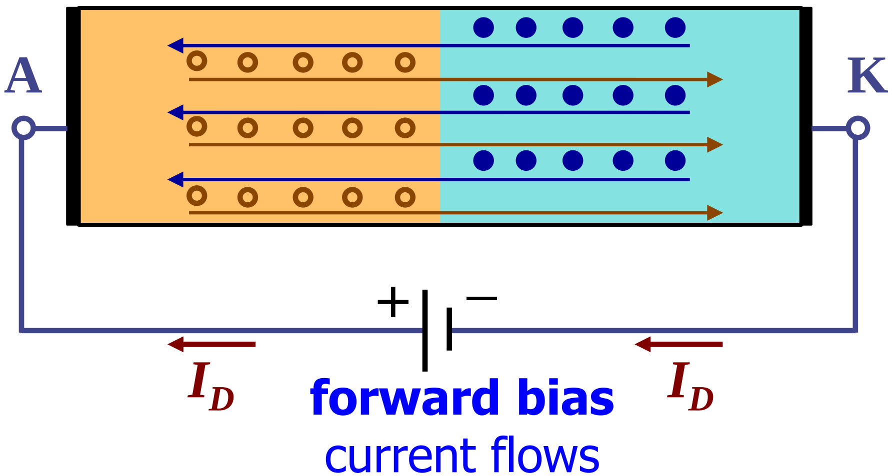
- the *p* (positive) side contains an excess of holes (positive charges)
- the *n* (negative) side contains an excess of electrons (negative charges)

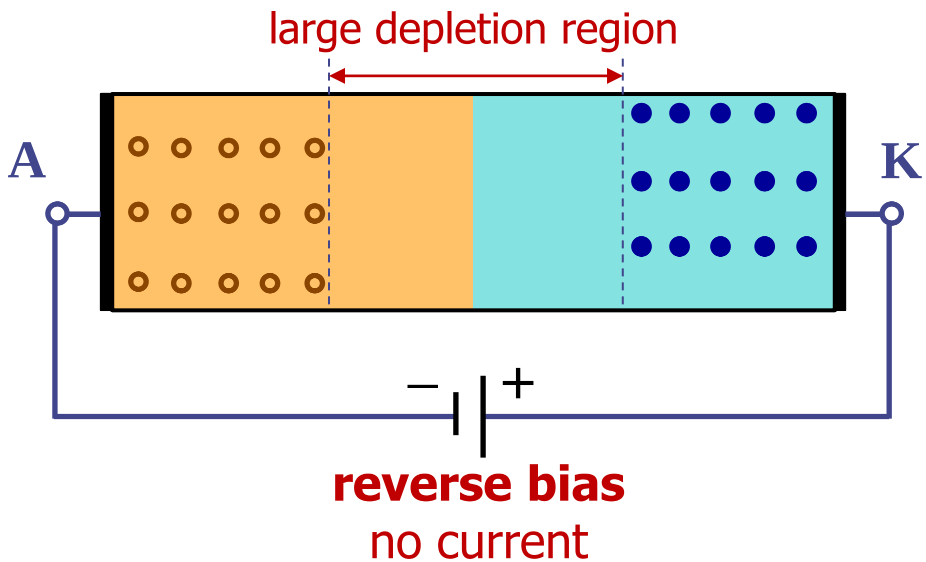
The *pn* junction is created by **doping**:

- ✓ *p*-type doping - an intrinsic semiconductor (e.g. Si) is doped with acceptor impurities (column 3 in the periodic table → excess of holes
- ✓ *n*-type doping - an intrinsic semiconductor (e.g. Si) is doped with donor impurities (column 5 in the periodic table → excess of electrons

A *pn* junction diode allows electric charges to flow only in one direction:

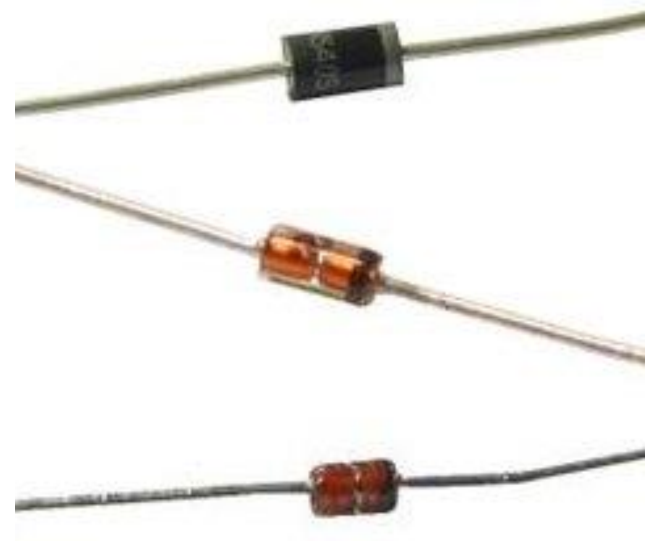
- negative charges (electrons) can flow through the junction from *n* to *p* but not from *p* to *n*,
- positive charges (holes) can flow through the junction from *n* to *p* but not from *p* to *n*,



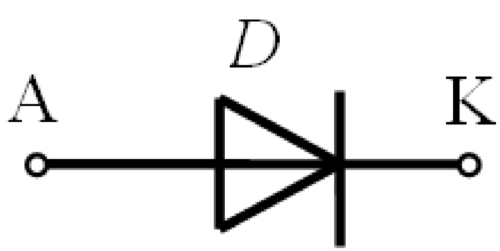


When the *pn* junction is forward-biased, electric charge flows freely due to reduced resistance of the *pn* junction.

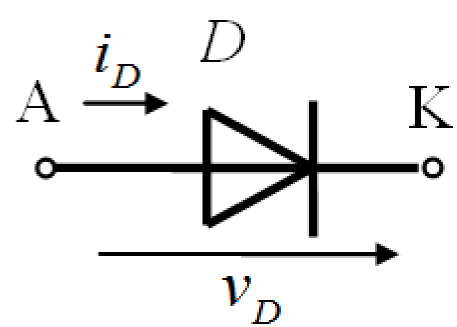
When the p–n junction is reverse-biased, the junction barrier (and therefore resistance) becomes greater and charge flow is minimal (zero).



Circuit symbol



Positive directions for current and voltage



The arrow in the diode’s symbol points in the direction of forward current flow

Current – voltage characteristic

The current flowing through the diode is controlled by the voltage drop across the diode itself – **nonlinear semiconductor device**

Shockley diode equation (diffusion equation)

$$\boxed{i_D = I_S\left(e^{\frac{v_D}{nV_T}} - 1\right) \approx I_S e^{\frac{v_D}{nV_T}}}$$

i_D depends exponentialy on v_D

I_S - saturation current (~ nA - pA)
depends on temperature

$$V_T = \frac{KT}{q}$$

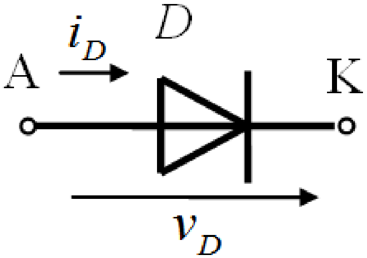
thermal voltage (*depends on temperature*)

$V_T = 25\text{mV} \ @ \ 20^{\text{O}}\text{C}$

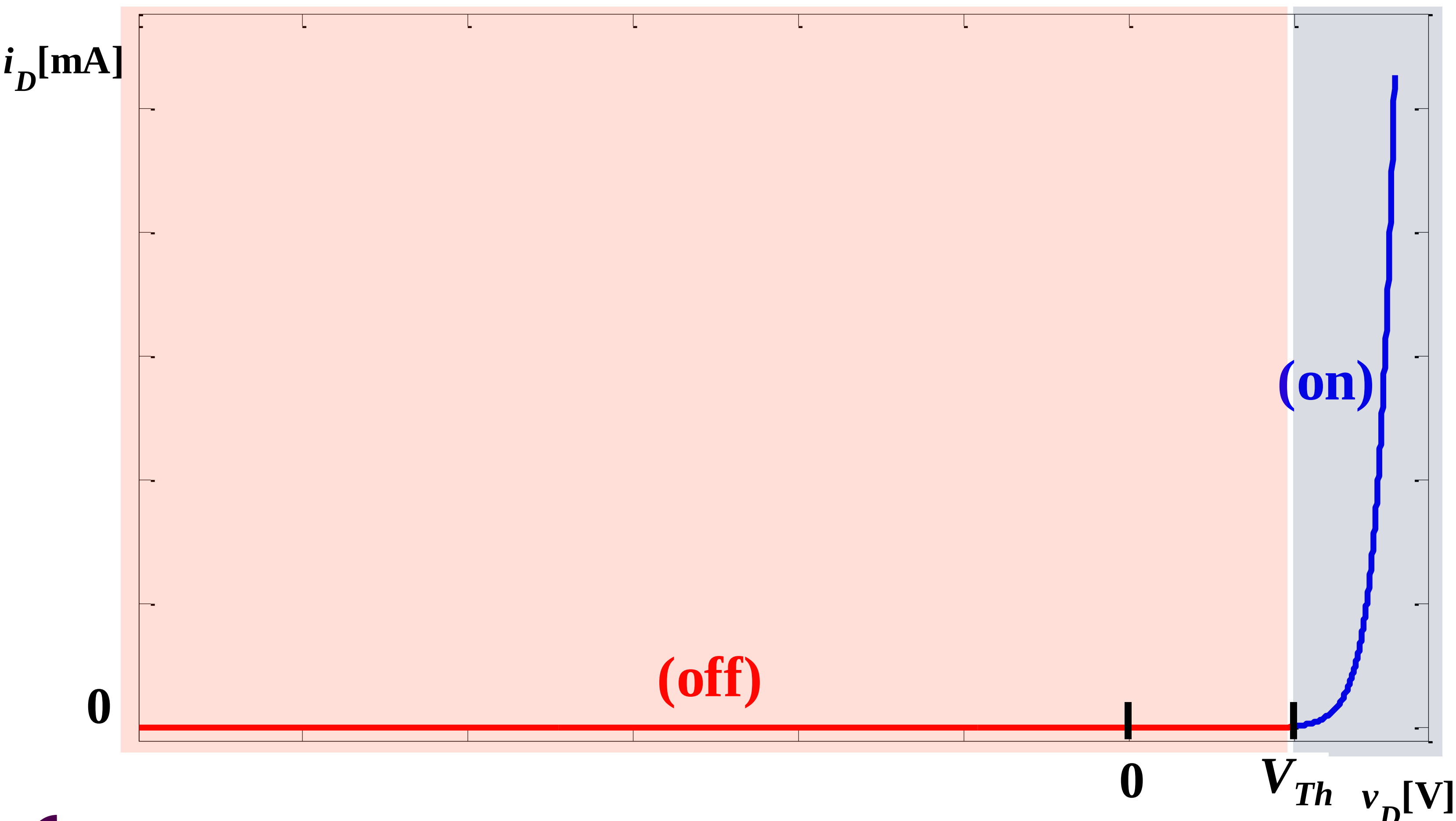
K - Boltzmann's constant
q – elementary charge (electric charge carried by a single electron)
T – absolute temperature measured in K degrees

n – ideality factor (emission coefficient)
n =2 discrete diodes
n =1 integrated diodes

Operating regions



$$i_D \approx I_S \cdot e^{\frac{v_D}{nV_T}}$$

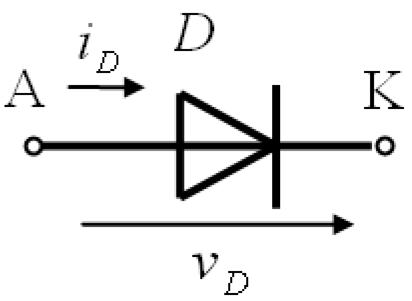


$\left\{\begin{array}{l}\text{reverse bias} \quad v_D < 0\text{V} \\ \text{forward bias} \quad v_D > 0\text{V}\end{array}\right.$

$\left\{\begin{array}{l}\textbf{(off)} \quad v_D < v_{Th};\ i_D = 0 \\ \textbf{(on)} \quad v_D > v_{Th};\ i_D > 0\end{array}\right.$

$V_{Th} \approx 0.6\text{V}$

Illustration



D is a rectifier diode, 1N400x with I_S=14nA, $n = 2$

Assuming a voltage drop across the diode in conduction

$$v_D = 0.7\text{V} = 700\text{ mV}$$

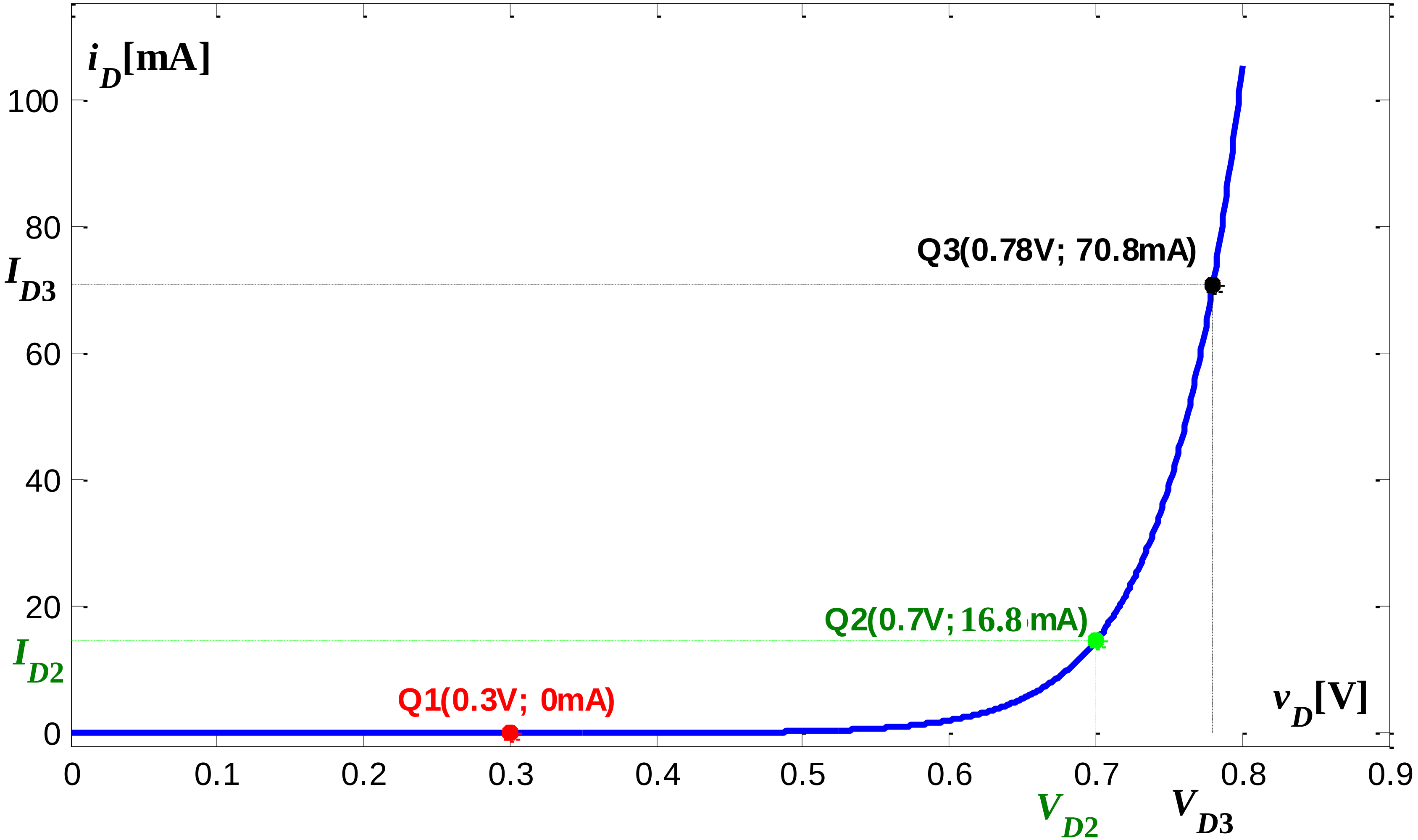
$$V_T = 25\text{mV} \ @\ 20^{\text{O}}\text{C}$$

