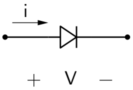
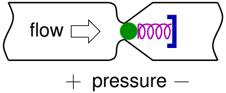
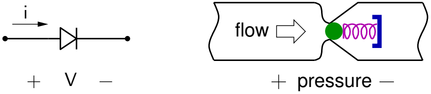
Diodes







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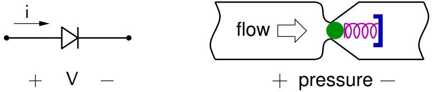

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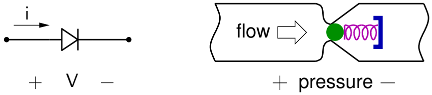

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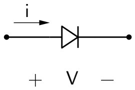

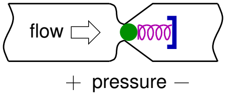

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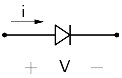
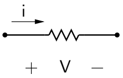
* A check valve presents a small resistance if the pressure $p > 0$, but blocks the flow (i.e., presents a large resistance) if $p < 0$.
* Similarly, a diode presents a small resistance in the forward direction and a large resistance in the reverse direction.
* Note: In a practical diode, the resistance $R_D = V/i$ is a nonlinear function of the applied voltage V. However, it is often a good approximation to treat it as a constant resistance which is small if V is positive and large if V is negative.

Simple models: $R_{\text{on}}/R_{\text{off}}$ model





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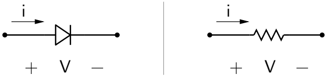

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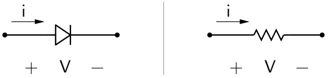

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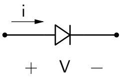

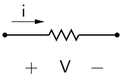

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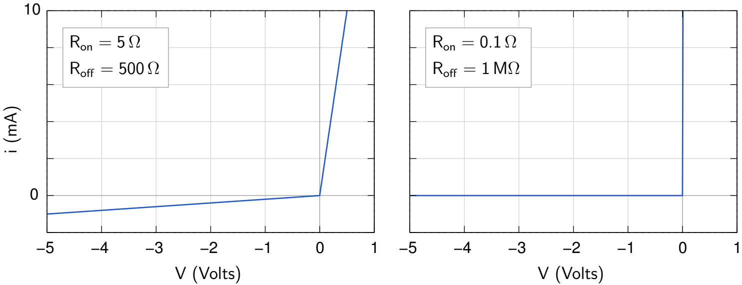
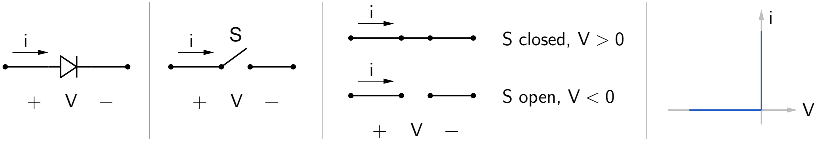
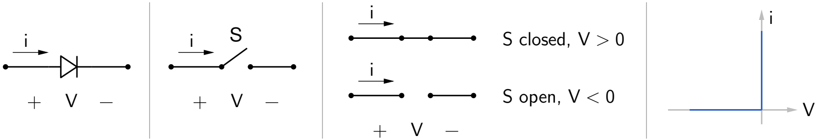


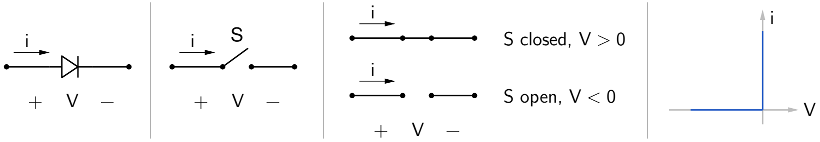


i
+ V −
i
S
+ V −
i
S closed, V > 0
i
S open, V < 0
+ V −
i
V

Simple models: ideal switch



$*$ Forward bias: $i > 0\,\text{A}$, $V = 0\,\text{V}$, $\rightarrow$ S is closed (a perfect contact).



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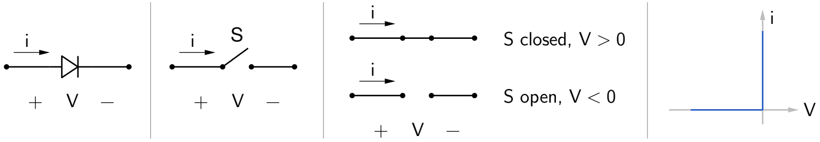

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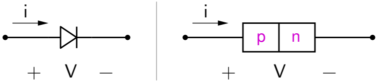
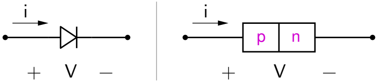
* The actual values of V and i for a diode in a circuit get determined by the i-V relationship of the diode *and* the constraints on V and i imposed by the circuit.


i
+
V
−
i
p
n
+
V
−

Shockley diode equation



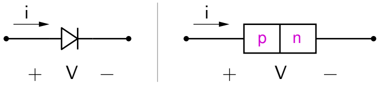
$$i = I_s \left[\exp\left(\frac{V}{V_T}\right) - 1 \right], \text{ where } V_T = k_B T/q\,.$$

$k_B =$ Boltzmann's constant $= 1.38 \times 10^{-23}\ J/K$.

$q =$ electron charge $= 1.602 \times 10^{-19}$ Coul.

$T =$ temperature in $^\circ K$.

$V_T \approx 25\ \mathrm{m}V$ at room temperature (27 °C).



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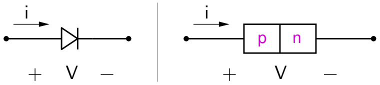

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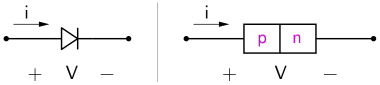

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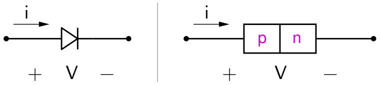

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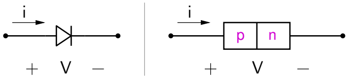
* The "turn-on" voltage (V_{on}) of a diode depends on the value of I_s. V_{on} may be defined as the voltage at which the diode starts carrying a substantial forward current (say, a few mA).
  For a silicon diode, $V_{on} \approx 0.7\ V$.
  For LEDs, V_{on} varies from about 1.8 V (red) to 3.3 V (blue).

Shockley diode equation



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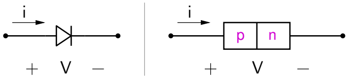

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0.1	3.87	0.479×10^{2}	0.469×10^{-11}
0.2	7.74	0.229×10^{4}	0.229×10^{-9}
0.3	11.6	0.110×10^{6}	0.110×10^{-7}
0.4	15.5	0.525×10^{7}	0.525×10^{-6}
0.5	19.3	0.251×10^{9}	0.251×10^{-4}
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0.62	24.0	0.260×10^{11}	0.260×10^{-2}
0.64	24.8	0.565×10^{11}	0.565×10^{-2}
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0.68	26.3	0.265×10^{12}	0.265×10^{-1}
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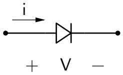

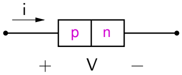

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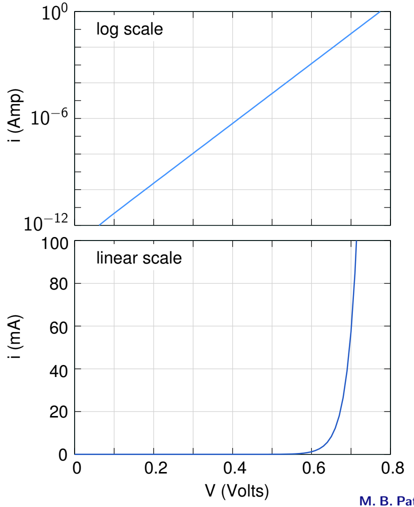
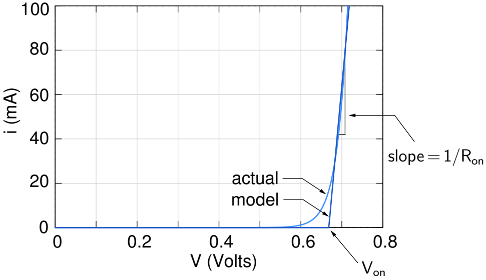
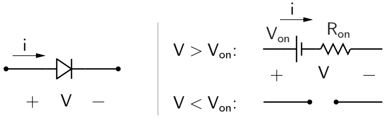
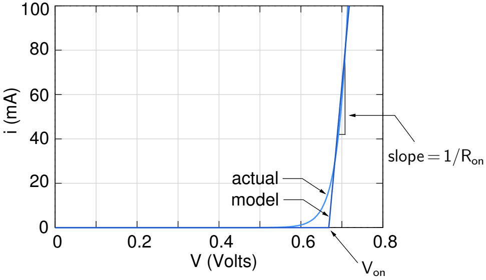


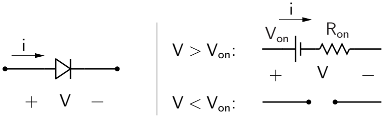




∗ In many circuits, R_{on} can be neglected (assumed to be $0\,\Omega$) since it is much smaller than the other resistances in the circuit. In that case, the diode in forward conduction can be replaced with simply a battery.

Diode circuit model





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* Note that the "battery" shown in the above model is not a "source" of power! It can only absorb power (see the direction of the current), causing heat dissipation.

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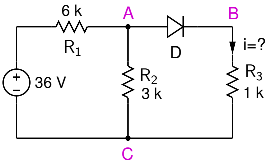
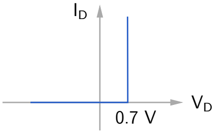
* In transient analysis, we need to find the time points at which a diode turns on or off, and analyse the circuit in intervals between these time points.
* In some diode circuits, the exponential nature of the diode I-V relationship (the Shockley model) is made use of. For these circuits, computation is usually difficult, and computer simulation may be required to solve the resulting non-linear equations.

Diode circuit example





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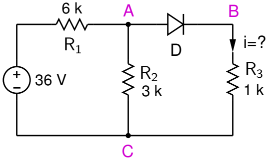
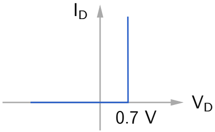
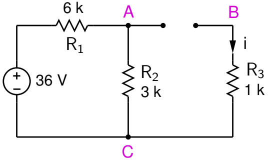




Case 1: D is off.



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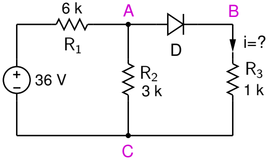

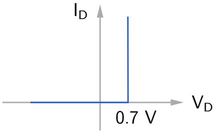

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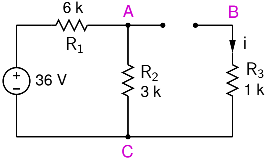

$$V_{AB} = V_{AC} = \frac{3}{9} \times 36 = 12\ \text{V}\,,$$

which is not consistent with our assumption of D being off.

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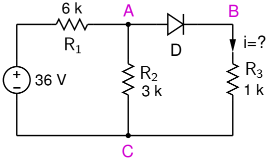

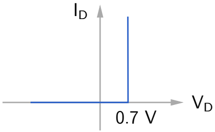

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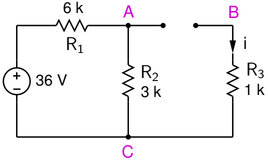

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$\rightarrow$ D must be on.

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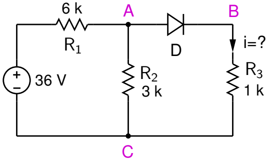
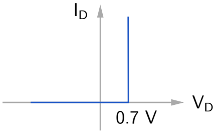
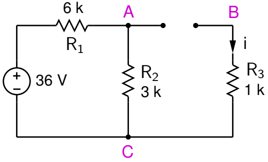




Case 1: D is off.

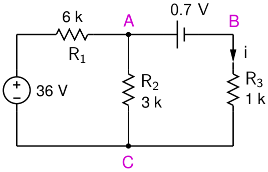


$$V_{AB} = V_{AC} = \frac{3}{9} \times 36 = 12 \text{ V},$$

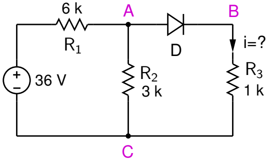
which is not consistent with our assumption of D being off.

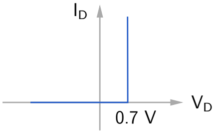
$\rightarrow$ D must be on.

Case 2: D is on.

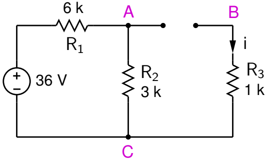


Diode circuit example





Case 1: D is off.

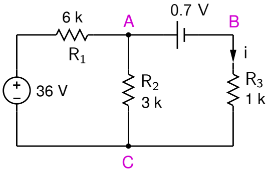


$$V_{AB} = V_{AC} = \frac{3}{9} \times 36 = 12\ \mathrm{V}\,,$$

which is not consistent with our assumption of D being off.

$\rightarrow$ D must be on.

Case 2: D is on.

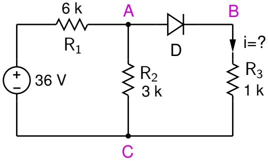


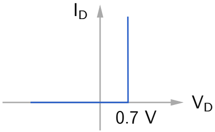
Taking $V_C = 0$ V,

$$\frac{V_A - 36}{6\ \mathrm{k}} + \frac{V_A}{3\ \mathrm{k}} + \frac{V_A - 0.7}{1\ \mathrm{k}} = 0\,,$$

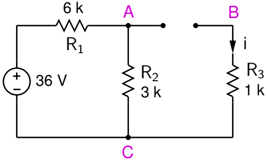
$\rightarrow\ V_A = 4.47$ V, $i = 3.77$ mA.

Diode circuit example





Case 1: D is off.

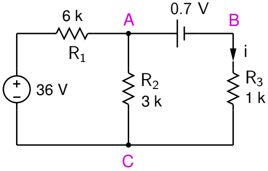


$$V_{AB} = V_{AC} = \frac{3}{9} \times 36 = 12\ \text{V}\,,$$

which is not consistent with our assumption of D being off.

$\rightarrow$ D must be on.

Case 2: D is on.