the current through the diode results as:

$$i_D = 14 \cdot 10^{-9} \cdot e^{\frac{700}{2 \cdot 25}} = 16.8\text{mA}$$

Operating (quiescent) point $Q(V_D; I_D)$

Illustration for 1N400x with I_S=14nA, n=2

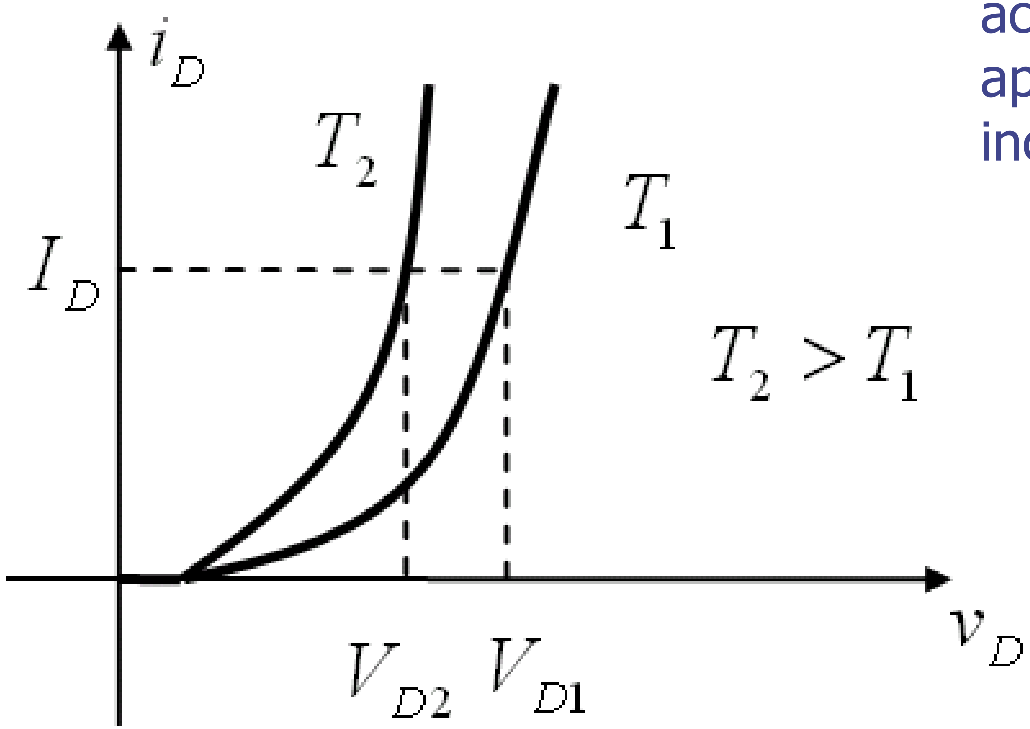


Temperature dependence

OPTIONAL

$$i_D \cong I_S e^{\frac{v_D}{nV_T}}$$

I_S, V_T - depend directly on the temperature



At a constant current the voltage across the diode decreases by approximately 2 mV for every 1°C increase in temperature.

Negative tempco

$$TC = -2\text{mV}/^{\text{O}}\text{C}$$

$20^{\text{O}}\text{C} \qquad v_D = 650\,\text{mV}$

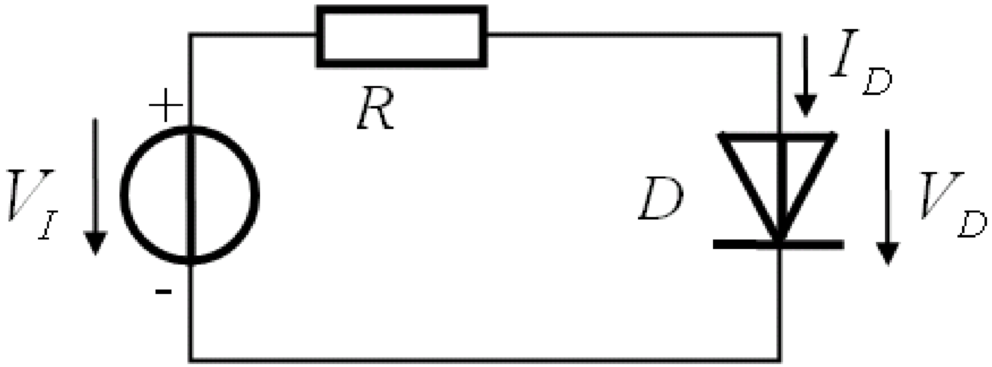
$40^{\text{O}}\text{C} \qquad v_D = 610\,\text{mV}$

$$v_D(T_2) = v_D(T_1) + TC \cdot (T_2 - T_1)\Big|_{I_D-cst}$$

At a constant voltage across the diode the current increases with the temperature

Determining the operating point

- Circuit with a dc voltage source and a resistor



I_D=? V_D=?

$$I_D = I_S e^{\frac{V_D}{nV_T}}$$ Diode equation

$$V_I = RI_D + V_D$$ Circuit equation (load line equation)

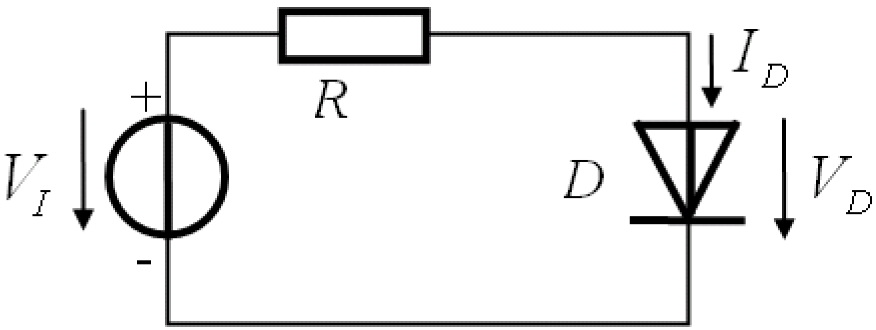
$$V_I - V_D = RI_D = RI_S e^{\frac{V_D}{nV_T}}$$

$\Rightarrow$ Transcendental equation

Two solving methods:

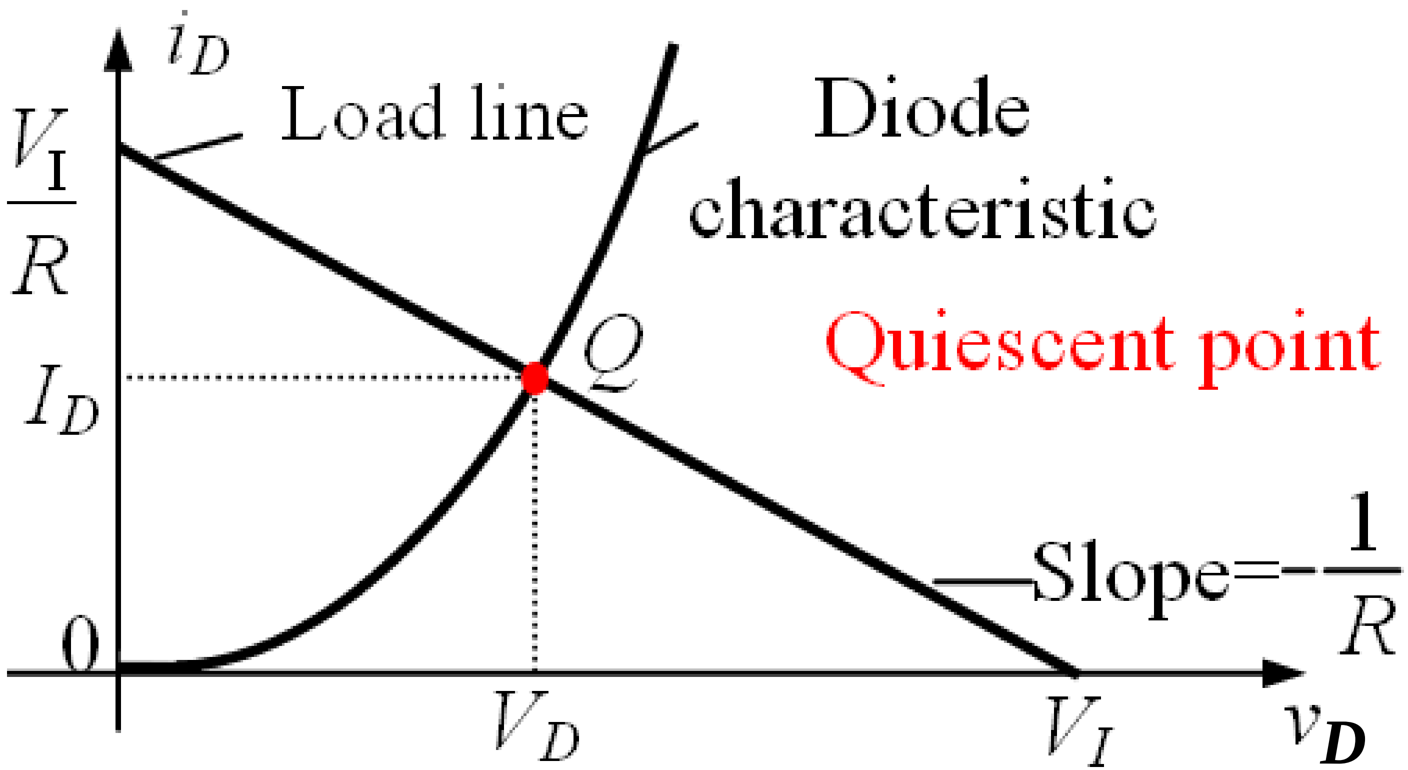
1. **Graphical method**
2. **Numerical method** (successive approximation)

Graphical method



Diode equation: $I_D = I_S e^{\frac{V_D}{nV_T}}$

Load line equation: $V_I = I_D R + V_D$

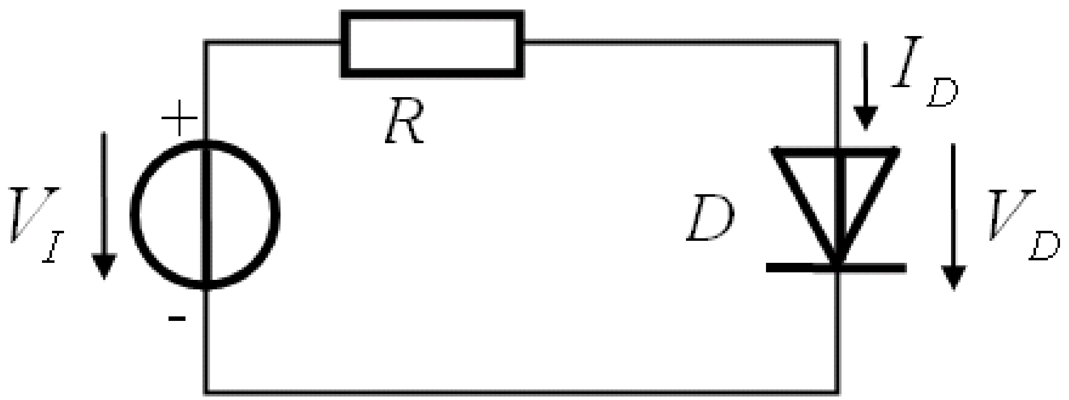


Numerical analysis - simplified

If V_I > 0.6 V, the D is on; (else D is off)

Assume the voltage drop across the conducting diode V_D **= 0.7V** and compute the current I_D using the load line (circuit) equation

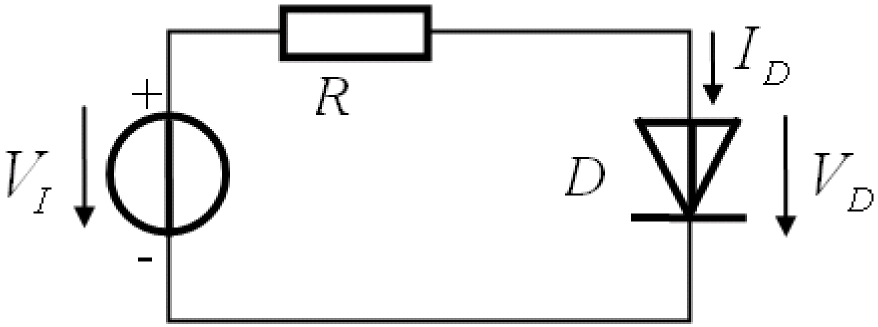
Circuit equation: $V_I = I_D R + V_D$



$$V_D = 0.7V$$

$$I_D = \frac{V_I - V_D}{R}$$

Illustration



$V_I = 9\text{V}$, $R = 0.5\text{K}\Omega$

a) What is the operating (quiescent) point of the diode *D*?

$V_D > 0.6\text{V}$ $\quad D-(\text{on})$

Assume $\quad V_D = 0.7\text{V}$ across the conducting diode

$$I_D = \frac{V_I - V_D}{R} \quad I_D = \frac{9-0.7}{0.5} = 16.6\text{mA}$$

$$\boxed{Q(0.7\text{V},\, 16.6\text{mA})}$$

Numerical analysis - iteratively

1. Consider an initial value of diode voltage, eg. $V_D^{(0)}$ **=0.7V** and **compute** the current $I_D^{(0)}$ using the load line equation.

$(V_D^{(0)}, I_D^{(0)})$ – **initial solution**

2. With $I_D^{(0)}$ compute the diode voltage from **diode equation**, then the current $I_D^{(1)}$ **from load line equation**

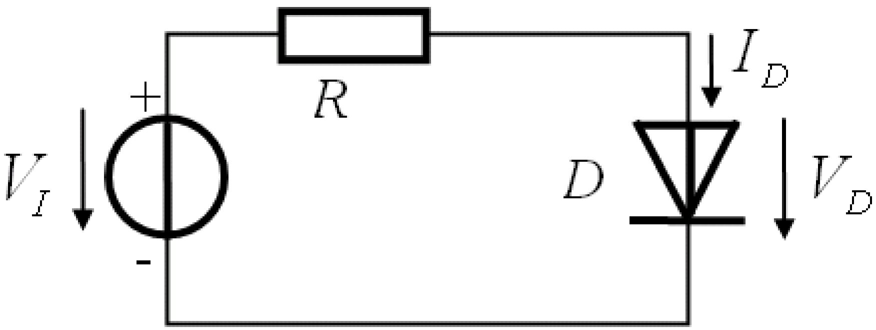
$(V_D^{(1)}, I_D^{(1)})$ – **solution after first iteration**

We finalize one iteration. If a more accurate solution is necessary, further iteration should be performed.

For quick, first order analysis of the circuit,

usually the initial solution is considered!

Illustration



Consider V_I=3V, R=0.5KΩ, D is 1N400x with I_S=14nA and n=2.

What is the operating (quiescent) point of the diode?

Quick, first order analysis:

$$V_D > 0.6\text{V} \qquad D-(\text{on})$$

$$\text{Assume} \quad V_D = 0.7\text{V in conduction}$$

$$I_D = \frac{V_I - V_D}{R} \qquad I_D = \frac{3-0.7}{0.5} = 4.6\text{mA} \qquad Q(0.7\text{V},\ 4.6\text{mA})$$

Detailed analysis:

OPTIONAL

$$I_D = \frac{V_I - V_D}{R} \qquad V_D = nV_T \ln\frac{I_D}{I_S}$$

$$V_D^{(0)} = 0.7\text{V}$$

$$I_D^{(0)} = \frac{3-0.7}{0.5} = 4.6\ \text{mA}$$

$Q^{(0)}(0.7\text{V}, 4.6\text{mA})$

$$V_D^{(1)} = nV_T \cdot \ln\frac{I_D^{(0)}}{I_S} = 2\cdot 0.025\cdot \ln\frac{4.6\text{mA}}{14\text{nA}} = 0.635\text{V}$$

$$I_D^{(1)} = \frac{V_I - V_D^{(1)}}{R} = \frac{3-0.635}{0.5} = 4.73\text{mA}$$

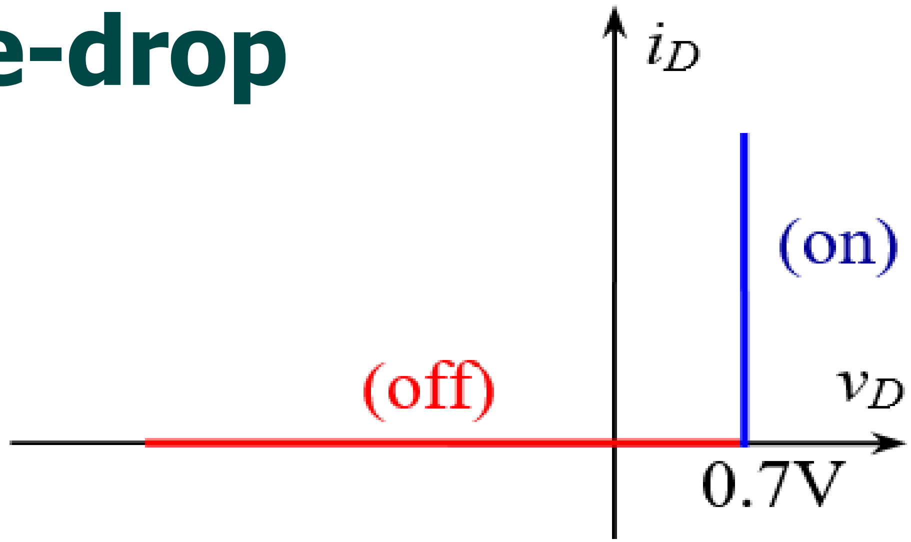
$Q^{(1)}(0.635\text{V}, 4.73\text{mA})$

$$V_D^{(2)} = n\cdot V_T \cdot \ln\frac{I_D^{(1)}}{I_S} = 2\cdot 0.025\cdot \ln\frac{4.73\text{mA}}{14\text{nA}} = 0.637\text{V}$$

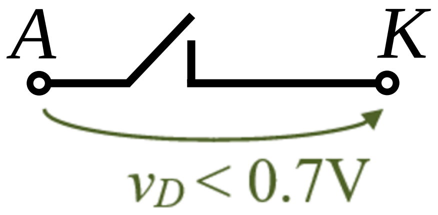
$$I_D^{(2)} = \frac{V_I - V_D^{(2)}}{R} = \frac{3-0.637}{0.5} = 4.726\text{mA}$$

$Q^{(2)}(0.637\text{V}, 4.726\text{mA})$

Constant-voltage-drop model

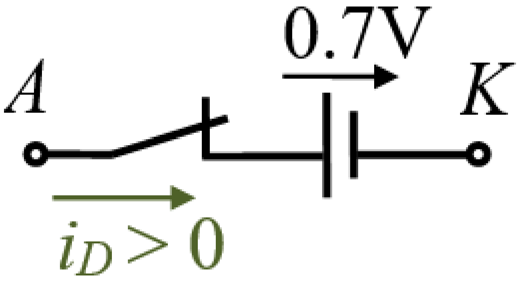


If v_D < 0.7V ***D*** **– (off)**



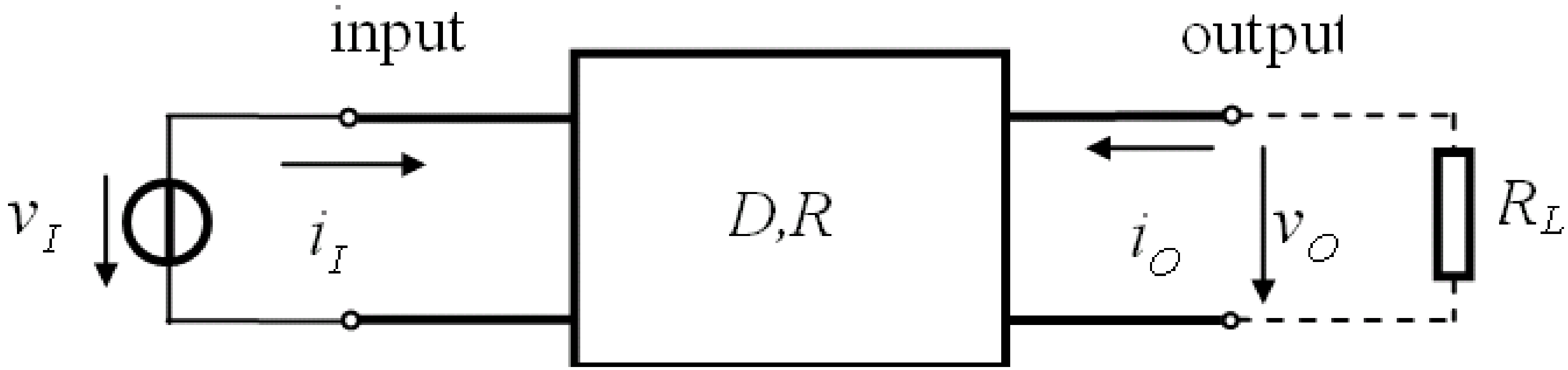
$$\begin{cases} v_D < 0.7\text{V} \\ i_D = 0 \end{cases}$$

If v_D *tends to be* > 0.7V ***D*** **– (on)**



$$\begin{cases} v_D = 0.7\text{V} \\ i_D > 0 \end{cases}$$

DR two-port networks analysis

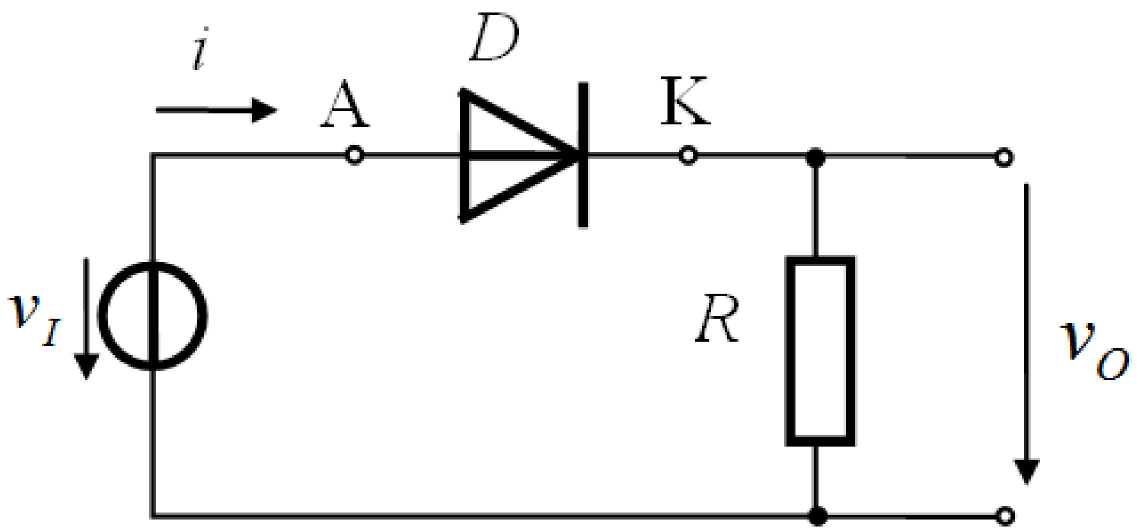


VTC **– voltage transfer characteristic**

1. Consider **all possible situations** resulting from the combination of the **diode states (*on*, *off*)**
2. For each situation :
   1. draw the equivalent circuit
   2. find v_O
   3. determine the range of v_I for that particular situation
3. Draw ***VTC***.

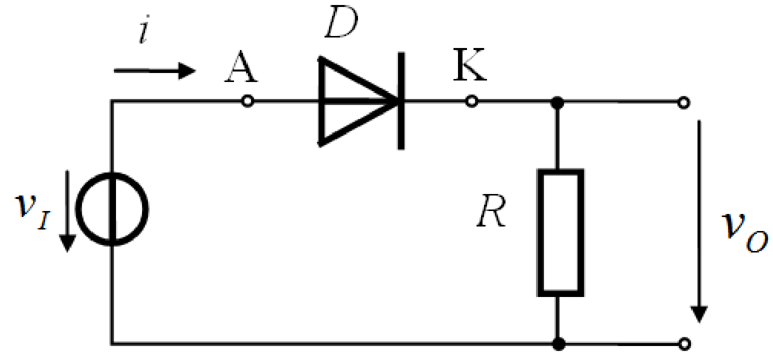
Example

What is the VTC $v_O(v_I)$?

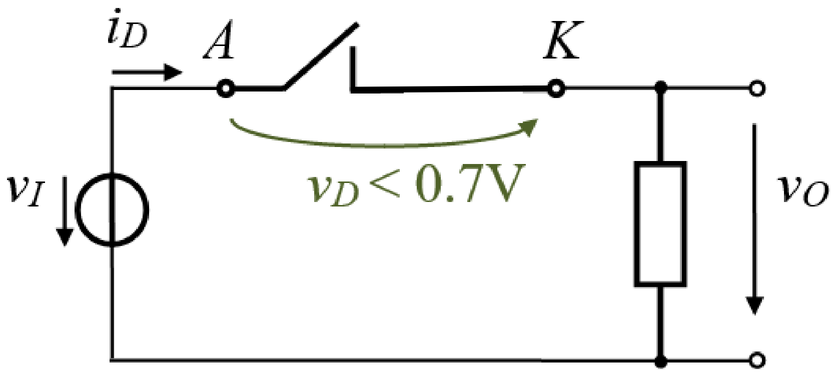


Example - cont

What is the VTC $v_O(v_I)$?



$\boldsymbol{D}$ – **(off)**



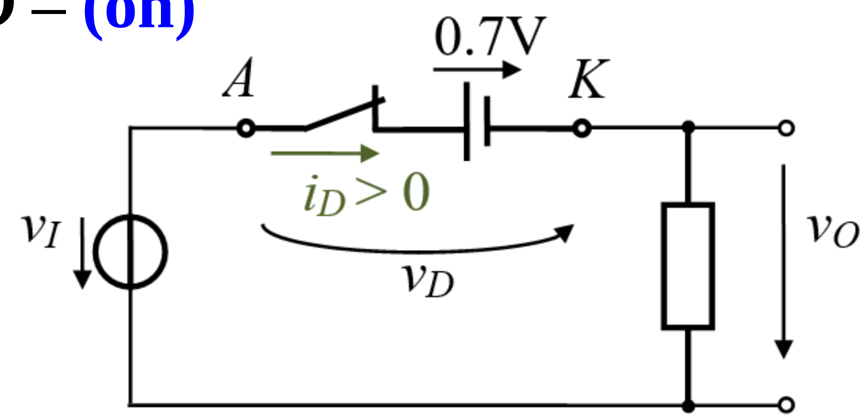
$$v_D < 0.7\text{V} \quad i_D = 0$$

$$\boxed{v_O = 0}$$

$$v_D = v_I - v_O$$

$$\boxed{v_I < 0.7\text{V}}$$

$\boldsymbol{D}$ – **(on)**



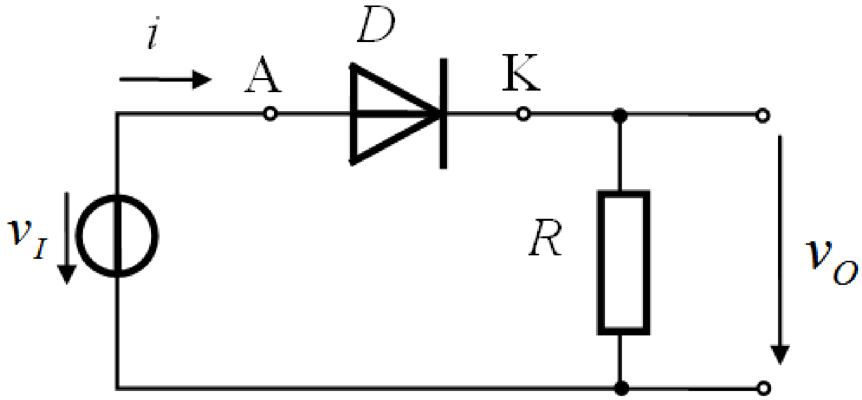
$$i_D > 0 \quad v_D = 0.7\text{V}$$

$$\boxed{v_O = v_I - v_D = v_I - 0.7\text{V}}$$

$$i_D = \frac{v_O}{R} = \frac{v_I - 0.7\text{V}}{R}$$

$$\boxed{v_I > 0.7\text{V}}$$

Example - cont

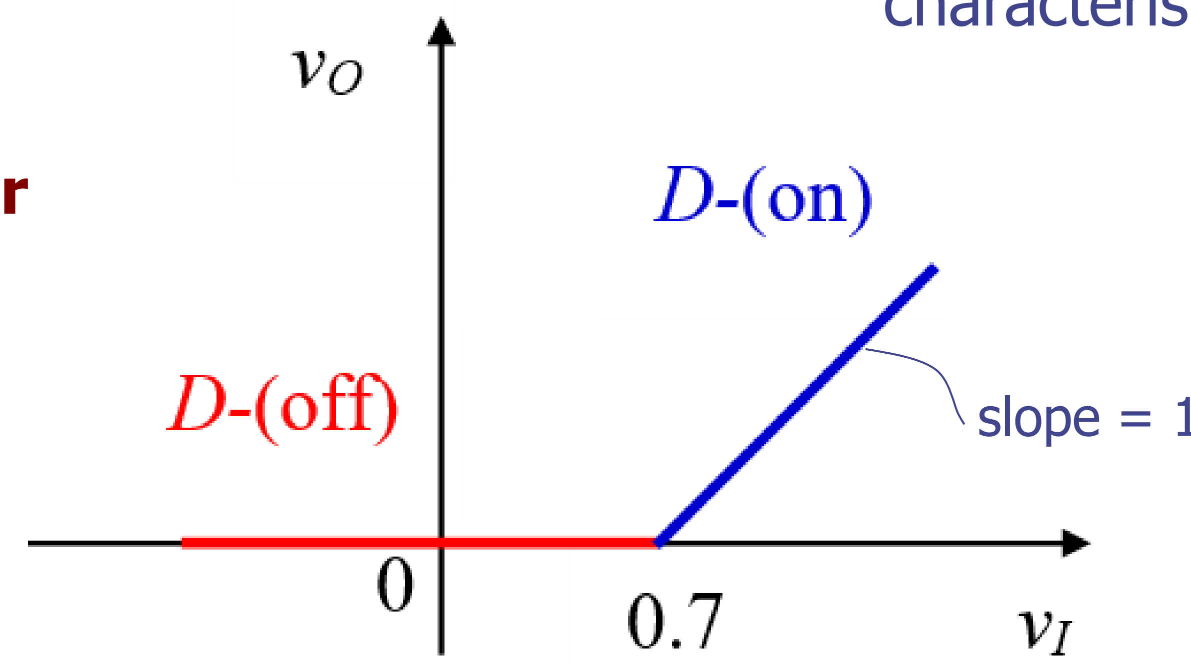


$$v_O = \begin{cases} 0 & v_I < 0.7\text{V} \\ v_I - 0.7\text{V} & v_I > 0.7\text{V} \end{cases}$$