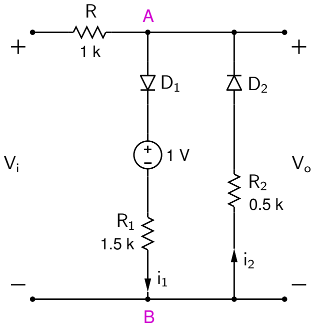


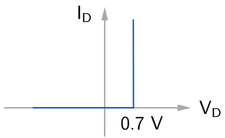
Taking $V_C = 0$ V,

$$\frac{V_A - 36}{6\ \text{k}} + \frac{V_A}{3\ \text{k}} + \frac{V_A - 0.7}{1\ \text{k}} = 0\,,$$

$\rightarrow\ V_A = 4.47$ V, $i = 3.77$ mA .

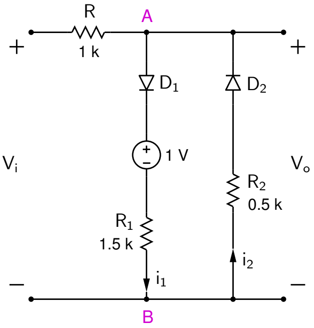
Remark: Often, we can figure out by inspection if a diode is on or off.

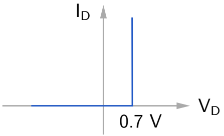




(a) Plot V_o versus V_i for $-5\ \text{V} < V_i < 5\ \text{V}$.

(b) Plot $V_o(t)$ for a triangular input:
-5 V to $+5$ V, 500 Hz.





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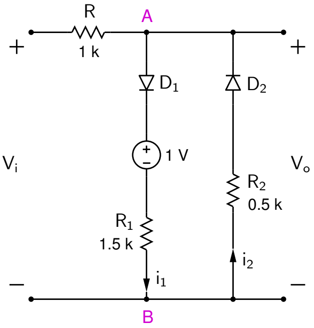
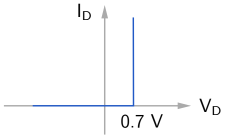
First, let us show that D_1 on $\Rightarrow$ D_2 off, and D_2 on $\Rightarrow$ D_1 off.





(a) Plot V_o versus V_i for $-5\ \mathrm{V} < V_i < 5\ \mathrm{V}$.

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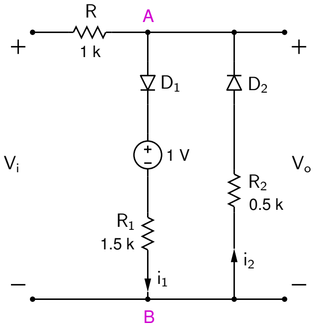
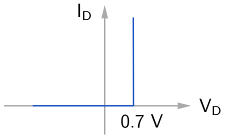
First, let us show that D_1 on $\Rightarrow$ D_2 off, and D_2 on $\Rightarrow$ D_1 off.

Consider D_1 to be on $\rightarrow$ $V_{AB} = 0.7 + 1 + i_1 R_1$.

Diode circuit example





(a) Plot V_o versus V_i for $-5\ V < V_i < 5\ V$.

(b) Plot $V_o(t)$ for a triangular input:
-5 V to $+5$ V, 500 Hz.

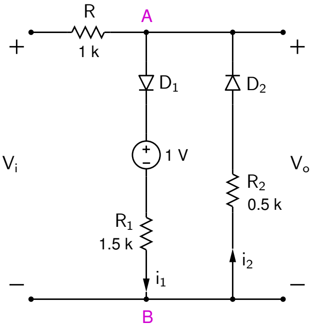
First, let us show that D_1 on $\Rightarrow$ D_2 off, and D_2 on $\Rightarrow$ D_1 off.

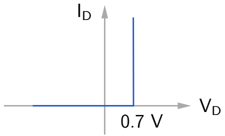
Consider D_1 to be on $\rightarrow$ $V_{AB} = 0.7 + 1 + i_1 R_1$.

Note that $i_1 > 0$, since D_1 can only conduct in the forward direction.

$\Rightarrow$ $V_{AB} > 1.7\ V \Rightarrow D_2$ cannot conduct.

Diode circuit example





(a) Plot V_o versus V_i for $-5\ V < V_i < 5\ V$.

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First, let us show that D_1 on $\Rightarrow$ D_2 off, and D_2 on $\Rightarrow$ D_1 off.

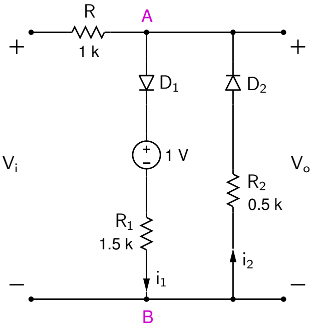
Consider D_1 to be on $\rightarrow$ $V_{AB} = 0.7 + 1 + i_1 R_1$.

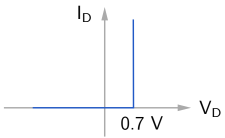
Note that $i_1 > 0$, since D_1 can only conduct in the forward direction.

$\Rightarrow$ $V_{AB} > 1.7\ V \Rightarrow D_2$ cannot conduct.

Similarly, if D_2 is on, $V_{BA} > 0.7\ V$, i.e., $V_{AB} < -0.7\ V \Rightarrow D_1$ cannot conduct.

Diode circuit example





(a) Plot V_o versus V_i for $-5\ V < V_i < 5\ V$.

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First, let us show that D_1 on $\Rightarrow$ D_2 off, and D_2 on $\Rightarrow$ D_1 off.

Consider D_1 to be on $\rightarrow$ $V_{AB} = 0.7 + 1 + i_1 R_1$.

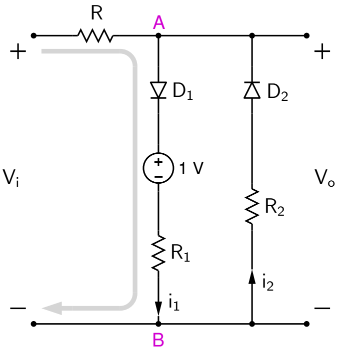
Note that $i_1 > 0$, since D_1 can only conduct in the forward direction.

$\Rightarrow V_{AB} > 1.7\ V \Rightarrow D_2$ cannot conduct.

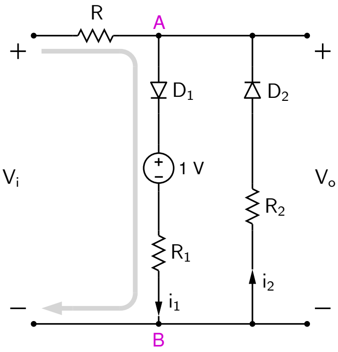
Similarly, if D_2 is on, $V_{BA} > 0.7\ V$, i.e., $V_{AB} < -0.7\ V \Rightarrow D_1$ cannot conduct.

Clearly, D_1 on $\Rightarrow$ D_2 off, and D_2 on $\Rightarrow$ D_1 off.

Diode circuit example



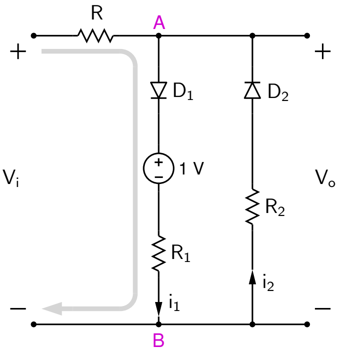
Diode circuit example



D_1 on:

$$V_i = i_1(R + R_1) + 1 + 0.7$$

Diode circuit example

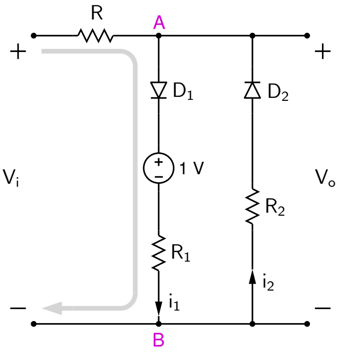


D_1 on:

$$V_i = i_1(R + R_1) + 1 + 0.7$$

Since $i_1 > 0$, $\boxed{V_i > 1.7\,\text{V}}$

Diode circuit example



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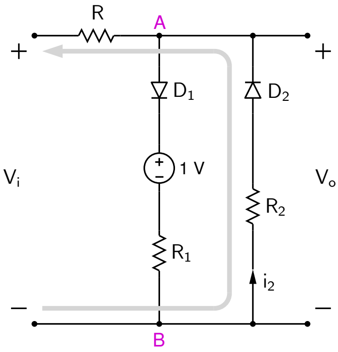
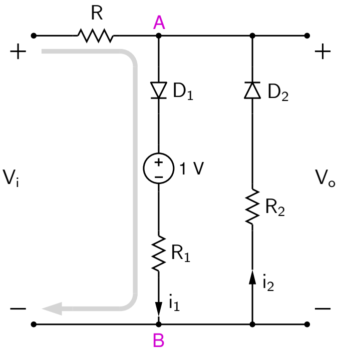


Diode circuit example



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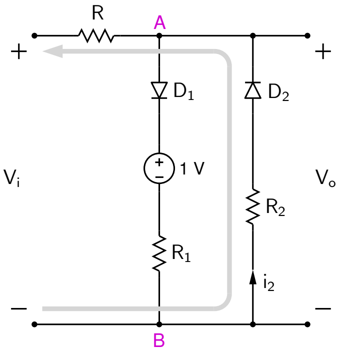
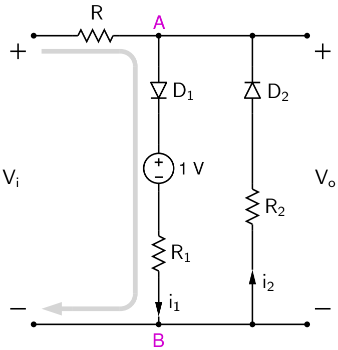


D_2 on:

$$i_2(R + R_2) + 0.7 + V_i = 0$$

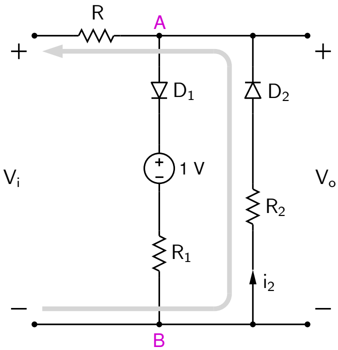
Diode circuit example



D_1 on:

$$V_i = i_1(R + R_1) + 1 + 0.7$$

Since $i_1 > 0$, $\boxed{V_i > 1.7\,\mathrm{V}}$

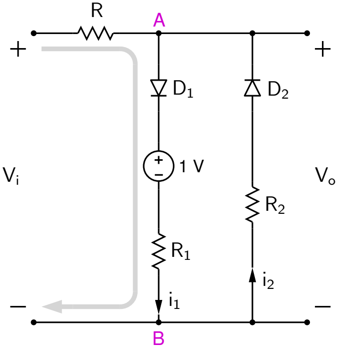


D_2 on:

$$i_2(R + R_2) + 0.7 + V_i = 0$$

$$V_i = -\left[0.7 + i_2(R + R_2)\right]$$

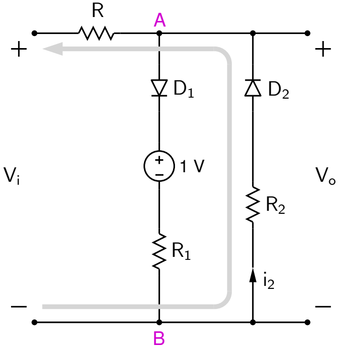
Diode circuit example



D_1 on:

$$V_i = i_1(R + R_1) + 1 + 0.7$$

Since $i_1 > 0$, $\boxed{V_i > 1.7\,\text{V}}$



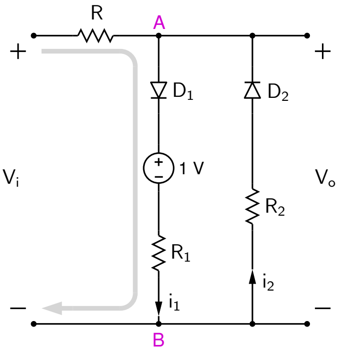
D_2 on:

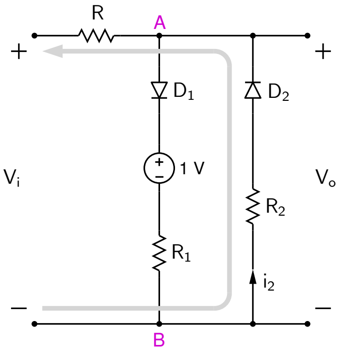
$$i_2(R + R_2) + 0.7 + V_i = 0$$

$$V_i = -\left[0.7 + i_2(R + R_2)\right]$$

Since $i_2 > 0$, $\boxed{V_i < -0.7\,\text{V}}$

Diode circuit example





D_1 on:

$$V_i = i_1(R + R_1) + 1 + 0.7$$

Since $i_1 > 0$, $\boxed{V_i > 1.7\,\mathrm{V}}$

D_2 on:

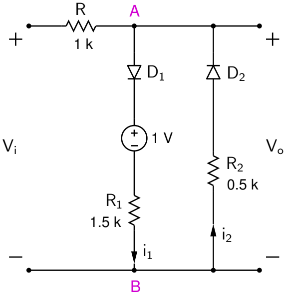
$$i_2(R + R_2) + 0.7 + V_i = 0$$

$$V_i = -\left[0.7 + i_2(R + R_2)\right]$$

Since $i_2 > 0$, $\boxed{V_i < -0.7\,\mathrm{V}}$

For $-0.7\,\mathrm{V} < V_i < 1.7\,\mathrm{V}$, neither D_1 nor D_2 can conduct.

* For $-0.7\ V < V_i < 1.7\ V$, both D_1 and D_2 are off.
  $\rightarrow$ no drop across R, and $V_o = V_i$. (1)



* For $-0.7\ V < V_i < 1.7\ V$, both D_1 and D_2 are off.
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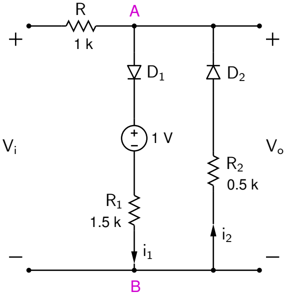
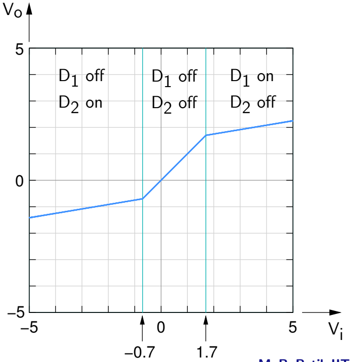


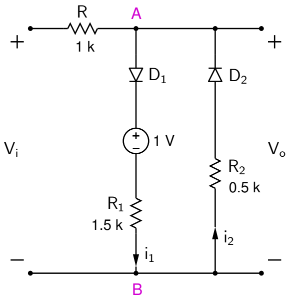


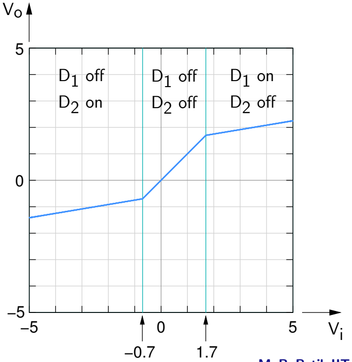
* For $-0.7\ V < V_i < 1.7\ V$, both D_1 and D_2 are off.
  $\rightarrow$ no drop across R, and $V_o = V_i$. (1)

* For $V_i < -0.7\ V$, D_2 conducts. $\rightarrow V_o = -0.7 - i_2 R_2$.
  Use KVL to get i_2: $V_i + i_2 R_2 + 0.7 + R i_2 = 0$.
  $\rightarrow i_2 = -\dfrac{V_i + 0.7}{R + R_2}$, and

$$V_o = -0.7 - R_2 i_2 = \frac{R_2}{R + R_2}\, V_i - 0.7\, \frac{R}{R + R_2}\,. \qquad (2)$$

  Slope $\dfrac{dV_o}{dV_i} = \dfrac{R_2}{R + R_2} = \dfrac{0.5\,\mathrm{k}}{1\,\mathrm{k} + 0.5\,\mathrm{k}} = \dfrac{1}{3}$.





* For $-0.7\ V < V_i < 1.7\ V$, both D_1 and D_2 are off.
  $\rightarrow$ no drop across R, and $V_o = V_i$. (1)

* For $V_i < -0.7\ V$, D_2 conducts. $\rightarrow V_o = -0.7 - i_2 R_2$.
  Use KVL to get i_2: $V_i + i_2 R_2 + 0.7 + R i_2 = 0$.

  $\rightarrow i_2 = -\dfrac{V_i + 0.7}{R + R_2}$, and

  $$V_o = -0.7 - R_2 i_2 = \frac{R_2}{R + R_2}\,V_i - 0.7\,\frac{R}{R + R_2}\,. \qquad (2)$$

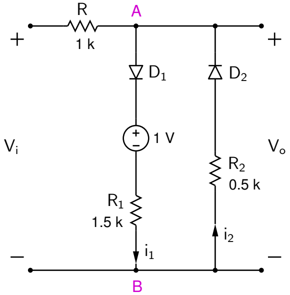
  Slope $\dfrac{dV_o}{dV_i} = \dfrac{R_2}{R + R_2} = \dfrac{0.5\text{ k}}{1\text{ k} + 0.5\text{ k}} = \dfrac{1}{3}$.

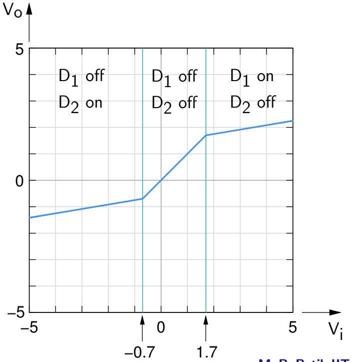
* For $V_i > 1.7\ V$, D_1 conducts. $\rightarrow V_o = 0.7 + 1 + i_1 R_1$.
  Use KVL to get i_1: $-V_i + i_1 R + 0.7 + 1 + i_1 R_1 = 0$.

  $\rightarrow i_1 = \dfrac{V_i - 1.7}{R + R_1}$, and

  $$V_o = 1.7 + R_1 i_1 = \frac{R_1}{R + R_1}\,V_i + 1.7\,\frac{R}{R + R_1}\,. \qquad (3)$$

  Slope $\dfrac{dV_o}{dV_i} = \dfrac{R_1}{R + R_1} = \dfrac{1.5\text{ k}}{1\text{ k} + 1.5\text{ k}} = \dfrac{3}{5}$.



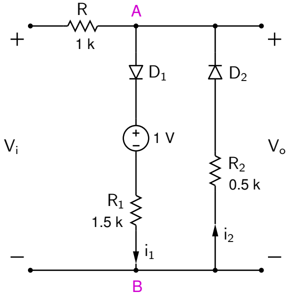


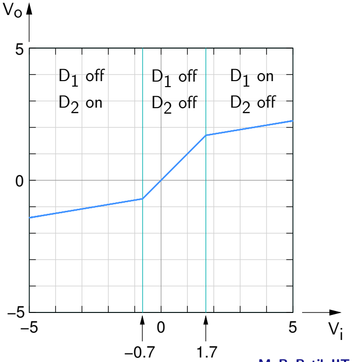
* For $-0.7\ V < V_i < 1.7\ V$, both D_1 and D_2 are off.
  $\rightarrow$ no drop across R, and $V_o = V_i$. (1)

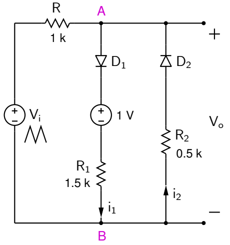
* For $V_i < -0.7\ V$, D_2 conducts. $\rightarrow V_o = -0.7 - i_2 R_2$.
  Use KVL to get i_2: $V_i + i_2 R_2 + 0.7 + R i_2 = 0$.
  $$\rightarrow i_2 = -\frac{V_i + 0.7}{R + R_2}\ \text{, and}$$
  $$V_o = -0.7 - R_2 i_2 = \frac{R_2}{R + R_2}\, V_i - 0.7\, \frac{R}{R + R_2}\ . \qquad (2)$$
  $$\text{Slope}\ \frac{dV_o}{dV_i} = \frac{R_2}{R + R_2} = \frac{0.5\,\text{k}}{1\,\text{k} + 0.5\,\text{k}} = \frac{1}{3}\ .$$

* For $V_i > 1.7\ V$, D_1 conducts. $\rightarrow V_o = 0.7 + 1 + i_1 R_1$.
  Use KVL to get i_1: $-V_i + i_1 R + 0.7 + 1 + i_1 R_1 = 0$.
  $$\rightarrow i_1 = \frac{V_i - 1.7}{R + R_1}\ \text{, and}$$
  $$V_o = 1.7 + R_1 i_1 = \frac{R_1}{R + R_1}\, V_i + 1.7\, \frac{R}{R + R_1}\ . \qquad (3)$$
  $$\text{Slope}\ \frac{dV_o}{dV_i} = \frac{R_1}{R + R_1} = \frac{1.5\,\text{k}}{1\,\text{k} + 1.5\,\text{k}} = \frac{3}{5}\ .$$

* Using Eqs. (1)-(3), we plot V_o versus V_i.
  (SEQUEL file: `ee101_diode_circuit_1.sqproj`)

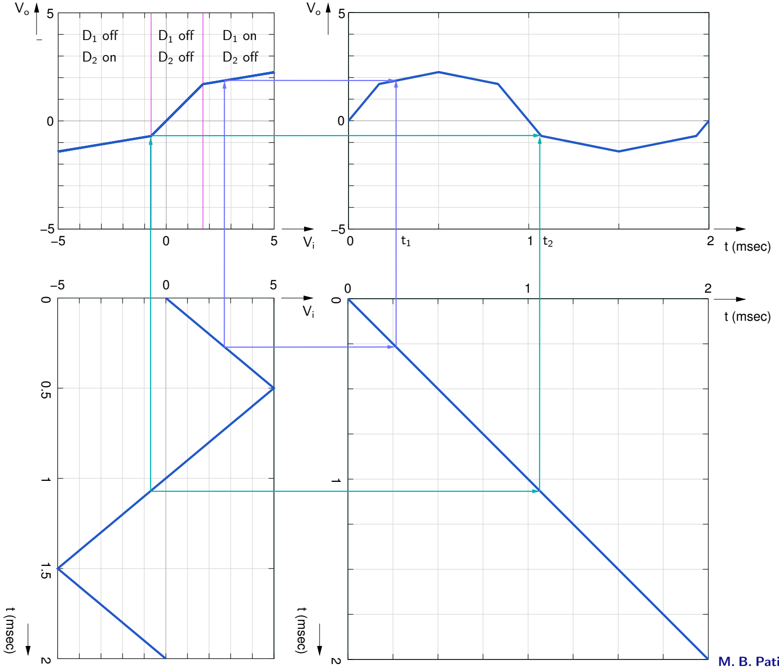




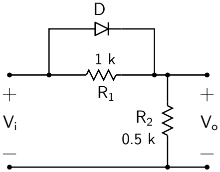


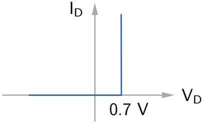
Point-by-point construction of V_o versus t:

Two time points, t_1 and t_2, are shown as examples.



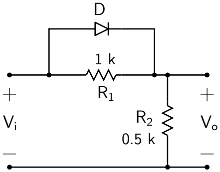
Diode circuit example

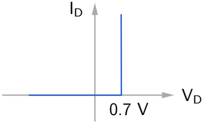




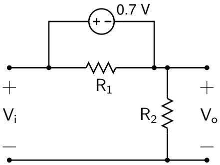
Plot V_o versus V_i for $-5\ \text{V} < V_i < 5\ \text{V}$.

Diode circuit example





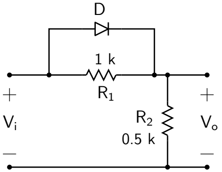
Plot V_o versus V_i for $-5\text{ V} < V_i < 5\text{ V}$.

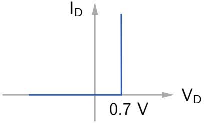


D on

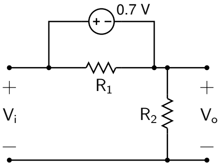
$V_o = V_i - 0.7$

Diode circuit example



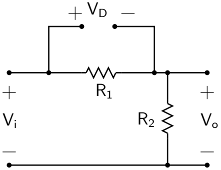


Plot V_o versus V_i for $-5\text{ V} < V_i < 5\text{ V}$.



D on

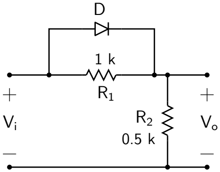
$$V_o = V_i - 0.7$$

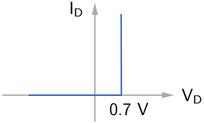


D off

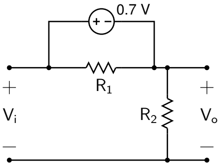
$$V_o = \frac{R_2}{R_1 + R_2} V_i$$

Diode circuit example





Plot V_o versus V_i for $-5\ \text{V} < V_i < 5\ \text{V}$.



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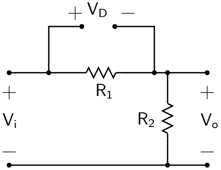
$$V_o = V_i - 0.7$$

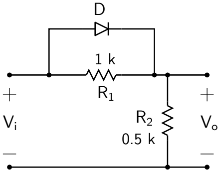


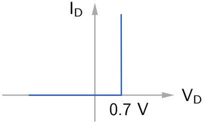
D off

$$V_o = \frac{R_2}{R_1 + R_2} V_i$$

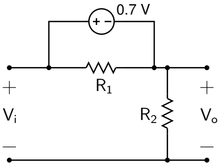
At what value of V_i will the diode turn on?

Diode circuit example



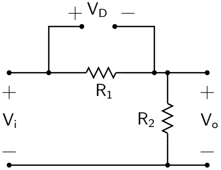


Plot V_o versus V_i for $-5\text{ V} < V_i < 5\text{ V}$.



D on

$V_o = V_i - 0.7$



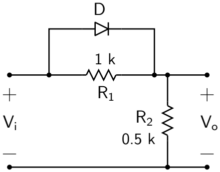
D off

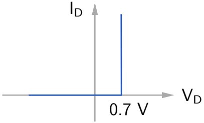
$$V_o = \frac{R_2}{R_1 + R_2} V_i$$

At what value of V_i will the diode turn on?

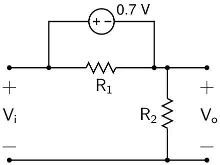
In the off state, $V_D = \dfrac{R_1}{R_1 + R_2}\, V_i$.

Diode circuit example



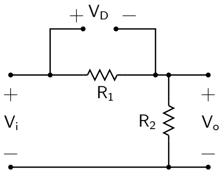


Plot V_o versus V_i for $-5\ V < V_i < 5\ V$.



D on

$V_o = V_i - 0.7$



D off

$V_o = \dfrac{R_2}{R_1 + R_2} V_i$

At what value of V_i will the diode turn on?

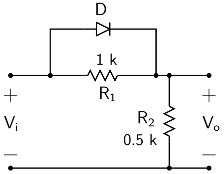
In the off state, $V_D = \dfrac{R_1}{R_1 + R_2}\, V_i$.

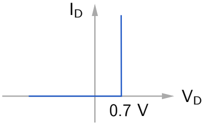
As V_i increases, V_D increases.

For D to turn on, we need $V_D =\ 0.7\ V$.

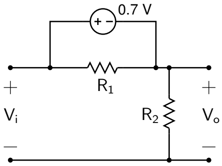
i.e., $V_i = \dfrac{R_1 + R_2}{R_1} \times 0.7 = 1.05\ V$.

Diode circuit example



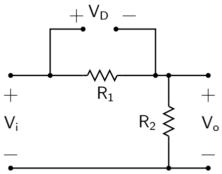


Plot V_o versus V_i for $-5\text{ V} < V_i < 5\text{ V}$.



D on

$V_o = V_i - 0.7$



D off

$$V_o = \frac{R_2}{R_1 + R_2} V_i$$

At what value of V_i will the diode turn on?

In the off state, $V_D = \dfrac{R_1}{R_1 + R_2} V_i$.

As V_i increases, V_D increases.

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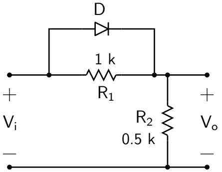
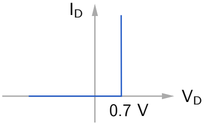
i.e., $V_i = \dfrac{R_1 + R_2}{R_1} \times 0.7 = 1.05\ V$.