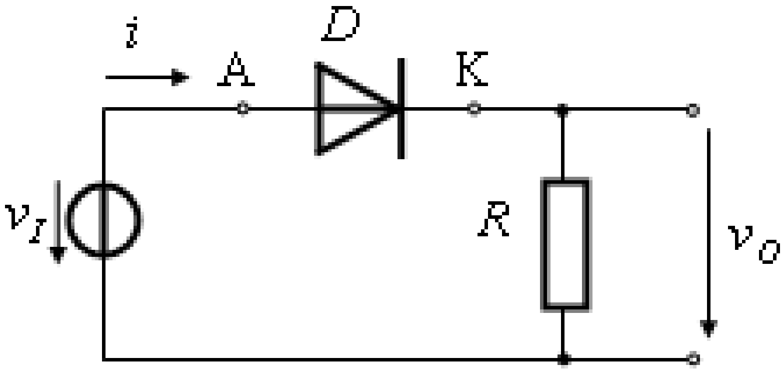
Voltage transfer characteristic

Application:

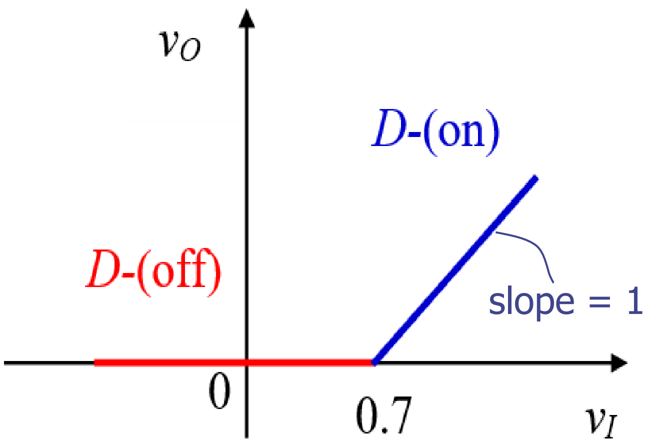
Voltage rectifier

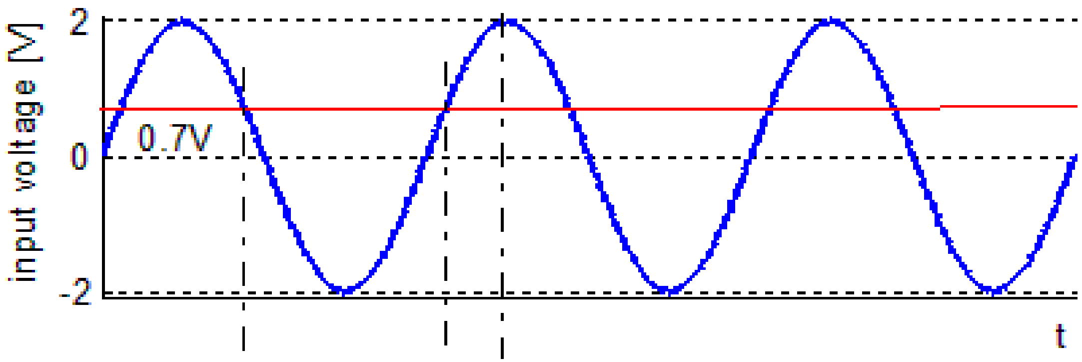


Waveforms for a voltage rectifier



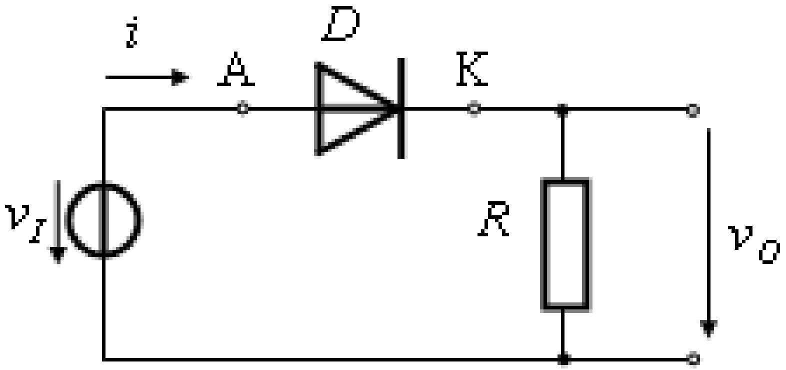
$$v_O = \begin{cases} 0 & v_I < 0.7\text{V} \\ v_I - 0.7\text{V} & v_I > 0.7\text{V} \end{cases}$$



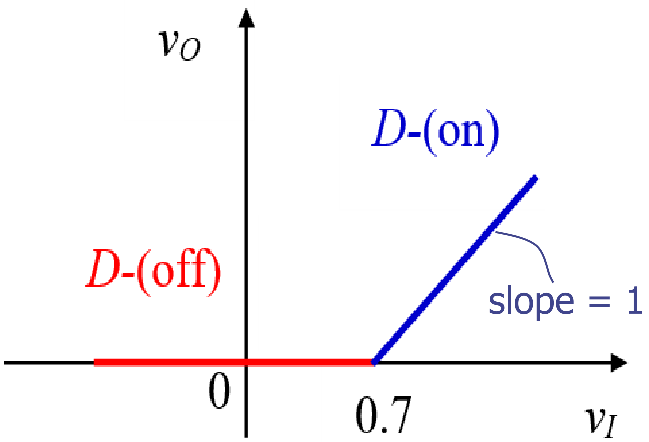


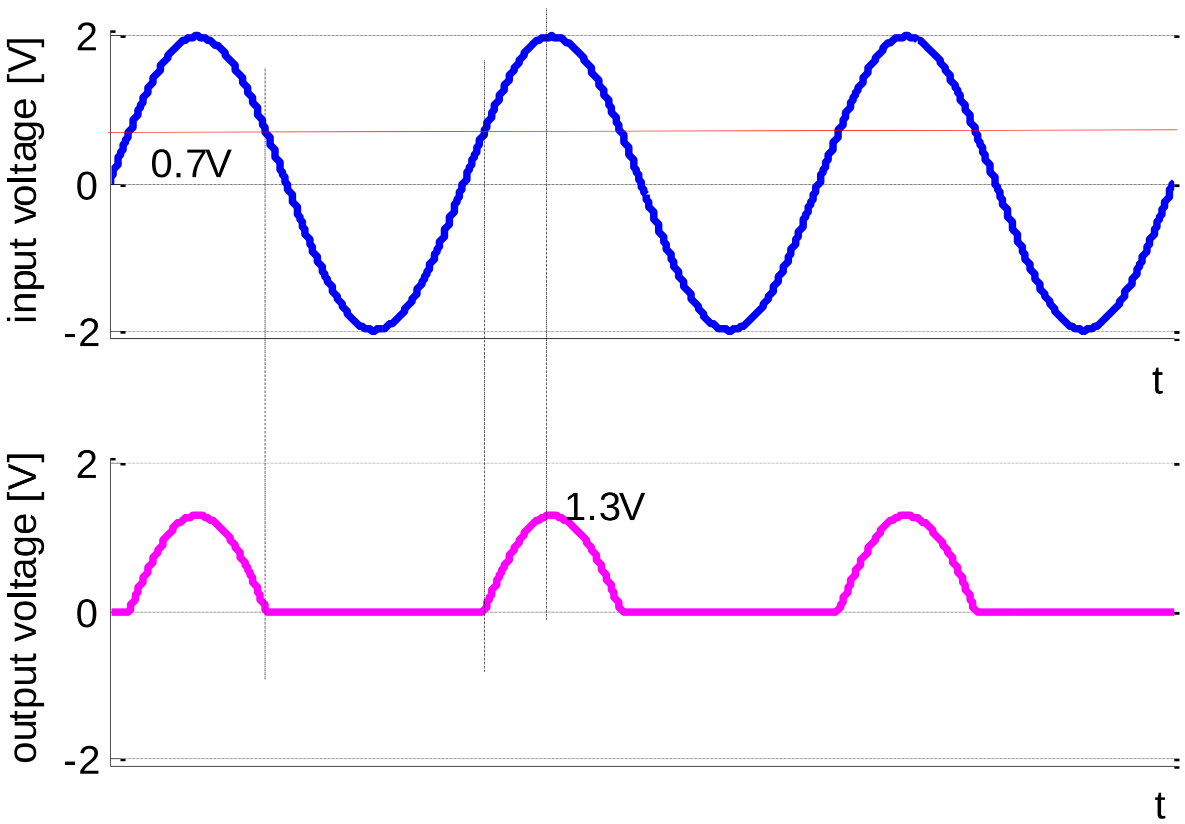
$$v_O(t) = ?$$

Waveforms for a voltage rectifier

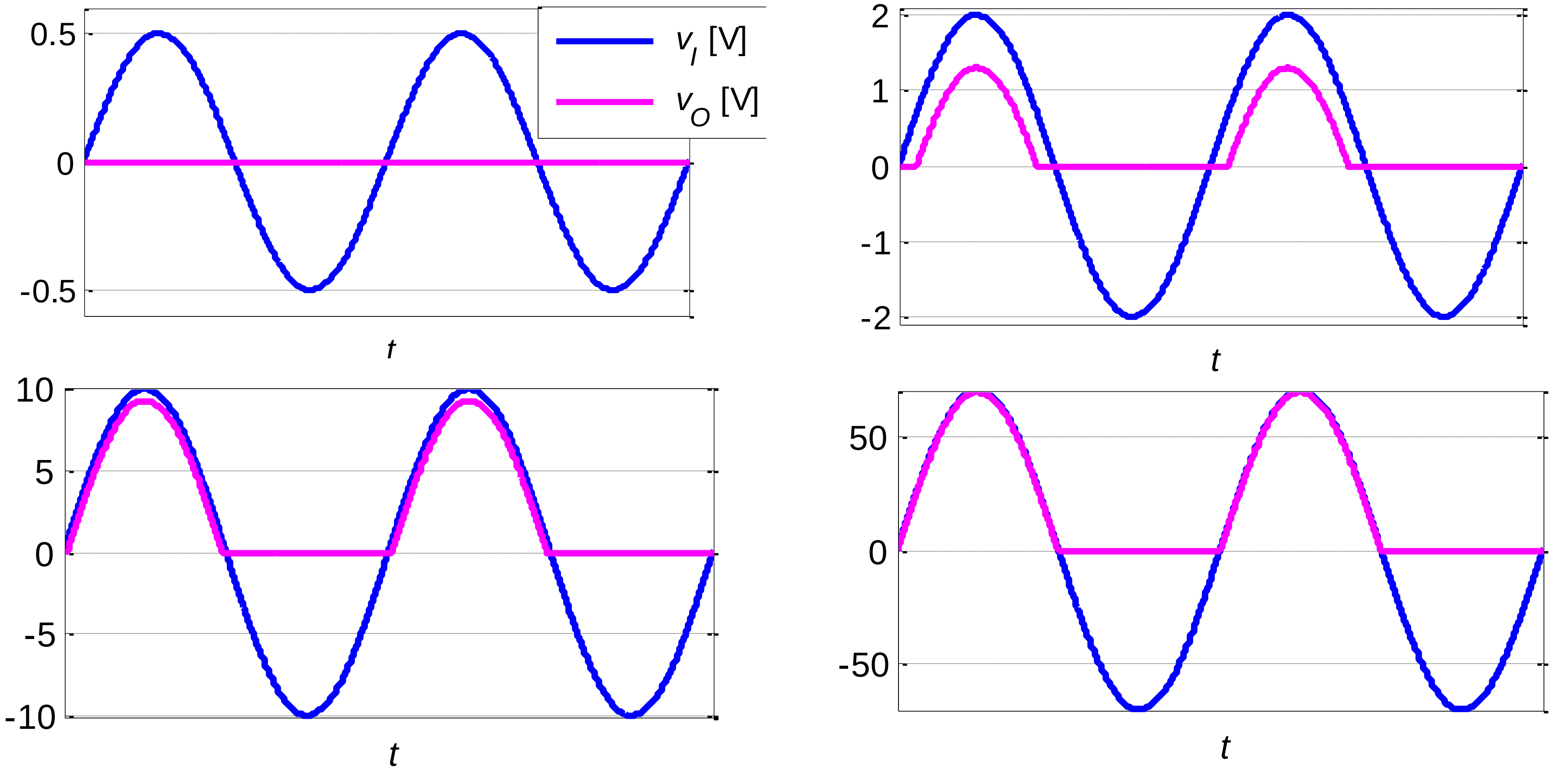


$$v_O = \begin{cases} 0 & v_I < 0.7\text{V} \\ v_I - 0.7\text{V} & v_I > 0.7\text{V} \end{cases}$$





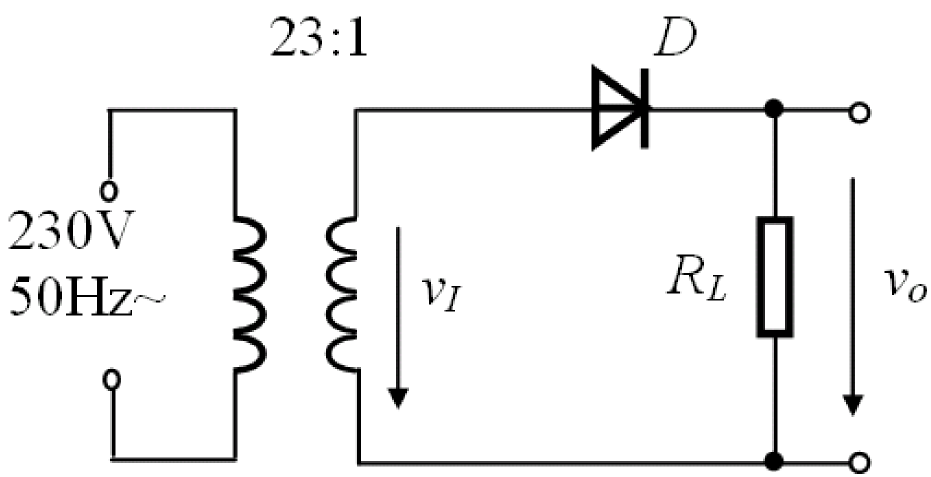
The influence of the threshold voltage and voltage drop across the diode in conduction



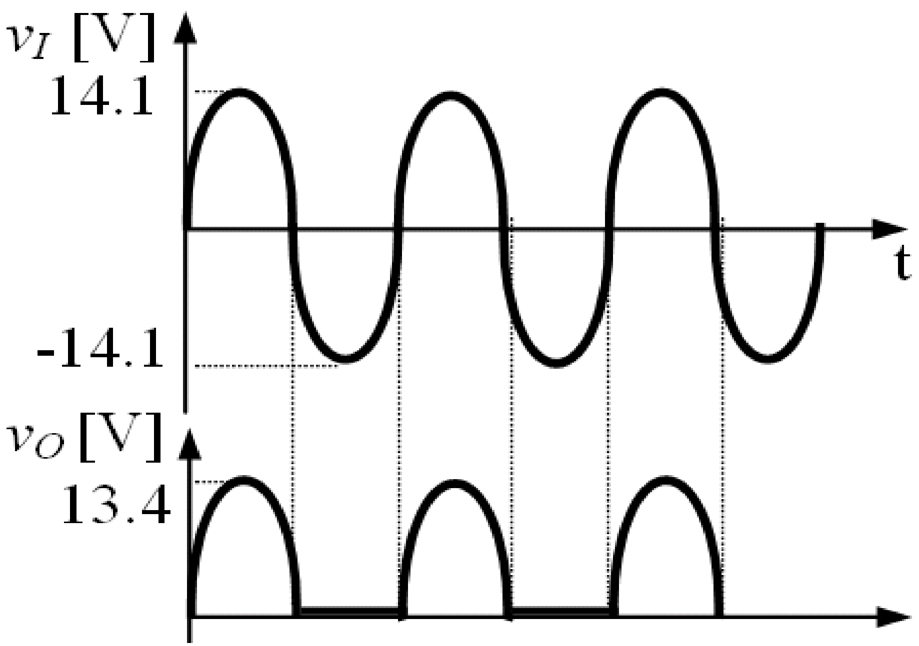
- If the input voltage is large enough (>> 0.7V)
  - the threshold voltage can be considered 0V
  - the voltage drop across the conducting diode can be neglected; $D-(\text{on});\ v_O = v_I$

Applications of *DR* two-port networks

- **Half-wave rectifier**

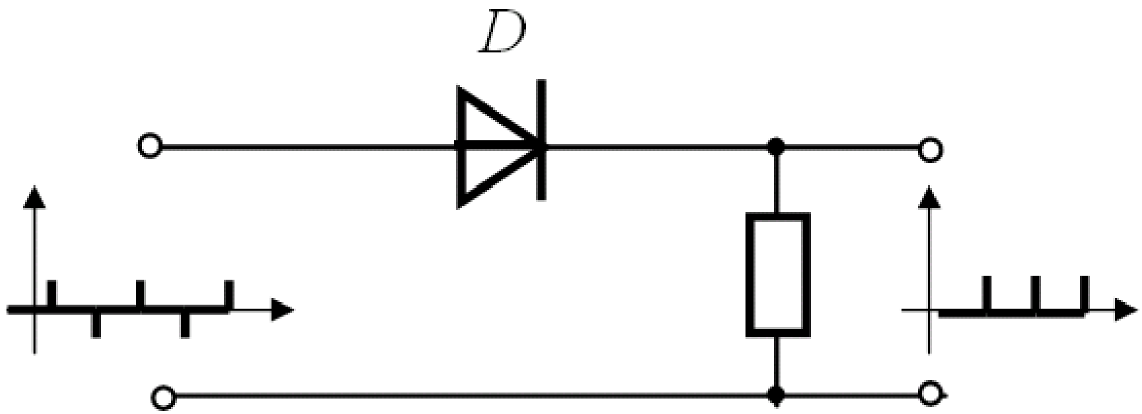


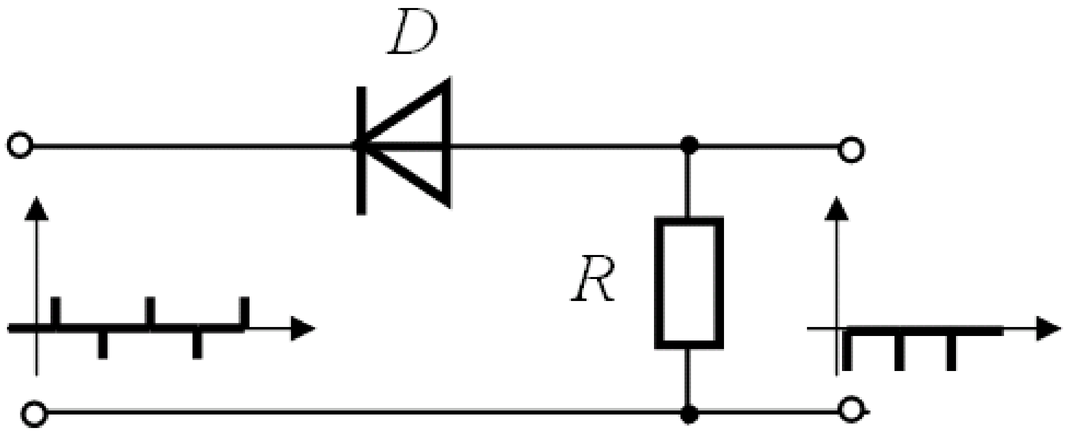
Step-down transformer



❖ Pulses selector

OPTIONAL

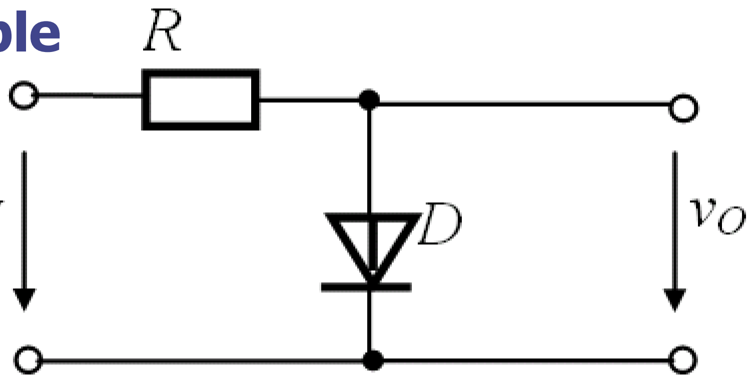




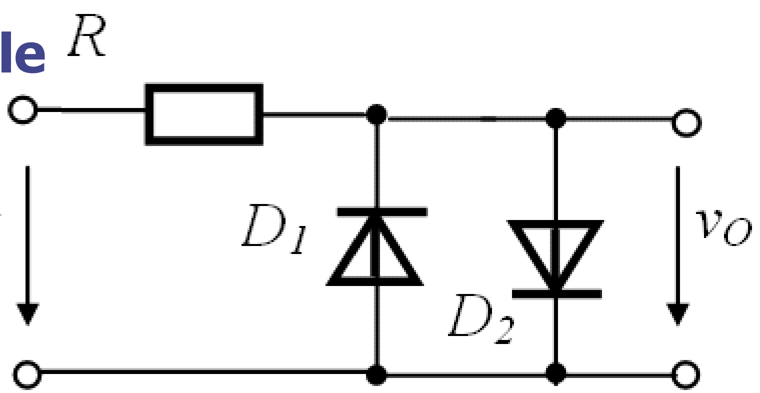
❖ Voltage limiters

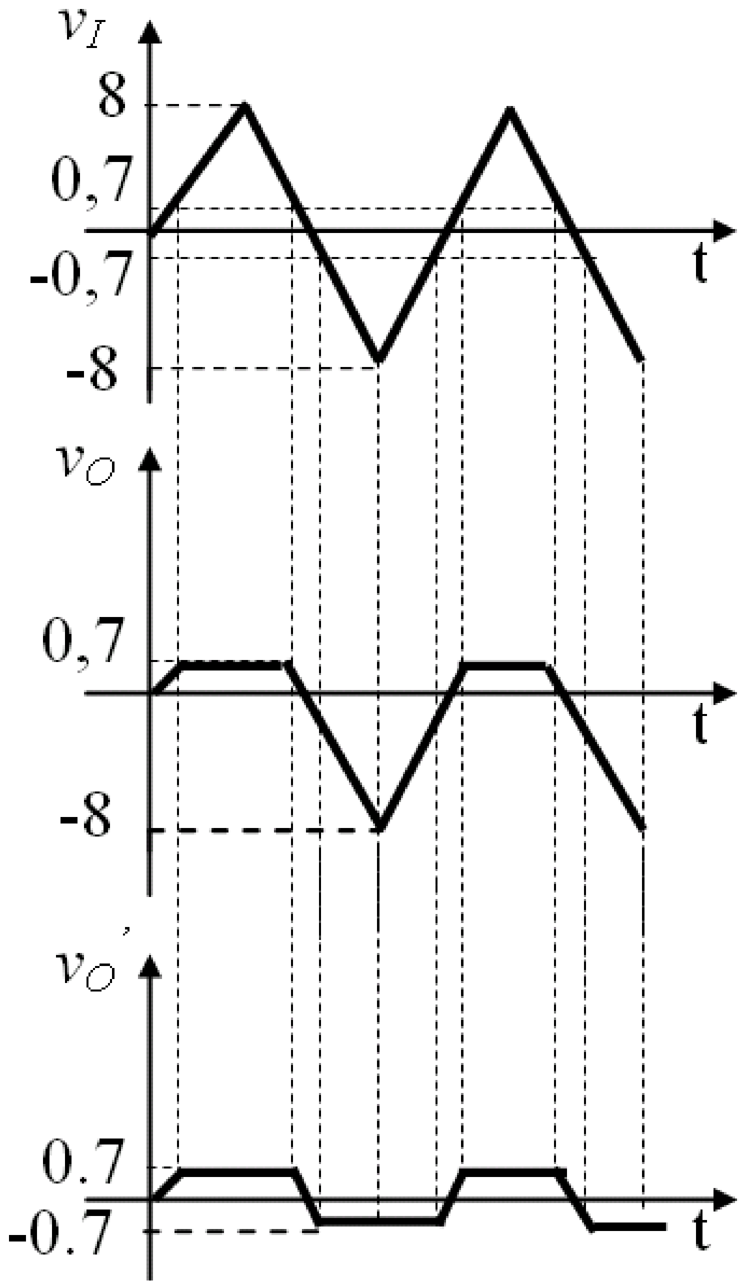
❖ VTC?

simple

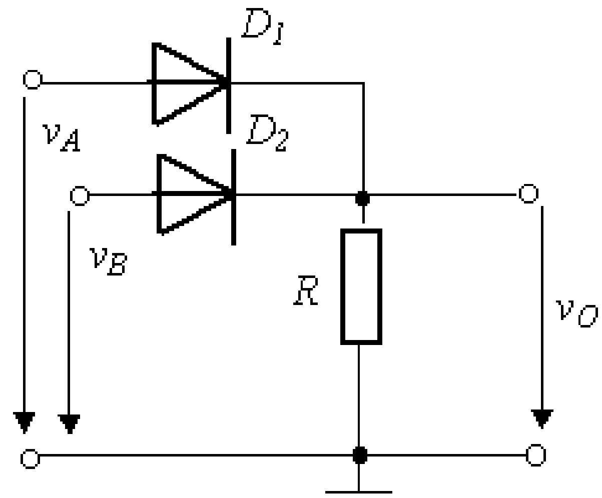


double





❖ **Maximum multi-port networks**



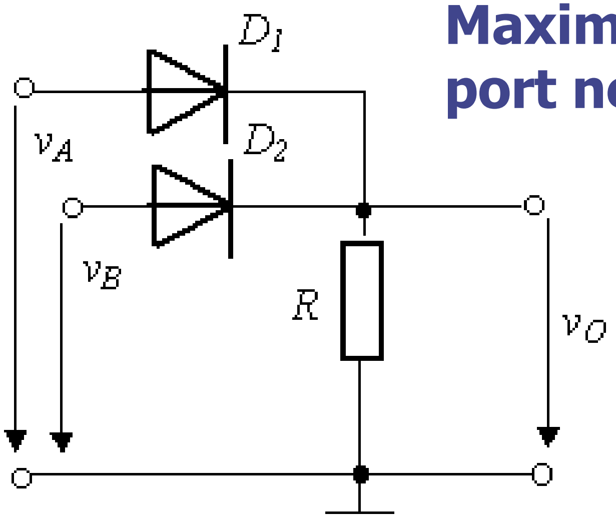
$$\begin{cases} v_A > v_B \\ v_A > 0.7\text{V} \end{cases} \qquad D_1-(on),\ D_2-(off);\quad v_O = v_A - 0.7\text{V}$$

$$\begin{cases} v_B > v_A \\ v_B > 0.7\text{V} \end{cases} \qquad D_1-(off),\ D_2-(on);\quad v_O = v_B - 0.7\text{V}$$

$$\begin{cases} v_A < 0.7\text{V} \\ v_B < 0.7\text{V} \end{cases} \qquad D_1-(off),\ D_2-(off);\quad v_O = 0$$