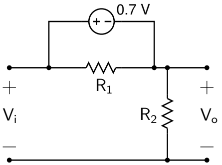
(SEQUEL file: `ee101_diode_circuit_2.sqproj`)

Diode circuit example



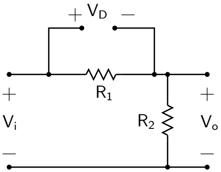


Plot V_o versus V_i for $-5\ V < V_i < 5\ V$.



D on

$$V_o = V_i - 0.7$$



D off

$$V_o = \frac{R_2}{R_1 + R_2} V_i$$

At what value of V_i will the diode turn on?

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As V_i increases, V_D increases.

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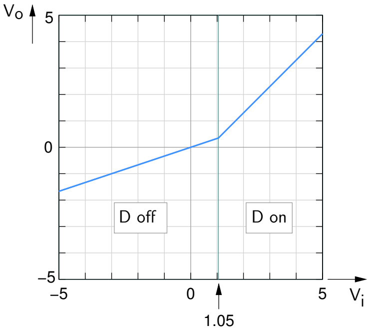
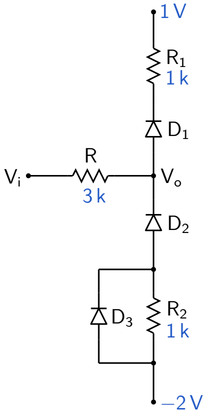
i.e., $V_i = \dfrac{R_1 + R_2}{R_1} \times 0.7 = 1.05\ V$.

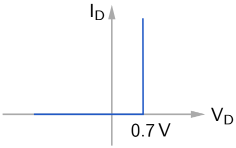
(SEQUEL file: `ee101_diode_circuit_2.sqproj`)



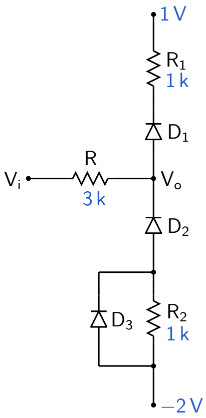
Diode circuit example



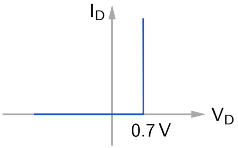
Plot V_o versus V_i (Ref: Sedra/Smith).



Diode circuit example

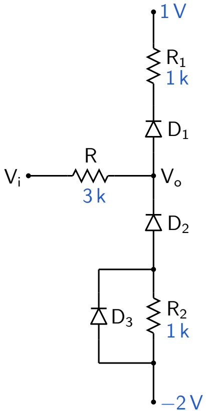


Plot V_o versus V_i (Ref: Sedra/Smith).



It is easier to find the status (on/off) of each diode w. r. t. V_o.

Diode circuit example



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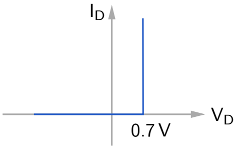

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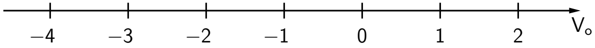
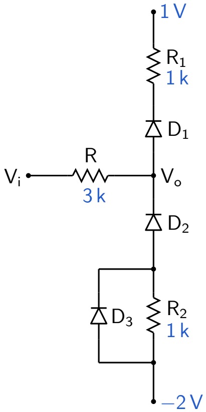


Diode circuit example



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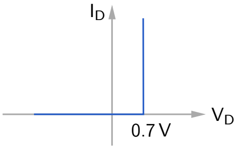

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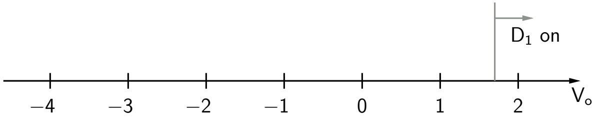
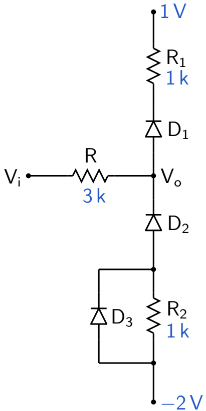


Diode circuit example



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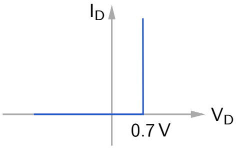

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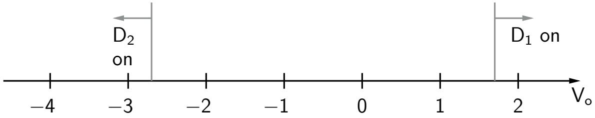
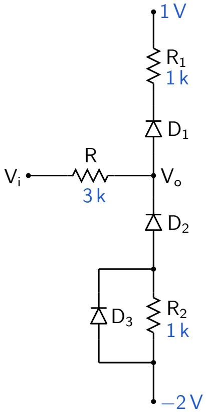


Diode circuit example



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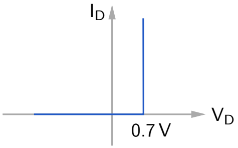

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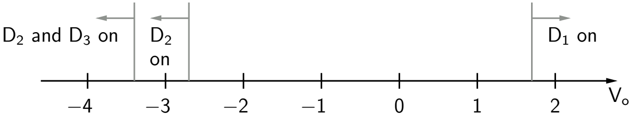
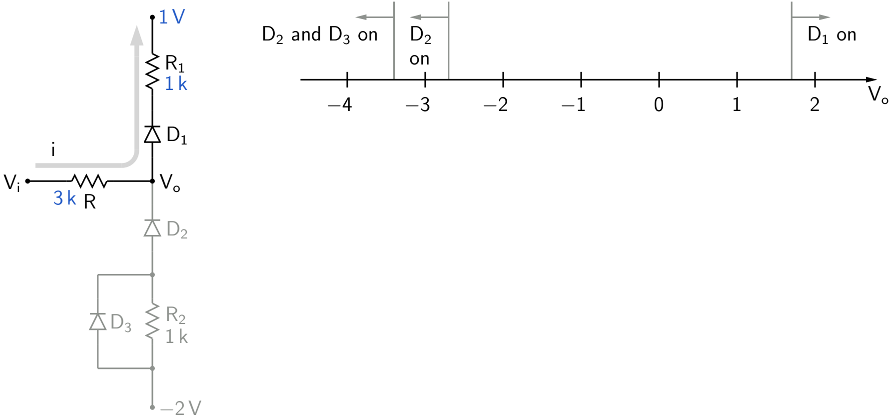
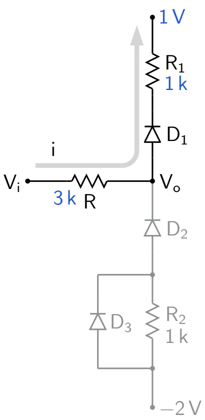
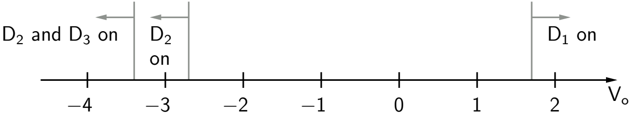


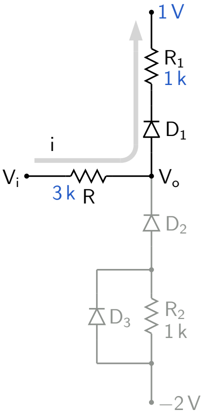

1 V
R1
1 k
D1
i
Vi
3 k
R
Vo
D2
D3
R2
1 k
−2 V
D2 and D3 on
D2
on
D1 on
−4
−3
−2
−1
0
1
2
Vo

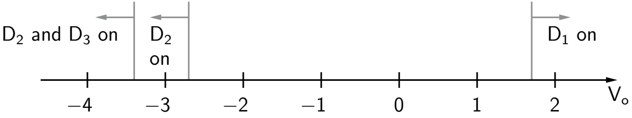




When D_1 just starts conducting,

$$V_o = 1.7\,\mathrm{V},\ i \approx 0 \rightarrow V_i = 1.7\,\mathrm{V}$$

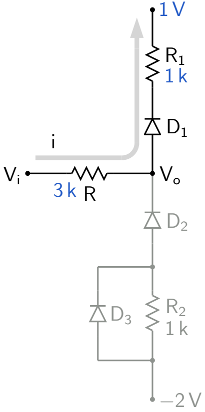


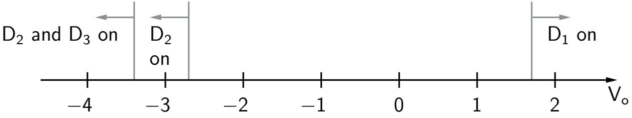


When D_1 just starts conducting,

$$V_o = 1.7\,\mathrm{V},\ i \approx 0 \rightarrow V_i = 1.7\,\mathrm{V}$$

For $V_i > 1.7\,\mathrm{V}$, $\quad V_o = 1.7 + \left(\dfrac{V_i - 1.7}{R + R_1}\right) R_1$





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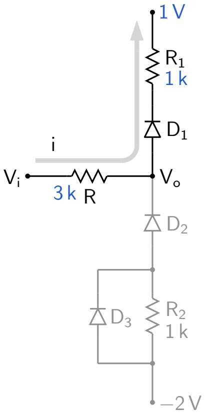
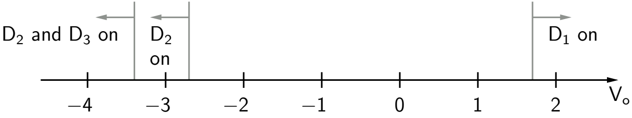
For $V_i > 1.7\,\mathrm{V}$, $V_o = 1.7 + \left(\dfrac{V_i - 1.7}{R + R_1}\right) R_1$

Slope $\dfrac{dV_o}{dV_i} = \dfrac{R_1}{R + R_1} = \dfrac{1}{4}$



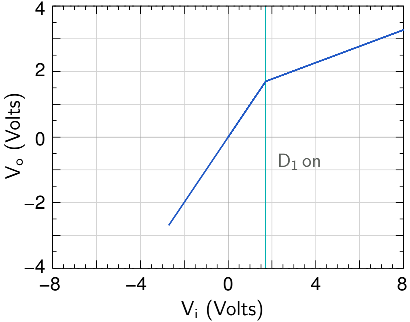


When D_1 just starts conducting,

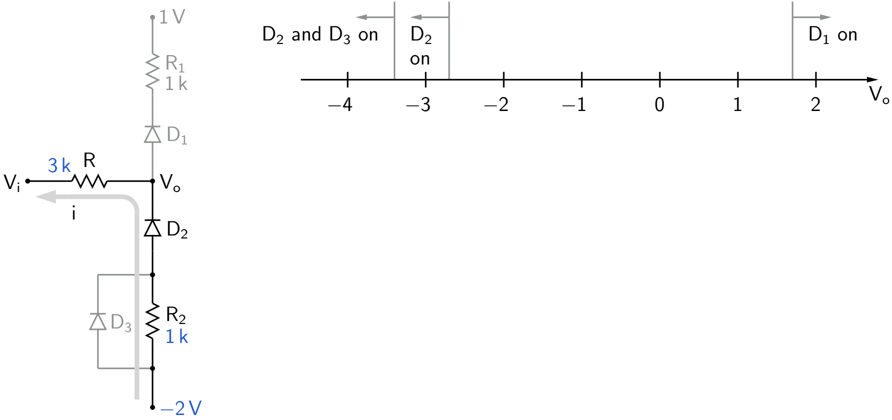
$$V_o = 1.7\,\text{V},\ i \approx 0 \rightarrow V_i = 1.7\,\text{V}$$

$$\text{For } V_i > 1.7\,\text{V},\quad V_o = 1.7 + \left(\frac{V_i - 1.7}{R + R_1}\right) R_1$$

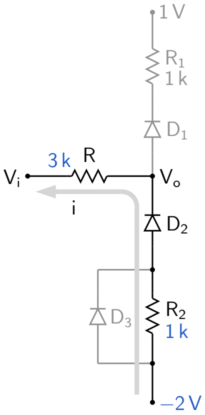
$$\text{Slope } \frac{dV_o}{dV_i} = \frac{R_1}{R + R_1} = \frac{1}{4}$$

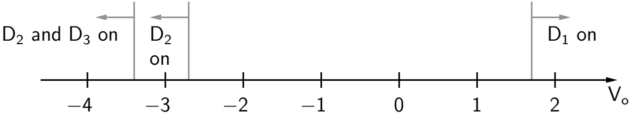


M. B. Patil, IIT Bombay



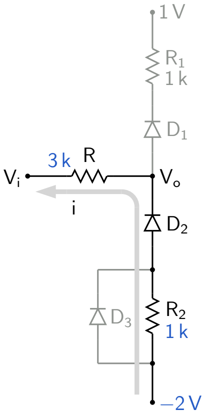
1 V
R1
1 k
D1
3 k
R
Vi
Vo
i
D2
D3
R2
1 k
−2 V
D2 and D3 on
D2
on
D1 on
−4
−3
−2
−1
0
1
2
Vo

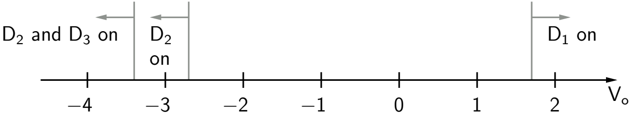




When D_2 just starts conducting,

$$V_o = -2.7\,\mathrm{V},\ i \approx 0 \rightarrow V_i = -2.7\,\mathrm{V}$$





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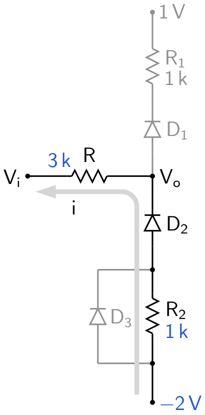

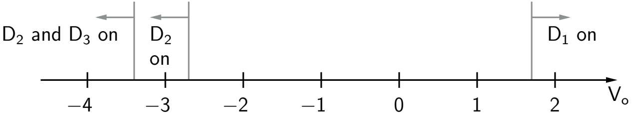

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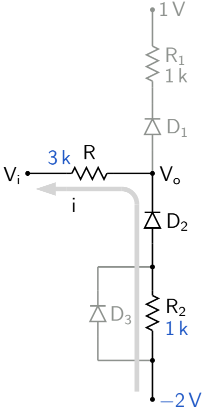
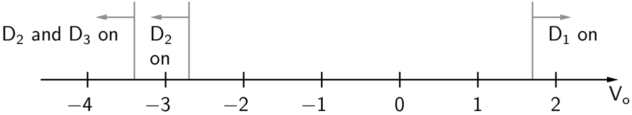
$$\text{Slope } \frac{dV_o}{dV_i} = 1 - \frac{R}{R + R_2} = \frac{R_2}{R + R_2} = \frac{1}{4}$$