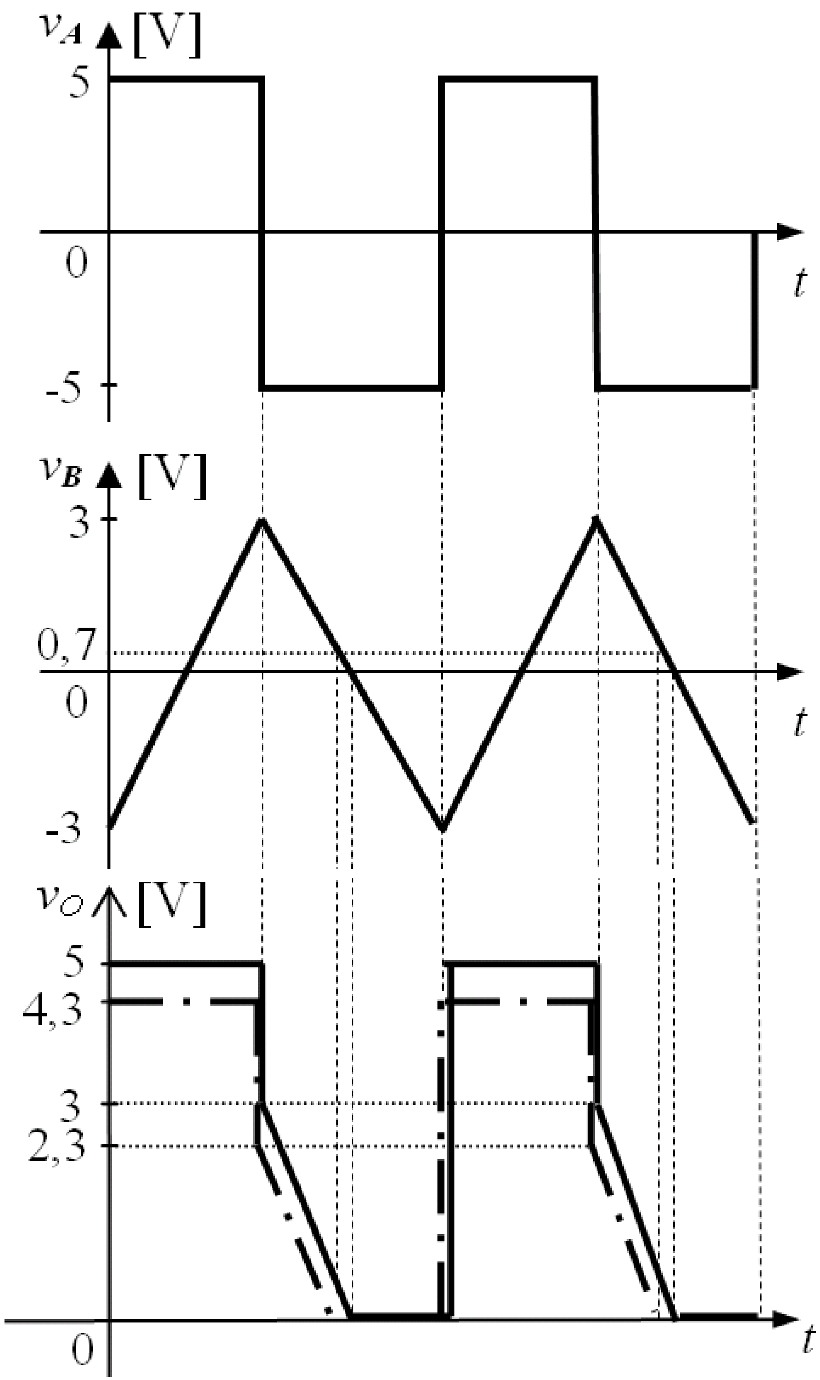
$$\boxed{v_O = \max(v_A - 0.7\text{V};\ v_B - 0.7\text{V};\ 0\text{V})}$$

Maximum multi-port networks



$$v_O = \max(v_A - 0.7\text{V};\ v_B - 0.7\text{V};\ 0)$$

$$v_O = \max(v_A;\ v_B;\ 0)$$ neglecting 0.7V



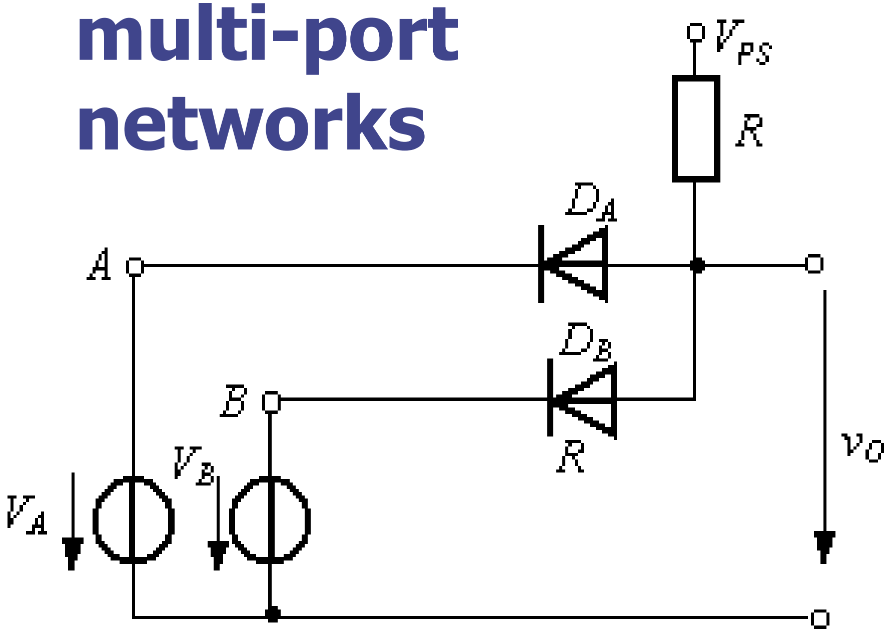
——— neglecting 0.7V

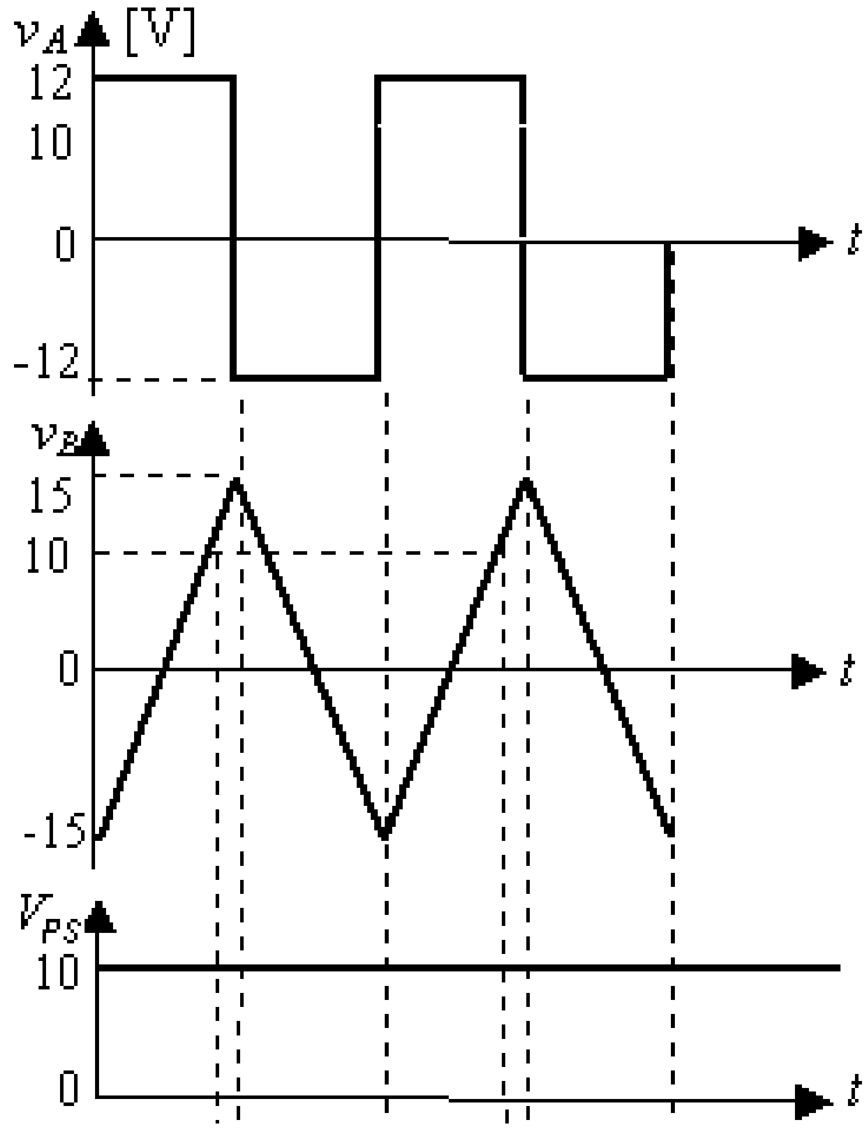
– · – · – *D* – constant-voltage-drop

What is the peak value of the current through each circuit element if R=5kΩ?

What is the range of values for R, if the peak forward current through diode is 200mA?

❖ Minimum multi-port networks





v_O = ?

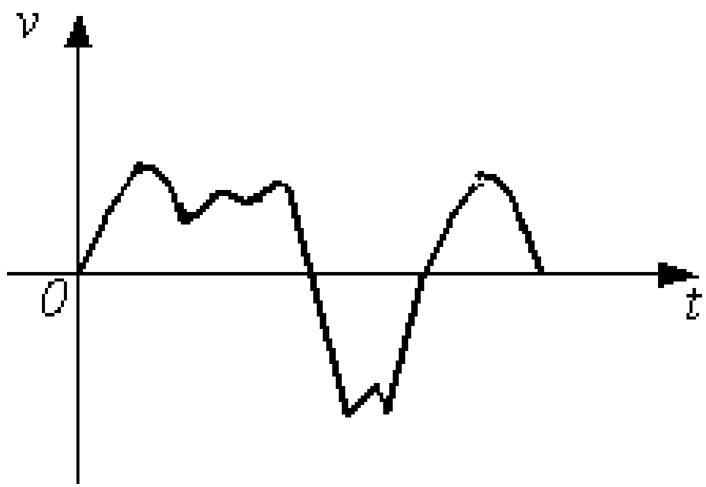
$v_O = \min(v_A + 0.7\text{V}; v_B + 0.7\text{V}; V_{PS})$

$v_O = \min(v_A, v_B, V_{PS})$ neglecting 0.7V

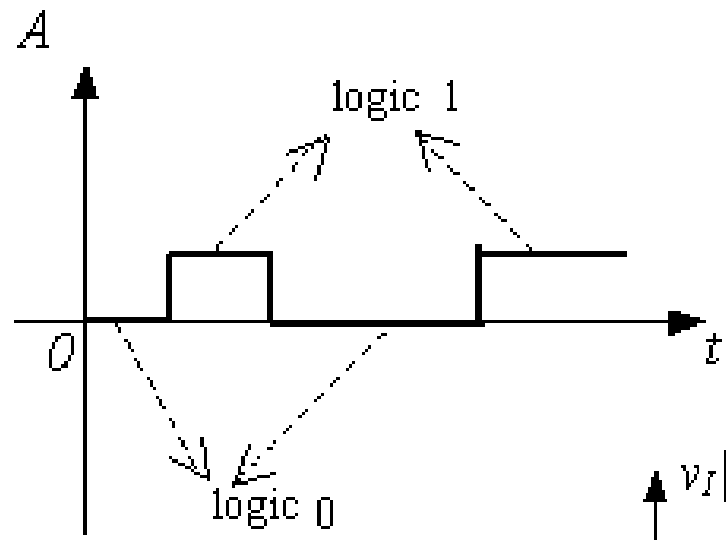
$v_O(t)$?

DR logic circuits

analog signal



digital signal

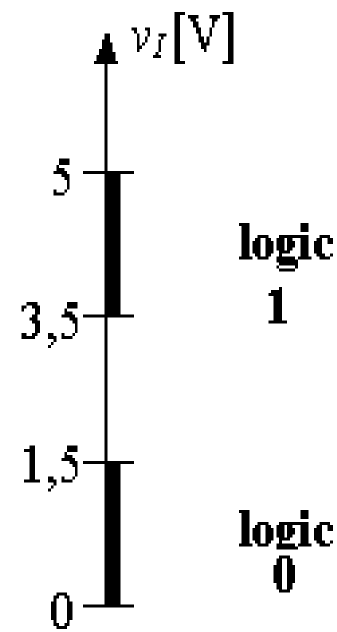


Logic 0 *false* *low*

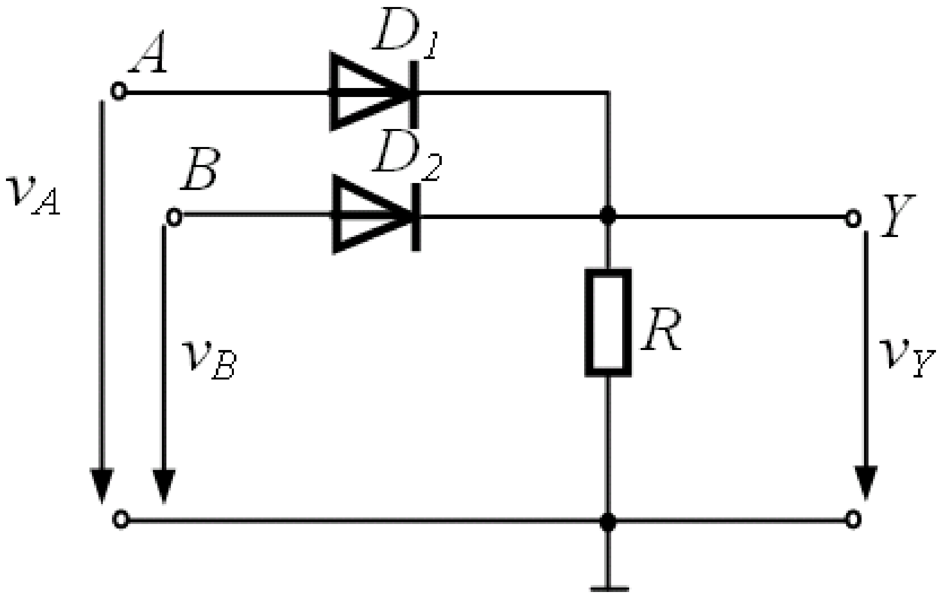
Logic 1 *true* *high*

0V → logic 0
5V → logic 1

CMOS logic family
supplied at +5V



❖ two-input OR circuit



0V $\rightarrow$ logic 0
5V $\rightarrow$ logic 1

v_A	v_B	v_Y	D_1	D_2
0V	0V	0V	(off)	(off)
0V	5V	4.3V	(off)	(on)
5V	0V	4.3V	(on)	(off)
5V	5V	4.3V	(on)	(on)

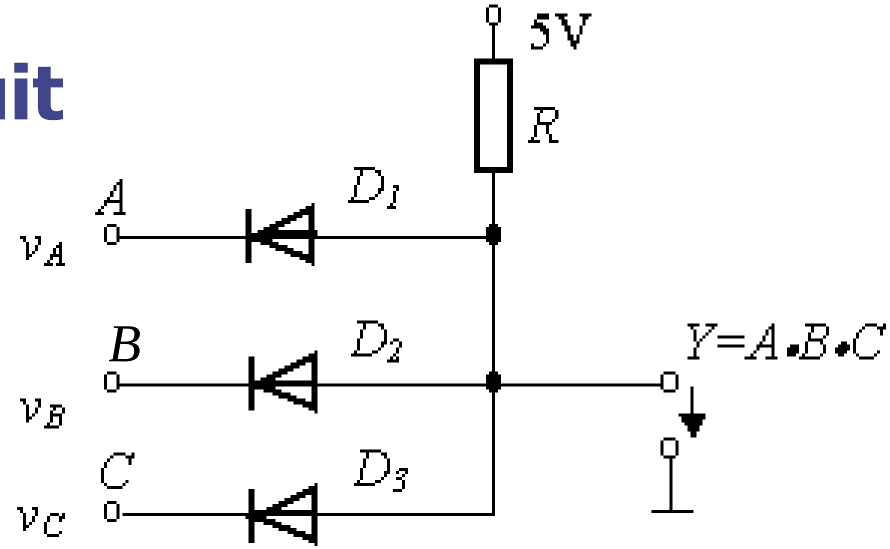
operating table

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

truth table

❖ three-input AND circuit

0V → logic 0
5V → logic 1



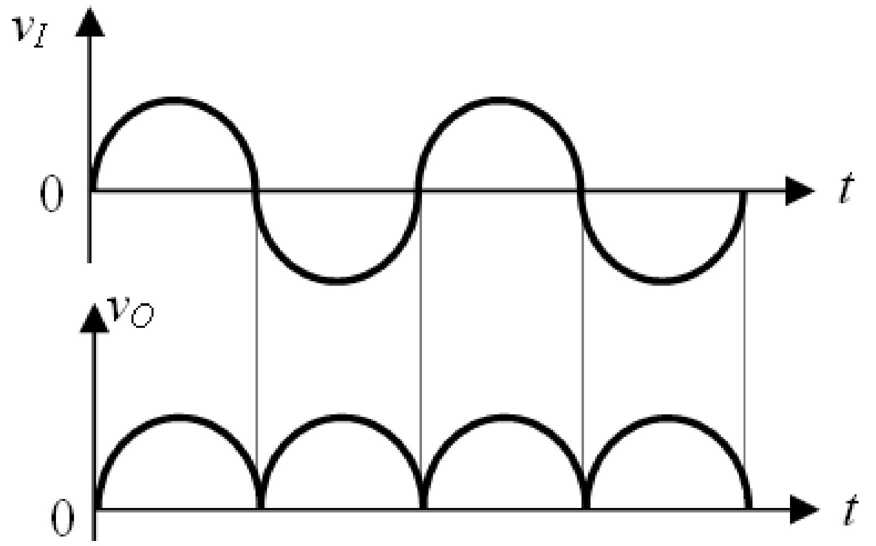
v_A[V]	v_B[V]	v_C[V]	v_Y[V]
0	0	0	0.7
0	0	5	0.7
0	5	0	0.7
0	5	5	0.7
5	0	0	0.7
5	0	5	0.7
5	5	0	0.7
5	5	5	5

operating table

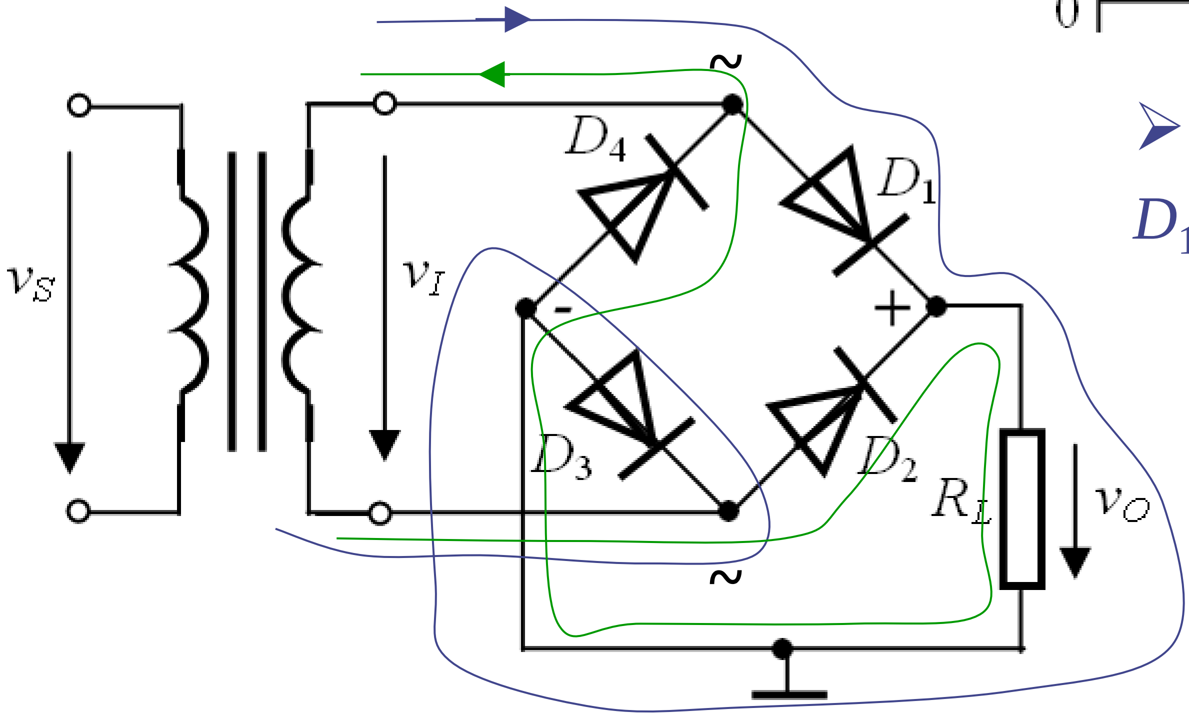
A	B	C	Y
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	0
1	0	0	0
1	0	1	0
1	1	0	0
1	1	1	1

truth table

❖ Full wave rectifier - diode bridge



neglecting 0.7V across the conducting diode



➢ positive half, $v_I > 0$

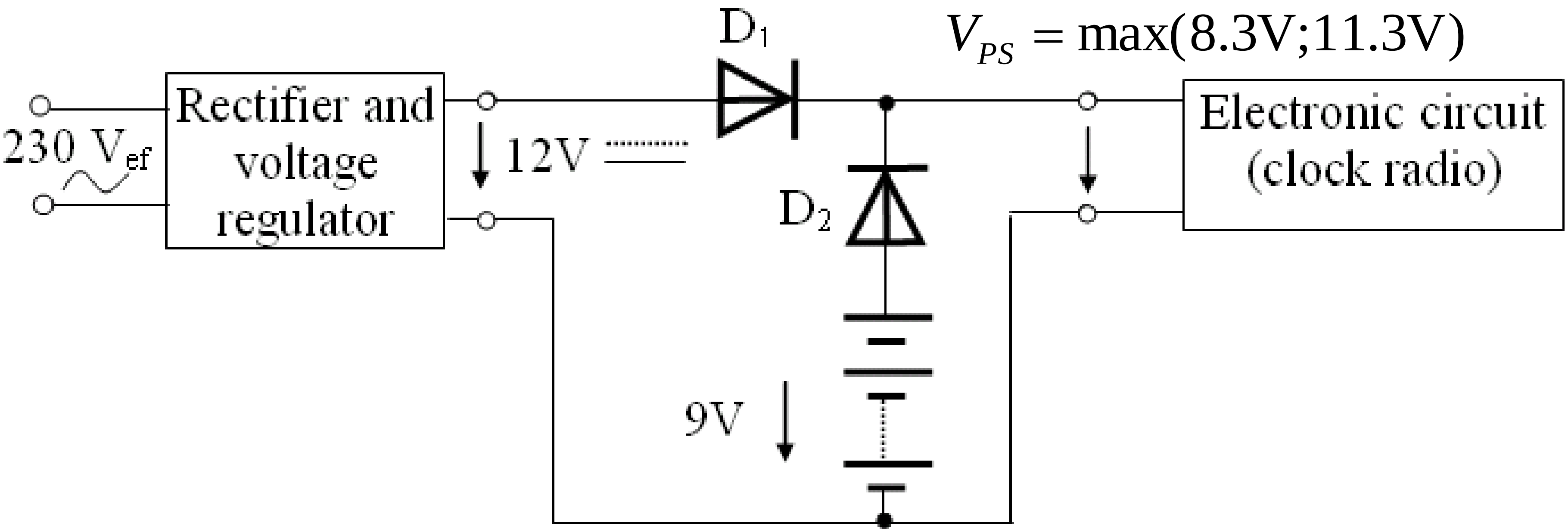
D_1, D_3 – (on) D_2, D_4 – (off)

➢ negative half, $v_I < 0$

D_1, D_3 – (off) D_2, D_4 – (on)

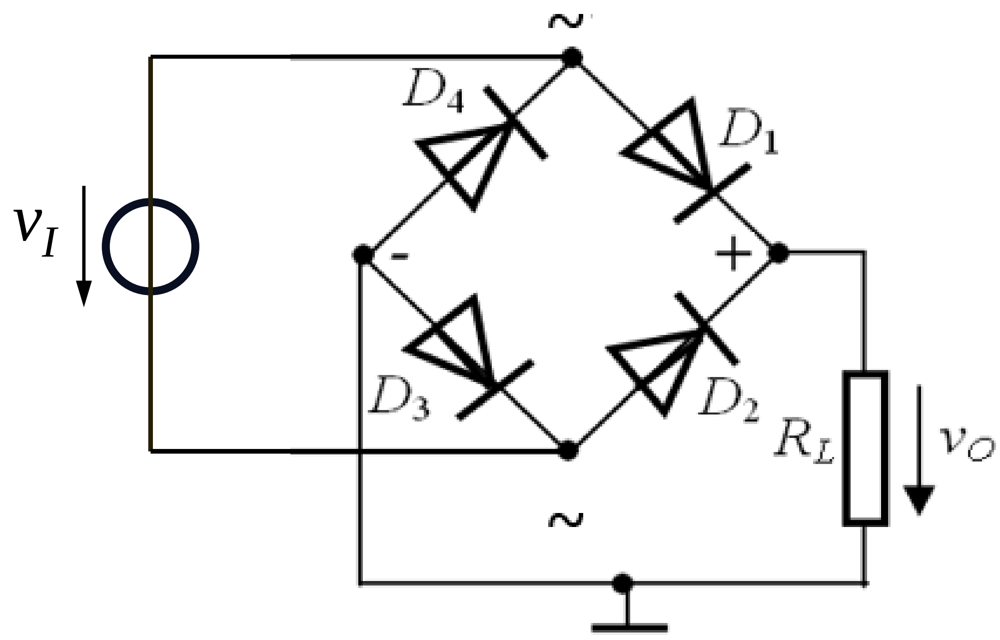
$v_I > 0V$ $v_I < 0V$

❖ Backup Supply



Problem

$$v_I(t) = \hat{V}_I \sin \omega t$$



For the circuit in the figure, R_L=50Ω. Assume $\hat{V}_I = 25\text{V}$

a) $v_O(t)$ and $i_O(t)$

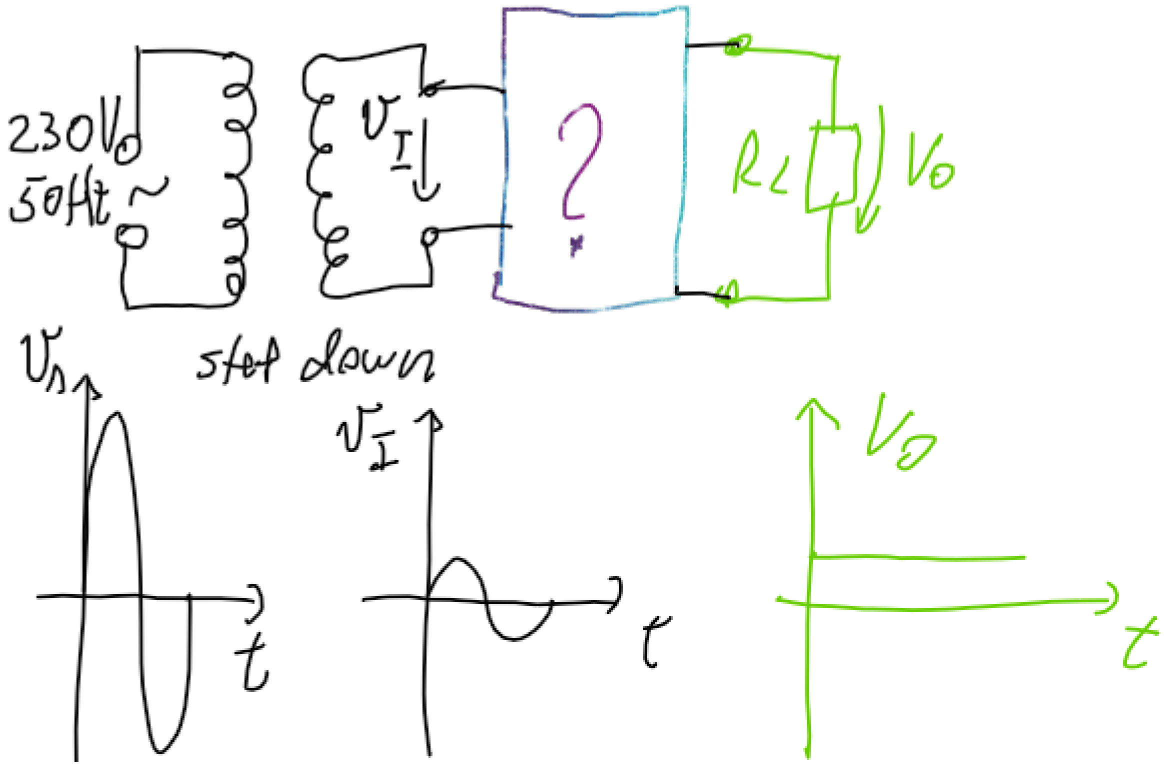
b) What are the value of the maximum reverse voltage v_{DR} across each diode and the maximum forward current through each diode?

c) Repeat a) and b) assuming $\hat{V}_I = 6.4\text{V}$

Power-supply filtering

v_I is the voltage in a secondary winding of a step-down line transformer.