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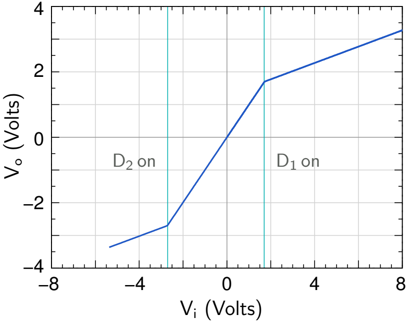

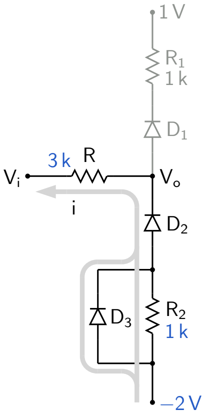
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R1
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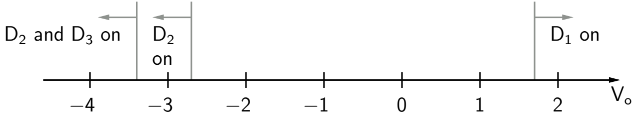
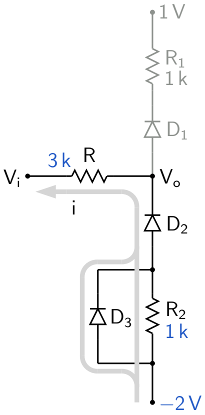
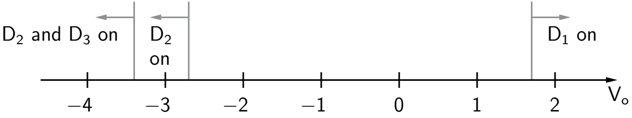

D2 and D3 on
D2
on
D1 on
−4
−3
−2
−1
0
1
2
Vo





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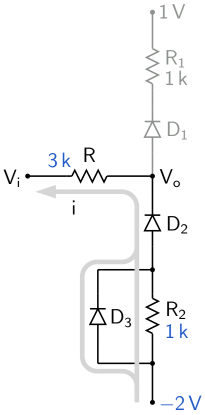

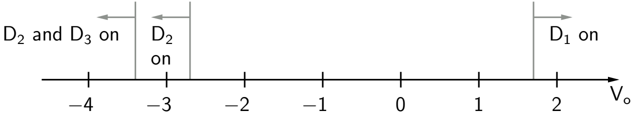

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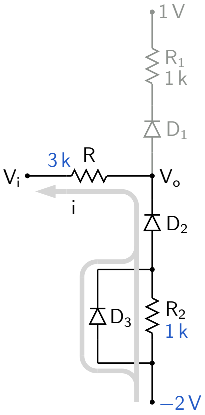

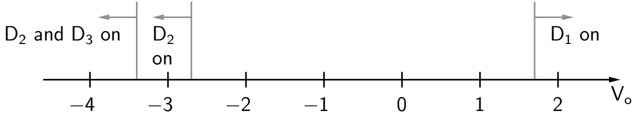

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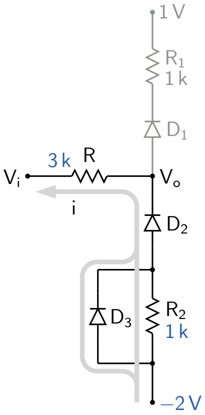

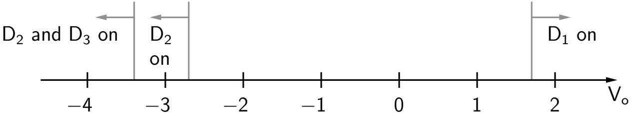

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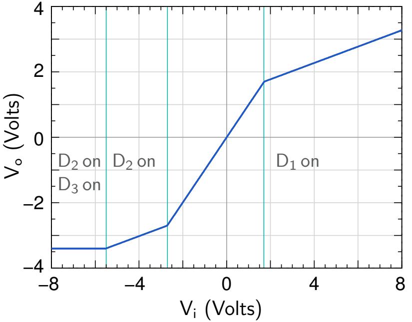

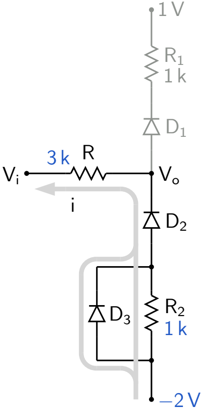

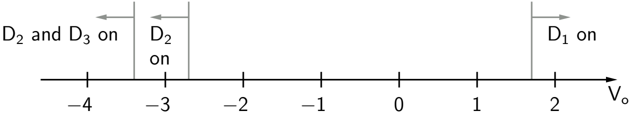

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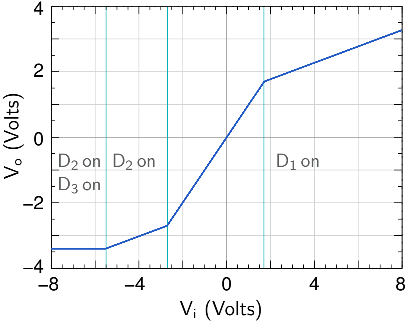

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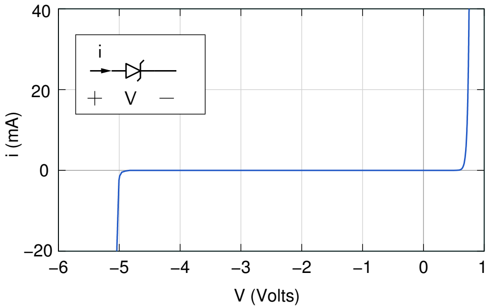
Reverse breakdown



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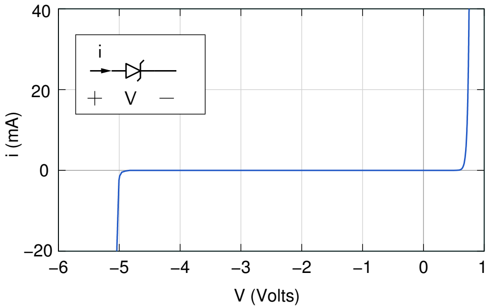

* In the reverse direction, an ideal diode presents a large resistance for *any* applied voltage.

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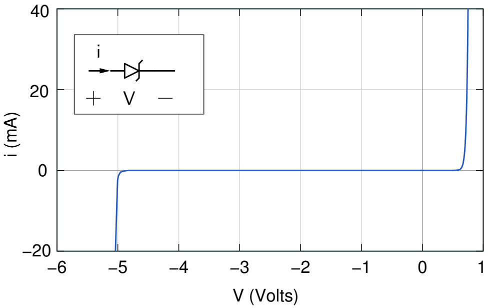

* In the reverse direction, an ideal diode presents a large resistance for *any* applied voltage.
* A real diode cannot withstand indefinitely large reverse voltages and "breaks down" at a certain voltage called the "breakdown voltage" (V_{BR}).

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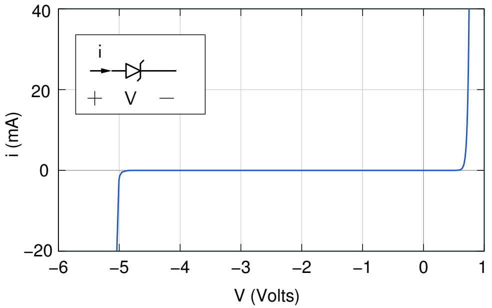

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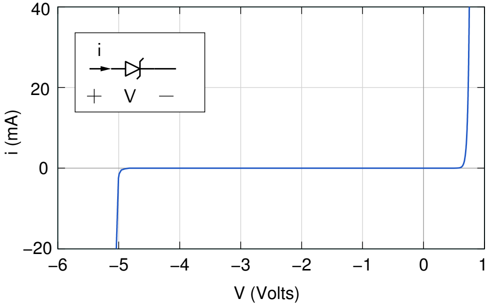
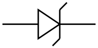
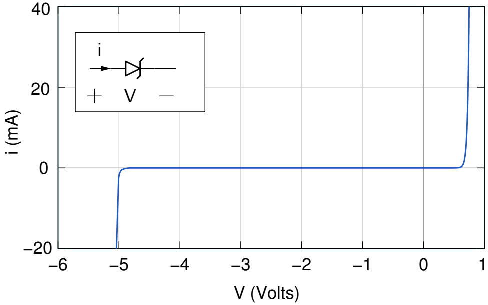
* When the reverse bias $V_R > V_{BR}$ (i.e., $V < -V_{BR}$), the diode allows a large amount of current. If the current is not constrained by the external circuit, the diode would get damaged.

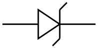




Symbol for a Zener diode

Reverse breakdown





Symbol for a Zener diode

* A wide variety of diodes is available, with V_{BR} ranging from a few Volts to a few thousand Volts! Generally, higher the breakdown voltage, higher is the cost.

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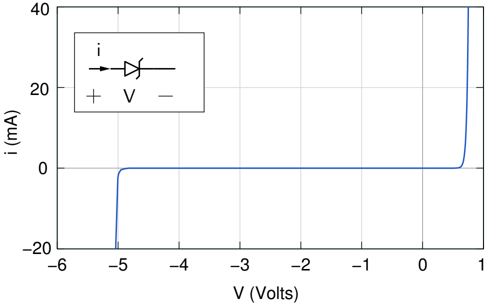

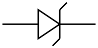

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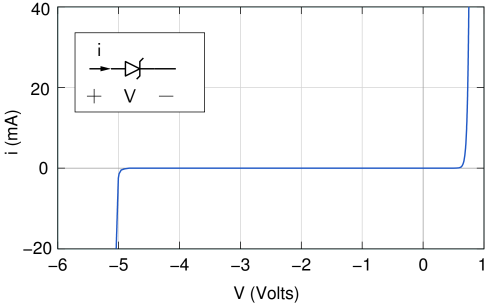

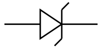

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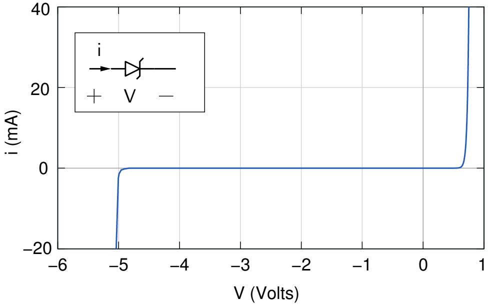

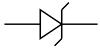

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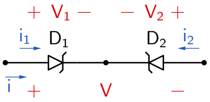
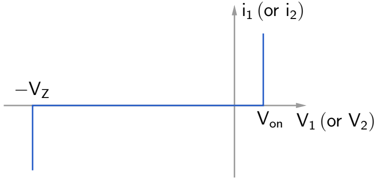
* Typically, circuits are designed so that the reverse bias across any diode is less than the V_{BR} rating for that diode.
* "Zener" diodes typically have V_{BR} of a few Volts, which is denoted by V_Z. They are often used to limit the voltage swing in electronic circuits.

Two Zener diodes connected "back-to-back"





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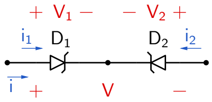

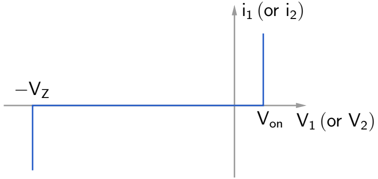

* $i > 0 \rightarrow D_1$ in forward conduction, D_2 in reverse conduction

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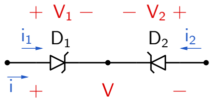

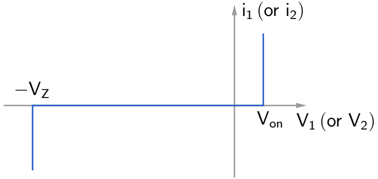

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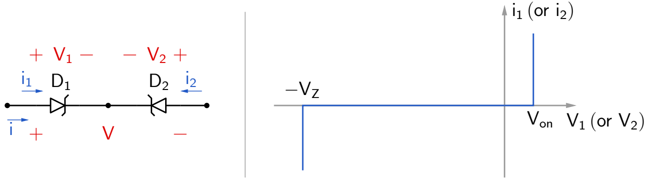

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  Total voltage drop $V = V_1 - V_2 = V_{\text{on}} + V_Z$.

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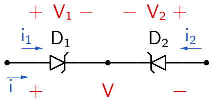

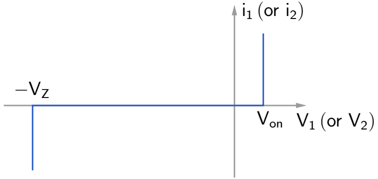

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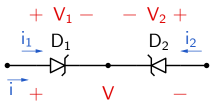

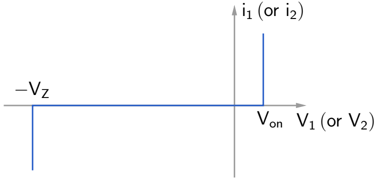

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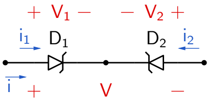

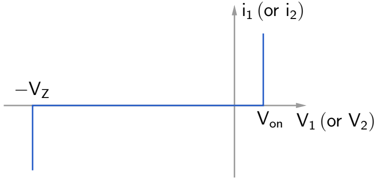

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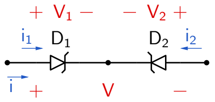

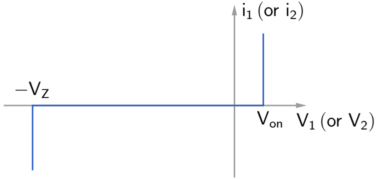

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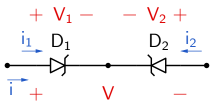
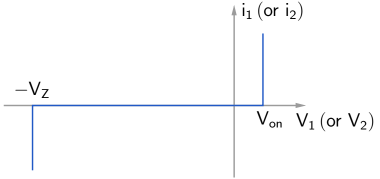
  $\rightarrow V_1 = V_{on}$, $V_2 = -V_Z$.
  Total voltage drop $V = V_1 - V_2 = V_{on} + V_Z$.
  Example: $V_{on} = 0.7\,\text{V}$, $V_Z = 5\,\text{V} \rightarrow V = 5.7\,\text{V}$.
* $i < 0 \rightarrow D_1$ in reverse conduction, D_2 in forward conduction
  $\rightarrow V_1 = -V_Z$, $V_2 = V_{on}$.
  Total voltage drop $V = V_1 - V_2 = -V_Z - V_{on} = -(V_Z + V_{on}) = -5.7\,\text{V}$.