It is required to obtain an almost dc voltage (on a load resistor)

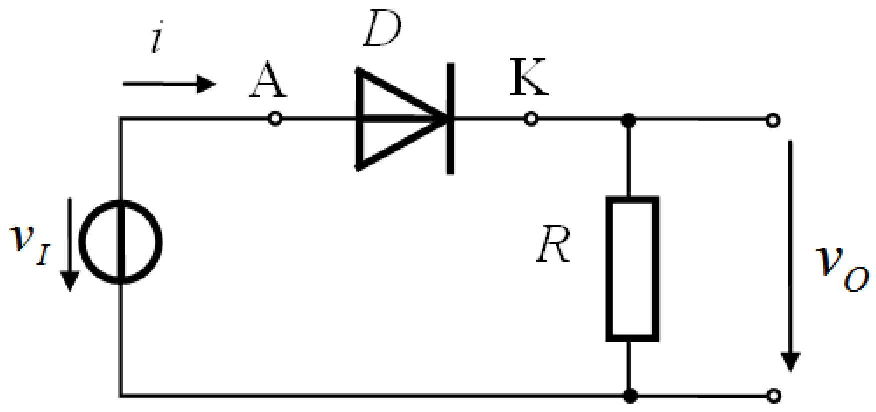


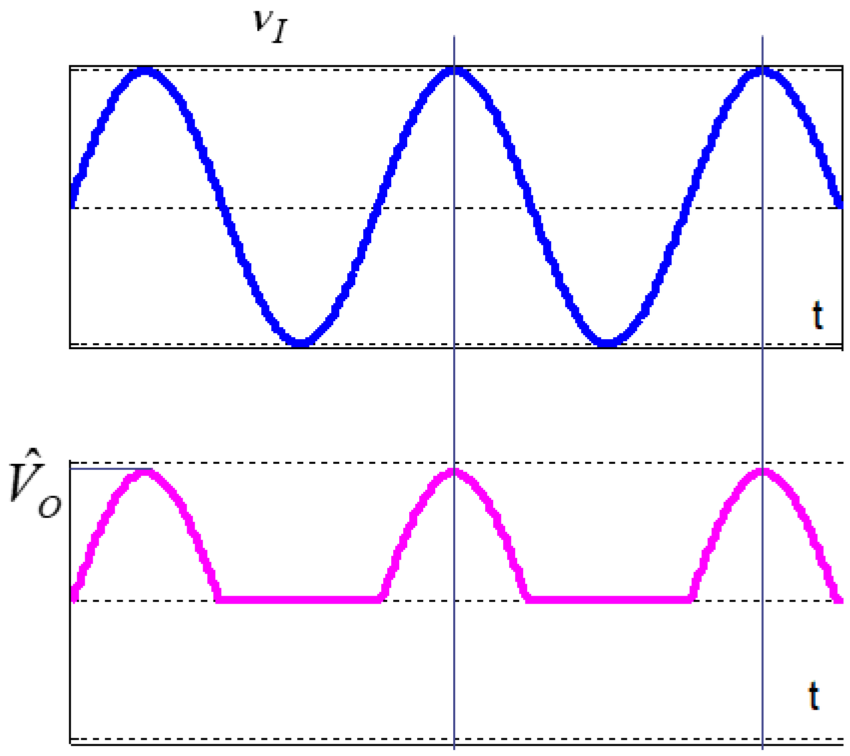
How “to smooth” the output voltage (as close as possible to dc)?

Power-supply filtering - cont.

1st step

Half-wave (full wave) rectifier

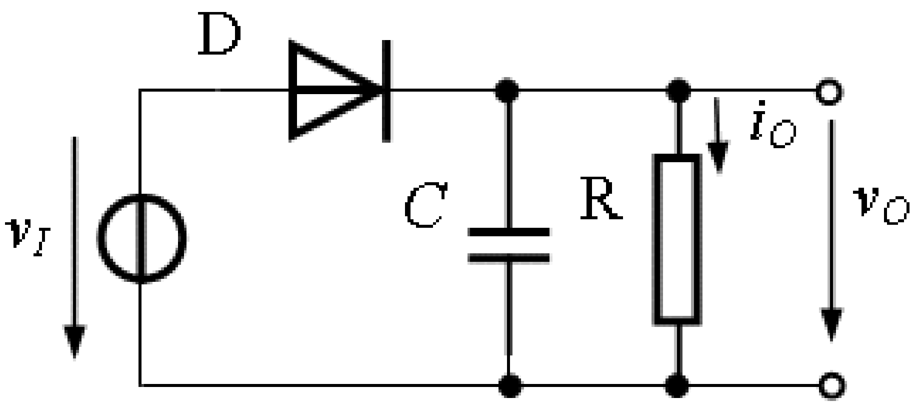


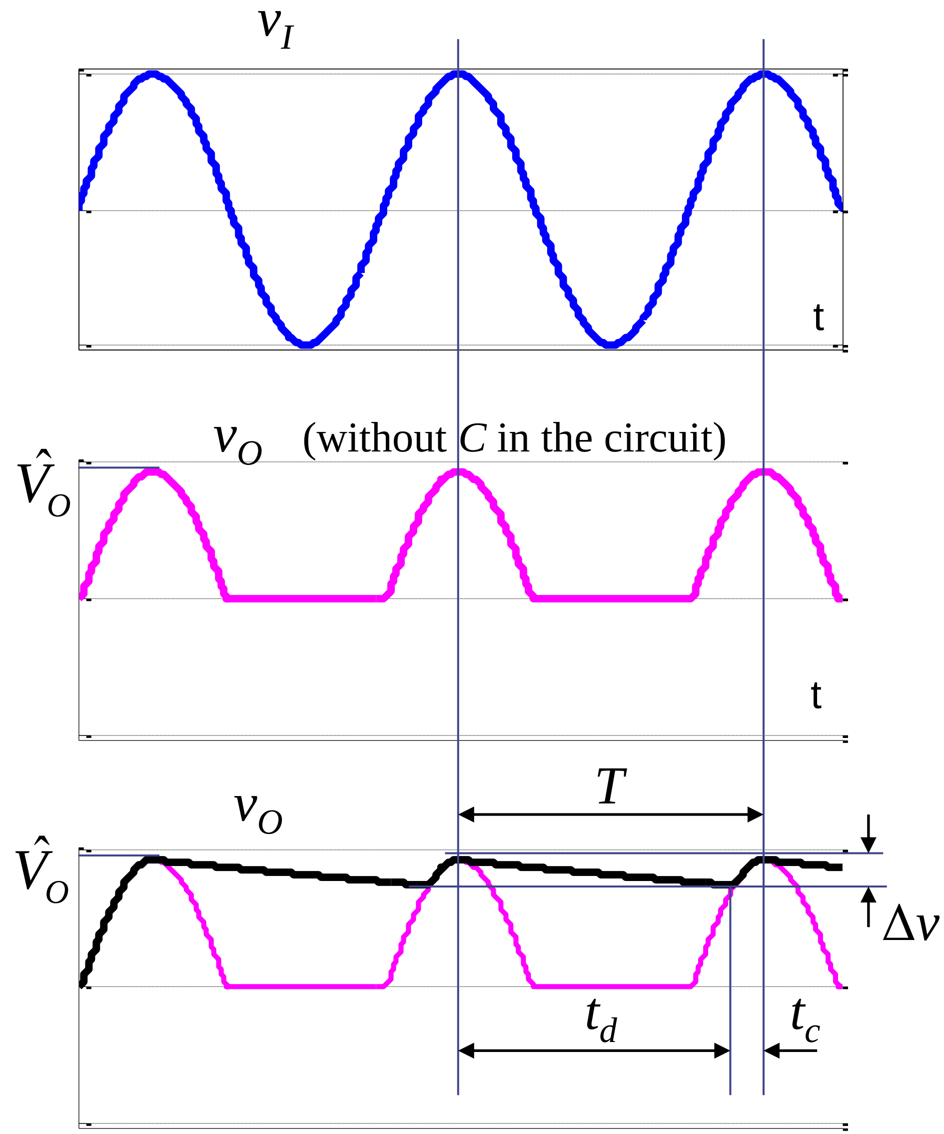


How "to smooth" the output voltage (as close as possible to dc)?

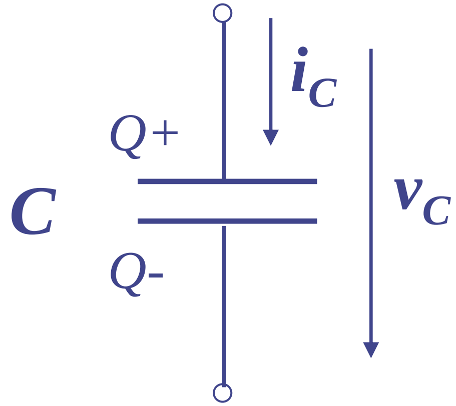
Power-supply filtering

Half-wave rectifier with capacitive filter (and load)





Between successive peeks of input voltage (and rectified voltage), D - *off*, the capacitor acts as a element of electrical energy storage, providing electrical energy in the load, with a decrease of its own voltage.



$$\boxed{C dv_C(t) = i_C(t)dt}$$

$$v_{c(t)} = \frac{1}{C}\int_{t_0}^{t} i_c(t)dt + v_c(t_0)$$

If the **current** through the capacitor, can be approximated as being a **constant** one I_C:

$$v_{c(t)} = \frac{1}{C} I_C(t - t_0) + v_c(t_0)$$

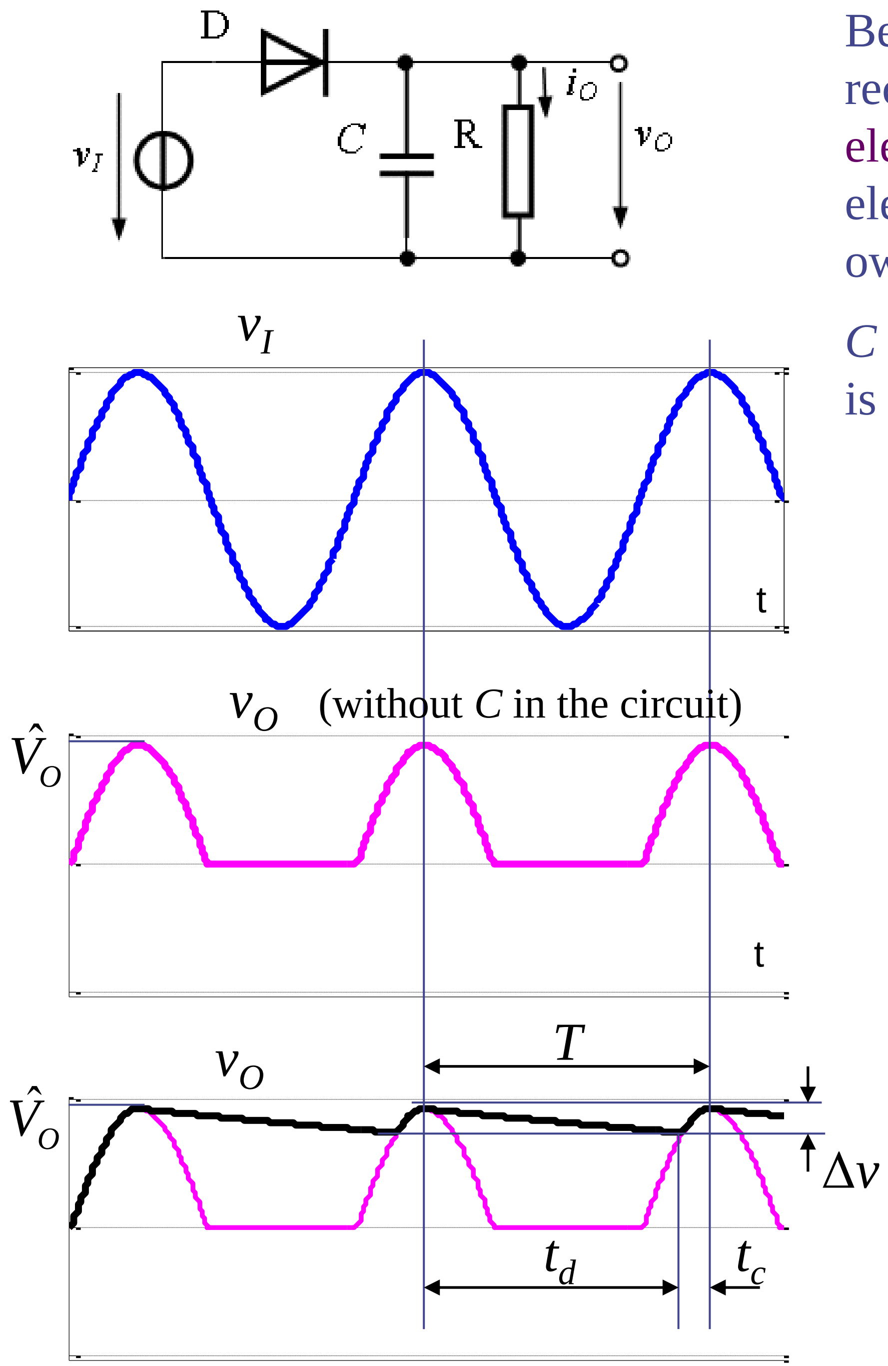
$$v_{c(t)} - v_c(t_0) = \frac{1}{C} I_C(t - t_0)$$

$$\Delta v_c = \frac{1}{C} I_C \Delta t$$

$$\boxed{C dv_C(t) = i_C(t)dt}$$

$$C\Delta v_c = I_C \Delta t$$

For I_C constant



Between successive peaks of input voltage (and rectified voltage), **D - *off***, the capacitor acts as a element of electrical energy storage, providing electrical energy in the load, with a decrease of its own voltage:

C discharges through *R;* the discharging current is supposed to be constant, to its maximum value.

$$\Delta v_c = \frac{1}{C} I_C \Delta t$$

$$I_C = \frac{\hat{V}_O}{R}$$

$$\Delta t = t_d = T - t_c \approx T$$

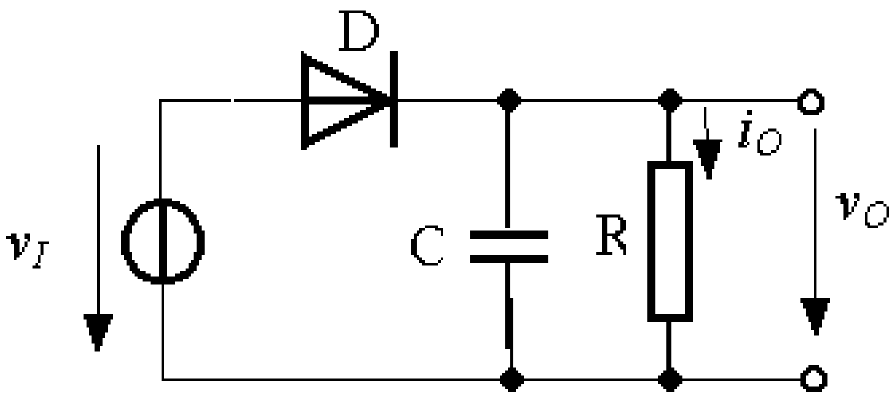
$$\Delta v_c = \Delta v = \frac{1}{C} I_C \Delta t = \frac{1}{C}\frac{\hat{V}_O}{R} T$$

$$\boxed{\Delta v = \hat{V}_O \frac{T}{RC} = \frac{1}{f}\frac{\hat{V}_O}{RC}}$$

RC – time constant of the circuit

Example

$\hat{V}_I = 10.7\text{V} \quad f = 50\text{ Hz} \quad R_L = 100\Omega \quad \Delta v < 1.5\text{V} \quad$ **C=?**



$$\hat{V}_O = \hat{V}_I - 0.7\text{V} = 10\text{V}$$

$$\Delta v = \frac{\hat{V}_O}{fRC} < 1.5\text{V}$$

$$C > \frac{\hat{V}_O}{1.5\, fR} = \frac{10}{1.5 \cdot 50 \cdot 100} = 1333\ \mu\text{F} \qquad C > 1333\mu\text{F}$$

We chose an electrolytic capacitor C =1500µF/25V

What is the actual value of the output ripple?

What should be a new value of C if the output ripple have to be reduce to the half?

Solve again in the case of full-wave rectification.