Two Zener diodes connected "back-to-back"





* $i > 0 \rightarrow D_1$ in forward conduction, D_2 in reverse conduction
  $\rightarrow V_1 = V_{on},\ V_2 = -V_Z$.
  Total voltage drop $V = V_1 - V_2 = V_{on} + V_Z$.
  Example: $V_{on} = 0.7\,\text{V},\ V_Z = 5\,\text{V} \rightarrow V = 5.7\,\text{V}$.
* $i < 0 \rightarrow D_1$ in reverse conduction, D_2 in forward conduction
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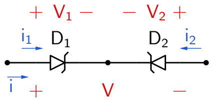
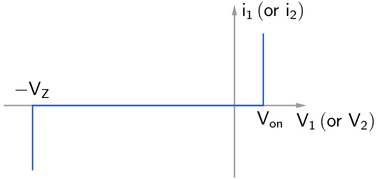
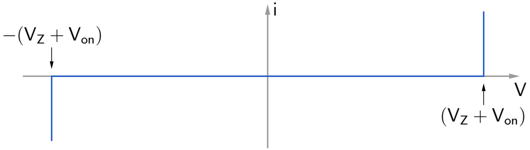
  Total voltage drop $V = V_1 - V_2 = -V_Z - V_{on} = -(V_Z + V_{on}) = -5.7\,\text{V}$.
* For $-(V_Z + V_{on}) < V < (V_Z + V_{on})$, conduction is not possible $\rightarrow i = 0$.

Two Zener diodes connected "back-to-back"

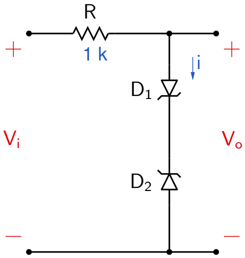




* $i > 0 \rightarrow D_1$ in forward conduction, D_2 in reverse conduction
  $\rightarrow V_1 = V_{\rm on}$, $V_2 = -V_Z$.
  Total voltage drop $V = V_1 - V_2 = V_{\rm on} + V_Z$.
  Example: $V_{\rm on} = 0.7\,\text{V}$, $V_Z = 5\,\text{V} \rightarrow V = 5.7\,\text{V}$.
* $i < 0 \rightarrow D_1$ in reverse conduction, D_2 in forward conduction
  $\rightarrow V_1 = -V_Z$, $V_2 = V_{\rm on}$.
  Total voltage drop $V = V_1 - V_2 = -V_Z - V_{\rm on} = -(V_Z + V_{\rm on}) = -5.7\,\text{V}$.
* For $-(V_Z + V_{\rm on}) < V < (V_Z + V_{\rm on})$, conduction is not possible $\rightarrow i = 0$.



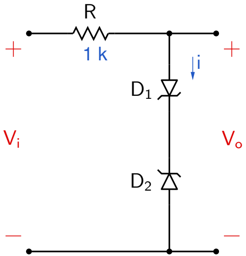
Diode circuit example (voltage limiter)

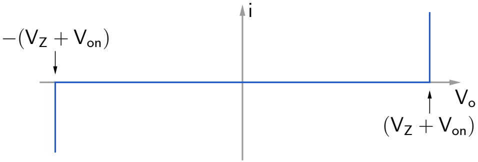


$V_{on} = 0.7$ V, $V_Z = 5$ V.

Plot V_o versus V_i.

Diode circuit example (voltage limiter)





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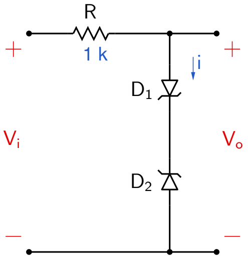
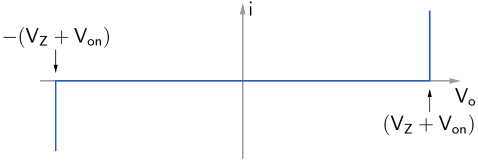
Diode circuit example (voltage limiter)



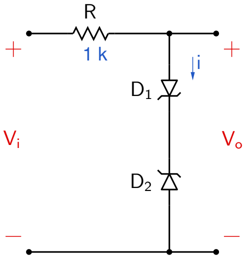


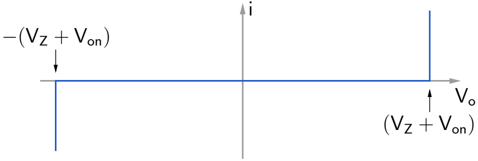
$V_{on} = 0.7$ V, $V_Z = 5$ V.

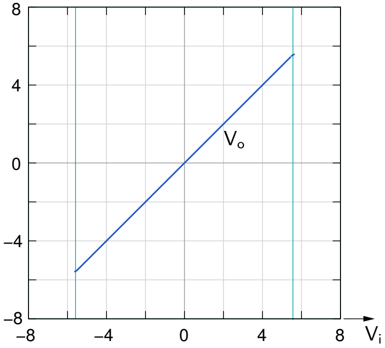
Plot V_o versus V_i.

* For $-5.7\,V < V_i < 5.7\,V$, no conduction is possible $\rightarrow V_o = V_i$.

Diode circuit example (voltage limiter)







$V_{on} = 0.7$ V, $V_Z = 5$ V.

Plot V_o versus V_i.

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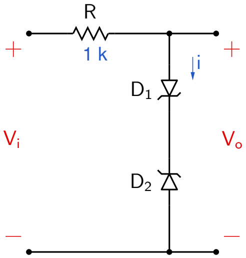
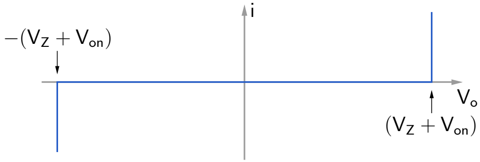
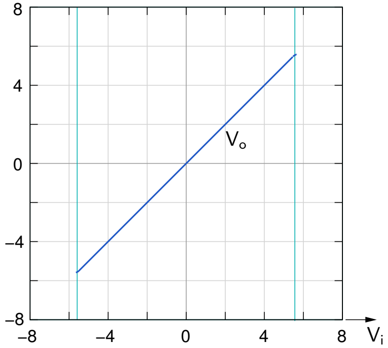
Diode circuit example (voltage limiter)



$V_{on} = 0.7$ V, $V_Z = 5$ V.

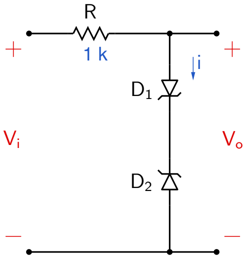
Plot V_o versus V_i.

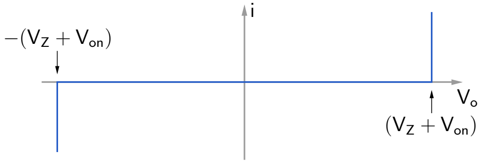


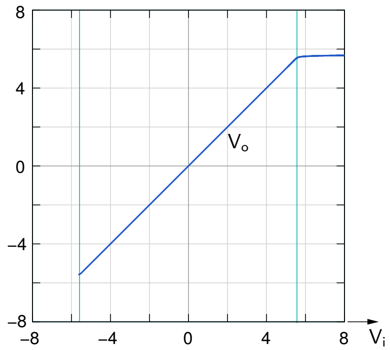


* For $-5.7\,\text{V} < V_i < 5.7\,\text{V}$, no conduction is possible $\rightarrow V_o = V_i$.
* For $V_i > 5.7\,\text{V}$, D_1 is forward-biased, D_2 is reverse-biased, and $V_o = (V_{\text{on}} + V_Z)$. The excess voltage $(V_i - (V_{\text{on}} + V_Z))$ drops across R.

Diode circuit example (voltage limiter)





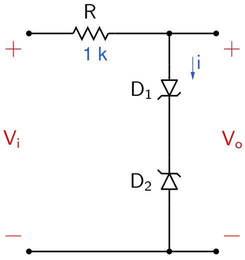


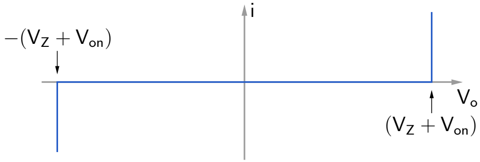
$V_{on} = 0.7$ V, $V_Z = 5$ V.

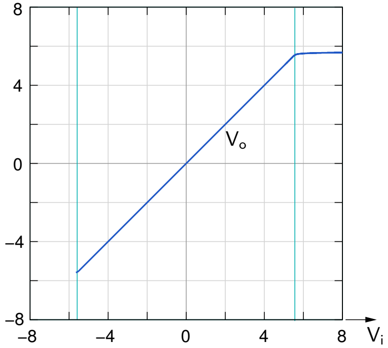
Plot V_o versus V_i.

* For $-5.7\,V < V_i < 5.7\,V$, no conduction is possible $\rightarrow$ $V_o = V_i$.
* For $V_i > 5.7\,V$, D_1 is forward-biased, D_2 is reverse-biased, and $V_o = (V_{on} + V_Z)$. The excess voltage $(V_i - (V_{on} + V_Z))$ drops across R.

Diode circuit example (voltage limiter)





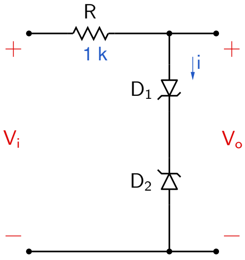


$V_{on} = 0.7$ V, $V_Z = 5$ V.

Plot V_o versus V_i.

* For $-5.7\,V < V_i < 5.7\,V$, no conduction is possible $\rightarrow V_o = V_i$.
* For $V_i > 5.7\,V$, D_1 is forward-biased, D_2 is reverse-biased, and $V_o = (V_{on} + V_Z)$. The excess voltage $(V_i - (V_{on} + V_Z))$ drops across R.
* For $V_i < -5.7\,V$, D_2 is forward-biased, D_1 is reverse-biased, and $V_o = -(V_{on} + V_Z)$. The excess voltage $(-V_i - (V_{on} + V_Z))$ drops across R.

Diode circuit example (voltage limiter)



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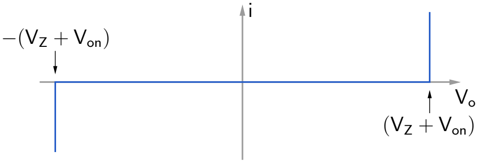
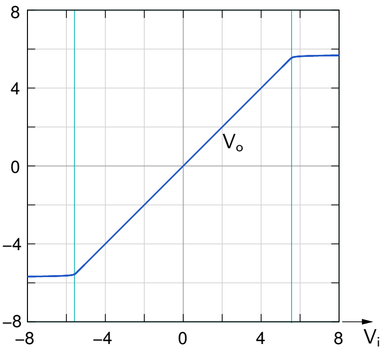
Plot V_o versus V_i.





* For $-5.7\,\text{V} < V_i < 5.7\,\text{V}$, no conduction is possible $\rightarrow V_o = V_i$.
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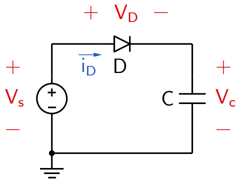
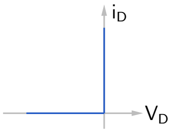
Peak detector (with $V_{on} = 0\,V$)



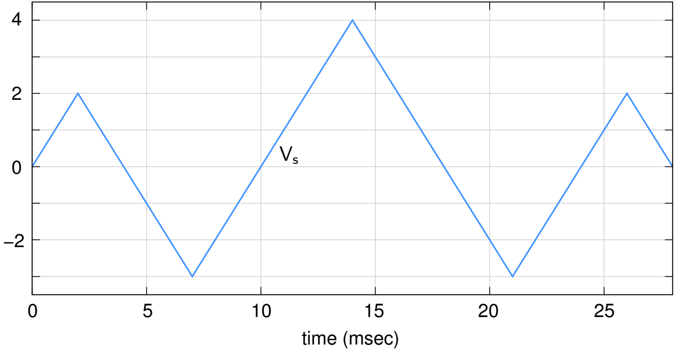


$V_c(0) = 0\,V$

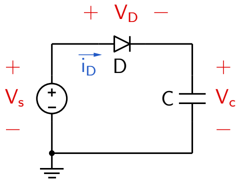
$V_{on} = 0\,V$

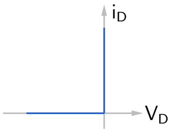
$R_{on} \to 0\,\Omega$

$R_{off} \to \infty\,\Omega$



Peak detector (with $V_{on} = 0\,\mathrm{V}$)





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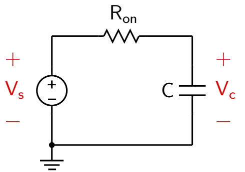
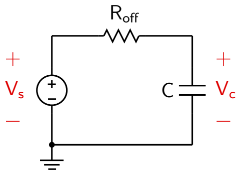


$V_s > V_c$

$\tau = R_{on} C$



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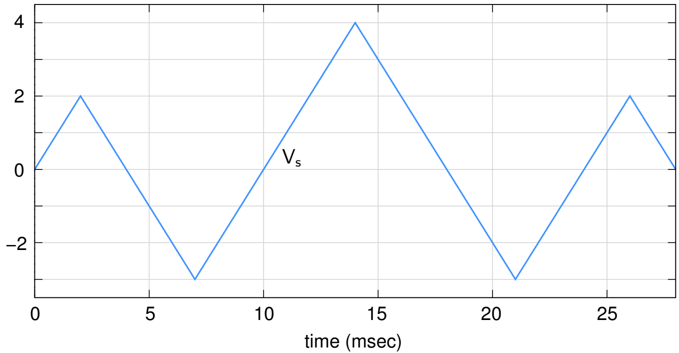
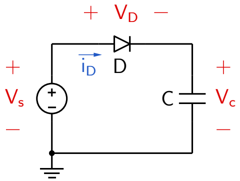
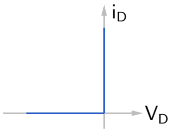


Peak detector (with $V_{on} = 0\,\mathrm{V}$)





$V_c(0) = 0\,\mathrm{V}$

$V_{on} = 0\,\mathrm{V}$

$R_{on} \to 0\,\Omega$

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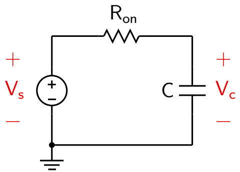

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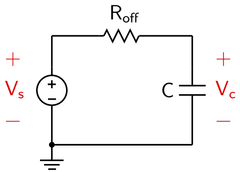

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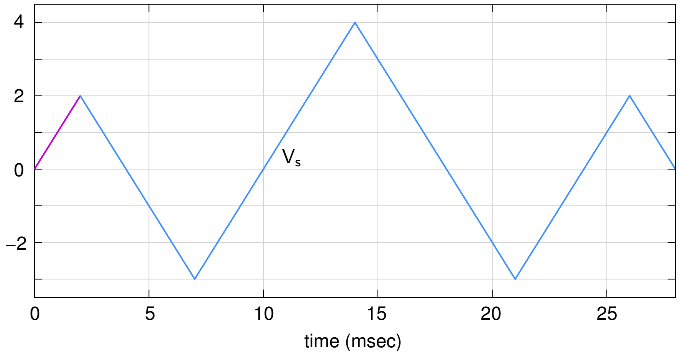
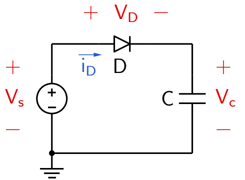
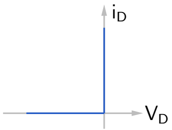


Peak detector (with $V_{on} = 0\,\text{V}$)





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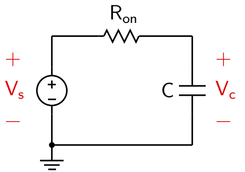

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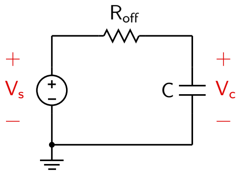
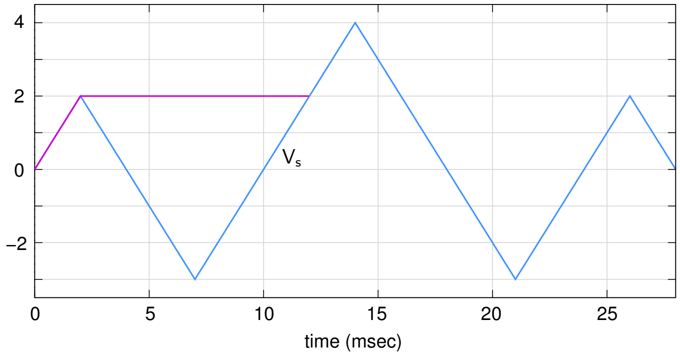


$V_s < V_c$

$\tau = R_{off}C$



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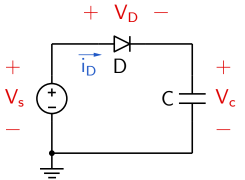

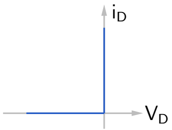

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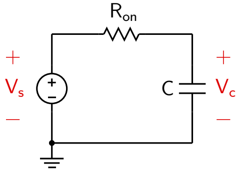

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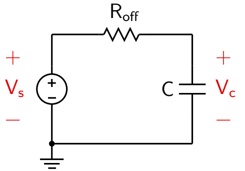

$V_s < V_c$

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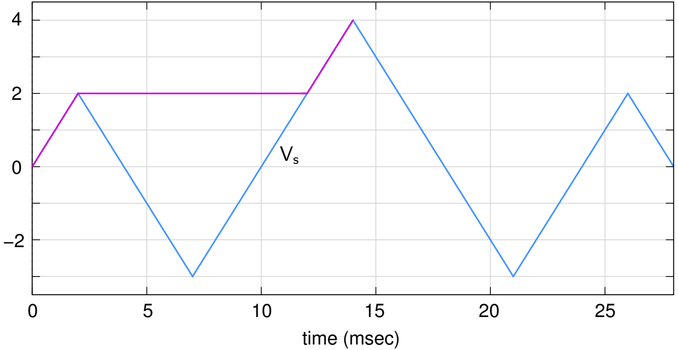
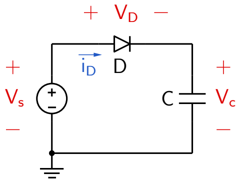
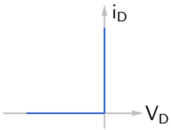


Peak detector (with $V_{on} = 0\,\text{V}$)





$V_c(0) = 0\,\text{V}$

$V_{on} = 0\,\text{V}$

$R_{on} \rightarrow 0\,\Omega$

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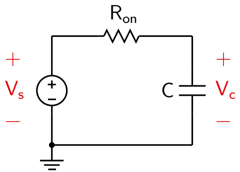

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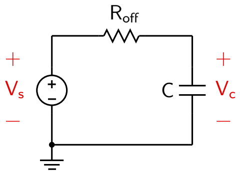
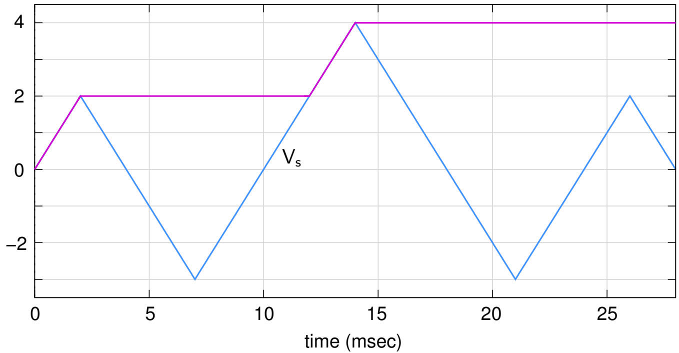
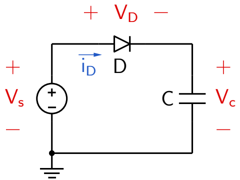


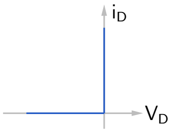
$V_s < V_c$

$\tau = R_{off}C$



Peak detector (with $V_{on} = 0\,V$)



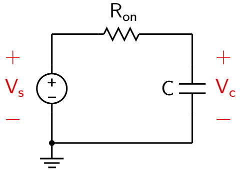


$V_c(0) = 0\,V$

$V_{on} = 0\,V$

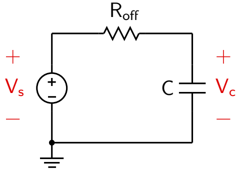
$R_{on} \rightarrow 0\,\Omega$

$R_{off} \rightarrow \infty\,\Omega$



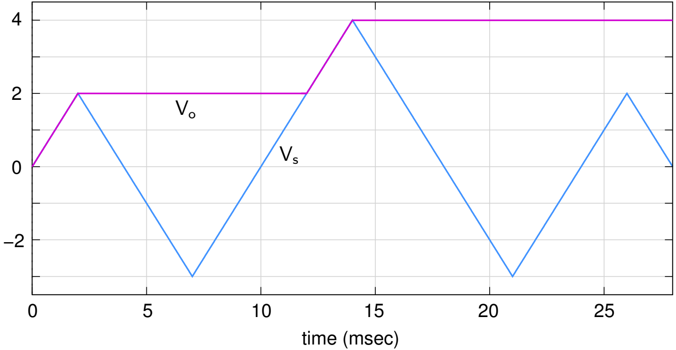
$V_s > V_c$

$\tau = R_{on}C$



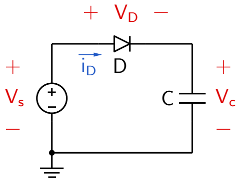
$V_s < V_c$

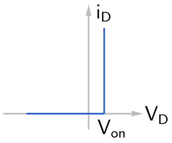
$\tau = R_{off}C$



SEQUEL file: `ee101_peak_detector_1.sqproj`

Peak detector (with $V_{on} = 0.7\,\text{V}$)



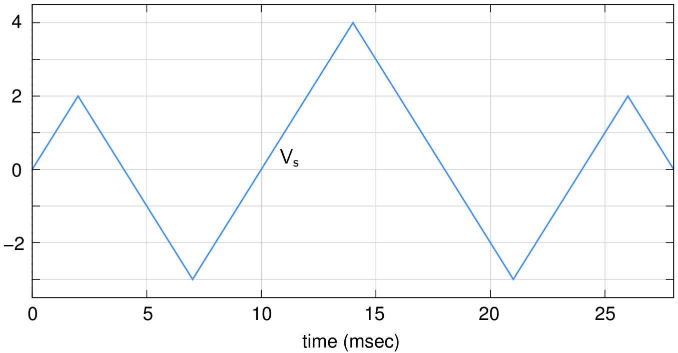


$V_c(0) = 0\,\text{V}$

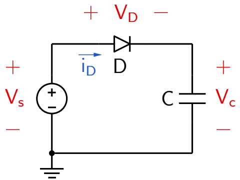
$V_{on} = 0.7\,\text{V}$

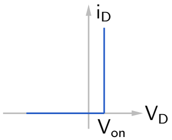
$R_{on} \to 0\,\Omega$

$R_{off} \to \infty\,\Omega$



Peak detector (with $V_{on} = 0.7\,V$)



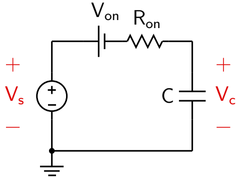


$V_c(0) = 0\,V$

$V_{on} = 0.7\,V$

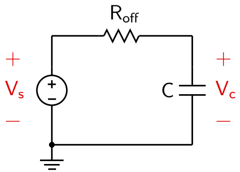
$R_{on} \to 0\,\Omega$

$R_{off} \to \infty\,\Omega$



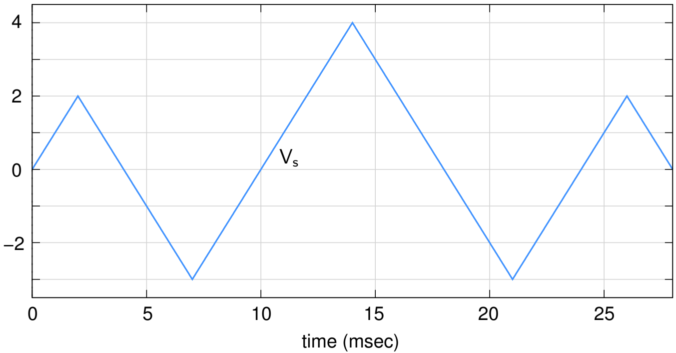
$V_s > V_c + V_{on}$

$\tau = R_{on} C$

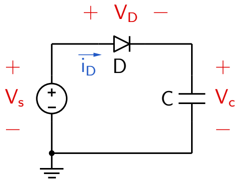


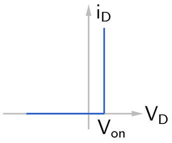
$V_s < V_c + V_{on}$

$\tau = R_{off} C$



Peak detector (with $V_{on} = 0.7\,\text{V}$)



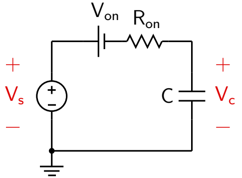


$V_c(0) = 0\,\text{V}$

$V_{on} = 0.7\,\text{V}$

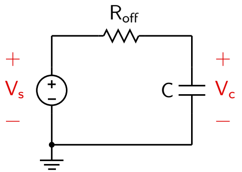
$R_{on} \to 0\,\Omega$

$R_{off} \to \infty\,\Omega$



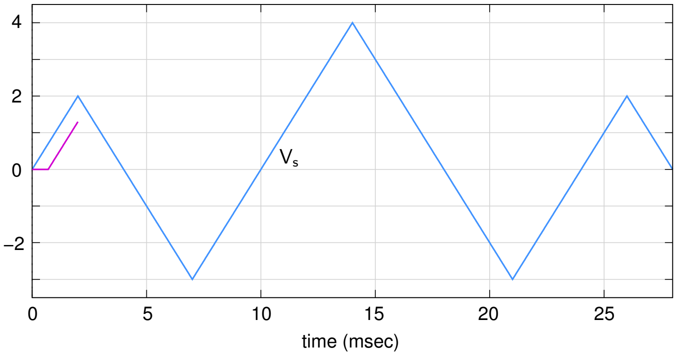
$V_s > V_c + V_{on}$

$\tau = R_{on} C$

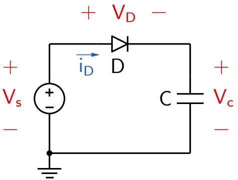


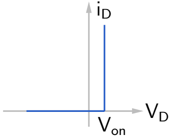
$V_s < V_c + V_{on}$

$\tau = R_{off} C$



Peak detector (with $V_{on} = 0.7\,\text{V}$)



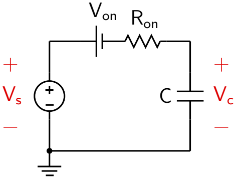


$V_c(0) = 0\,\text{V}$

$V_{on} = 0.7\,\text{V}$

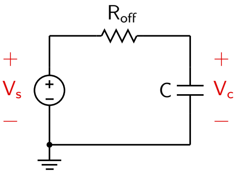
$R_{on} \to 0\,\Omega$

$R_{off} \to \infty\,\Omega$



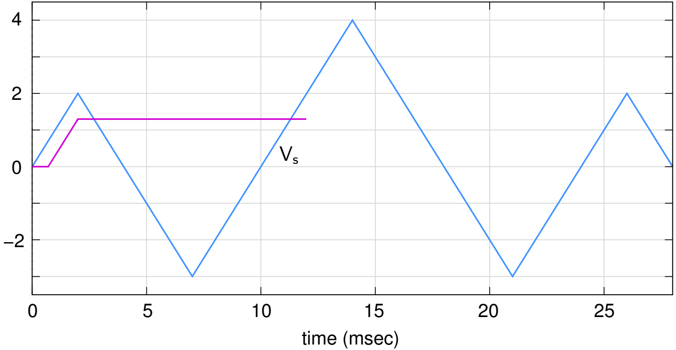
$V_s > V_c + V_{on}$

$\tau = R_{on} C$

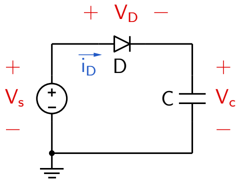


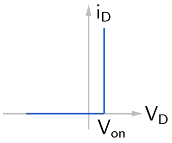
$V_s < V_c + V_{on}$

$\tau = R_{off} C$



Peak detector (with $V_{on} = 0.7\,\text{V}$)





$V_c(0) = 0\,\text{V}$

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$R_{on} \to 0\,\Omega$

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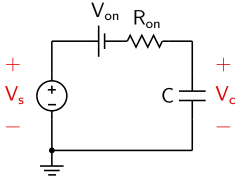
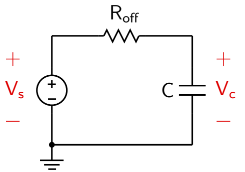


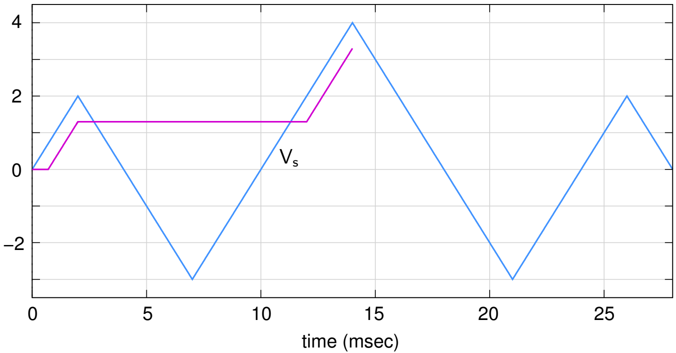
$V_s > V_c + V_{on}$

$\tau = R_{on} C$

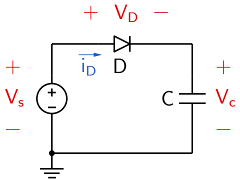


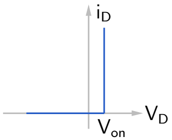
$V_s < V_c + V_{on}$

$\tau = R_{off} C$



Peak detector (with $V_{on} = 0.7\,\mathrm{V}$)





$V_c(0) = 0\,\mathrm{V}$

$V_{on} = 0.7\,\mathrm{V}$

$R_{on} \to 0\,\Omega$

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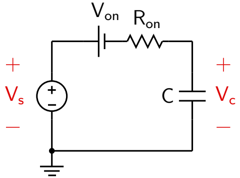
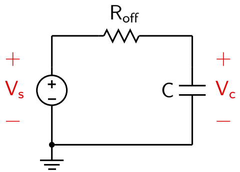


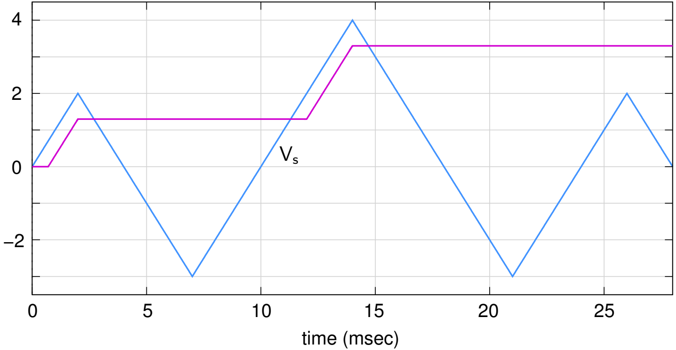
$V_s > V_c + V_{on}$

$\tau = R_{on} C$

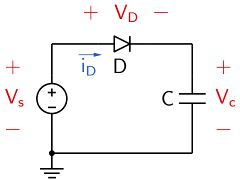


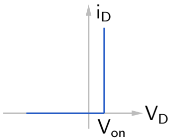
$V_s < V_c + V_{on}$

$\tau = R_{off} C$



Peak detector (with $V_{on} = 0.7\,\text{V}$)





$V_c(0) = 0\,\text{V}$

$V_{on} = 0.7\,\text{V}$

$R_{on} \rightarrow 0\,\Omega$

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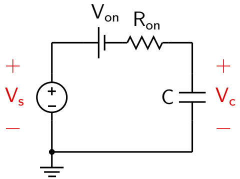
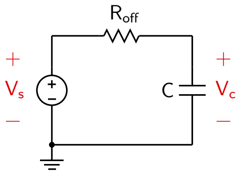


$V_s > V_c + V_{on}$

$\tau = R_{on} C$



$V_s < V_c + V_{on}$

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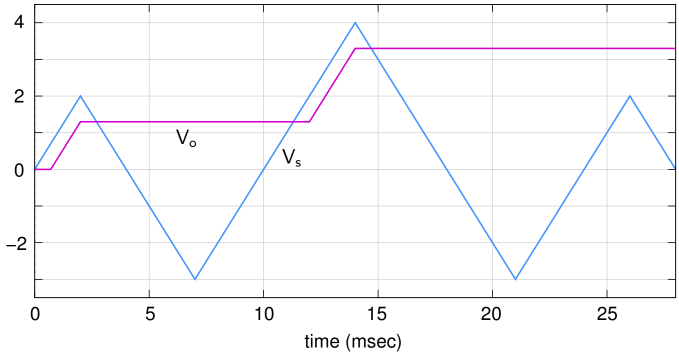
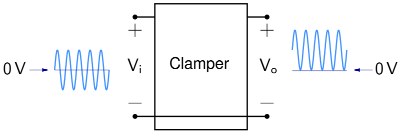


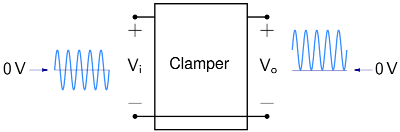
SEQUEL file: `ee101_peak_detector_1.sqproj`

Clamper circuits



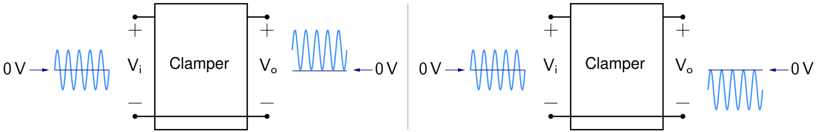
* A clamper circuit provides a "level shift." (The shape of the input signal is not altered.)

Clamper circuits

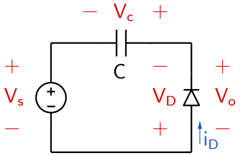


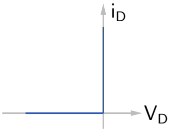
* A clamper circuit provides a "level shift." (The shape of the input signal is not altered.)
* The shift could be positive or negative.

Clamper circuits

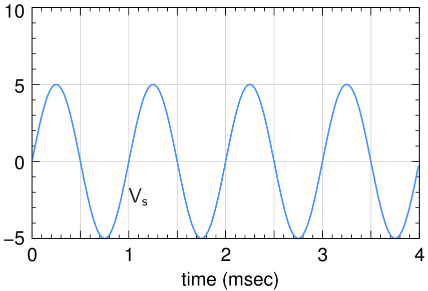


* A clamper circuit provides a "level shift." (The shape of the input signal is not altered.)
* The shift could be positive or negative.

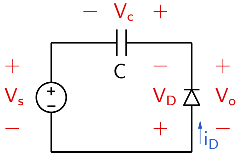


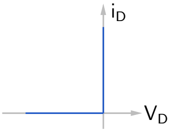


$$V_s(t) = V_m \sin \omega t$$
$$V_c(0) = 0\,\text{V}$$
$$V_{on} = 0\,\text{V}$$
$$R_{on} \rightarrow 0\,\Omega$$
$$R_{off} \rightarrow \infty\,\Omega$$



Clamper circuits





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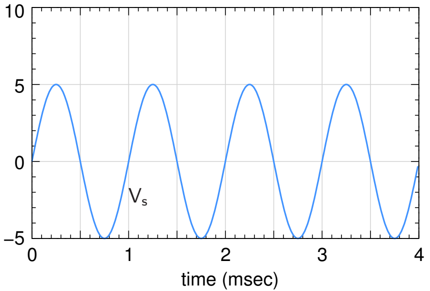
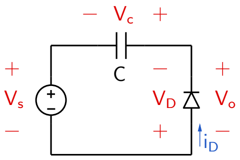
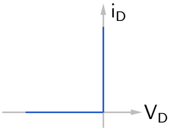


* When D conducts, the capacitor charges instantaneously since R_{on} is small. In this phase, $V_D = 0 \to V_c + V_s = 0 \to V_c = -V_s$.

Clamper circuits





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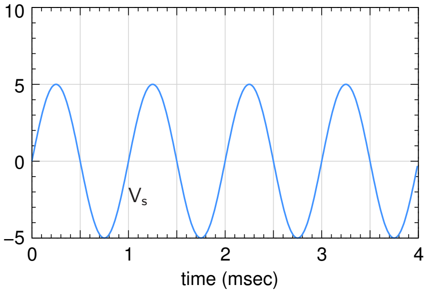
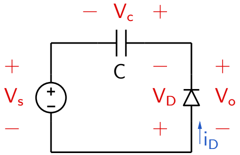
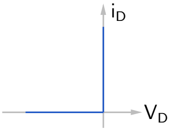


* When D conducts, the capacitor charges instantaneously since R_{on} is small. In this phase, $V_D = 0 \rightarrow V_c + V_s = 0 \rightarrow V_c = -V_s$.
* V_c can only increase since a decrease in V_c would require the diode to conduct in the reverse direction.

Clamper circuits





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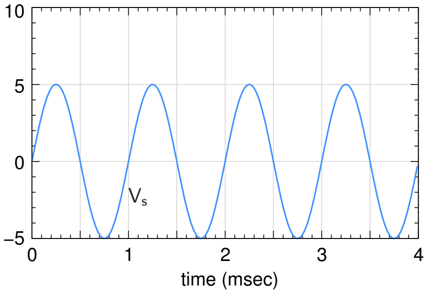
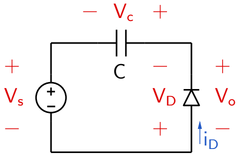
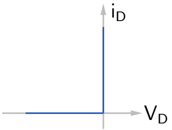


* When D conducts, the capacitor charges instantaneously since R_{on} is small. In this phase, $V_D = 0 \rightarrow V_c + V_s = 0 \rightarrow V_c = -V_s$.
* V_c can only increase since a decrease in V_c would require the diode to conduct in the reverse direction.
* After V_c reaches its maximum value (V_m), it cannot change any more. We then have $V_o(t) = V_s(t) + V_c(t) = V_s(t) + V_m$, i.e., a positive level shift.

Clamper circuits





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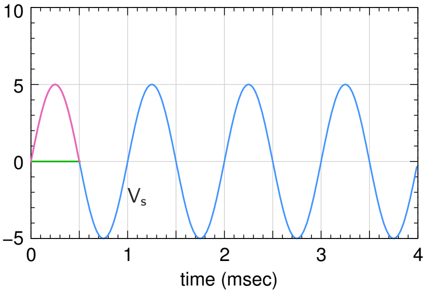

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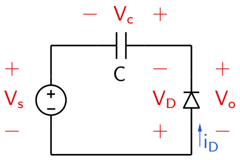
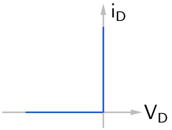
Clamper circuits





$V_s(t) = V_m \sin \omega t$

$V_c(0) = 0\,\text{V}$

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$R_{on} \rightarrow 0\,\Omega$

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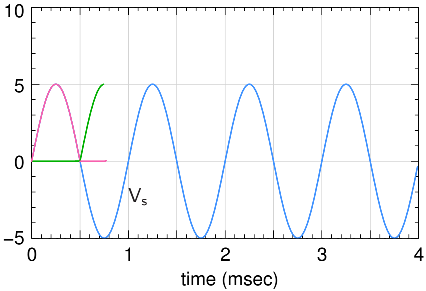
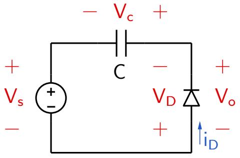
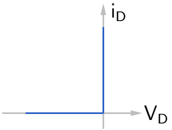


* When D conducts, the capacitor charges instantaneously since R_{on} is small. In this phase, $V_D = 0 \rightarrow V_c + V_s = 0 \rightarrow V_c = -V_s$.
* V_c can only increase since a decrease in V_c would require the diode to conduct in the reverse direction.
* After V_c reaches its maximum value (V_m), it cannot change any more. We then have $V_o(t) = V_s(t) + V_c(t) = V_s(t) + V_m$, i.e., a positive level shift.

Clamper circuits





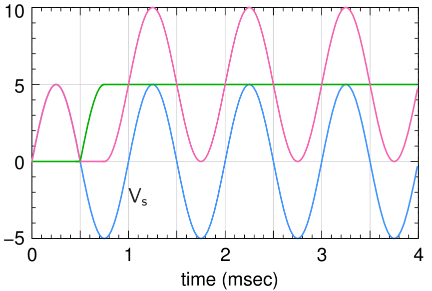
$V_s(t) = V_m \sin \omega t$

$V_c(0) = 0\,\mathrm{V}$

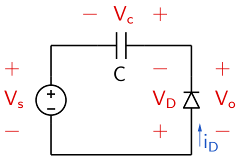
$V_{on} = 0\,\mathrm{V}$

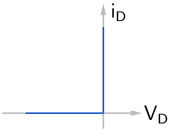
$R_{on} \rightarrow 0\,\Omega$

$R_{off} \rightarrow \infty\,\Omega$

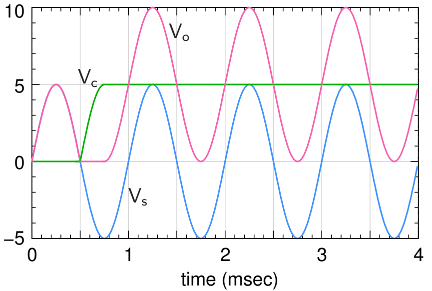


* When D conducts, the capacitor charges instantaneously since R_{on} is small. In this phase, $V_D = 0 \rightarrow V_c + V_s = 0 \rightarrow V_c = -V_s$.
* V_c can only increase since a decrease in V_c would require the diode to conduct in the reverse direction.
* After V_c reaches its maximum value (V_m), it cannot change any more. We then have $V_o(t) = V_s(t) + V_c(t) = V_s(t) + V_m$, i.e., a positive level shift.





$V_s(t) = V_m \sin \omega t$
$V_c(0) = 0\,V$
$V_{on} = 0\,V$
$R_{on} \rightarrow 0\,\Omega$
$R_{off} \rightarrow \infty\,\Omega$



* When D conducts, the capacitor charges instantaneously since R_{on} is small. In this phase, $V_D = 0 \rightarrow V_c + V_s = 0 \rightarrow V_c = -V_s$.
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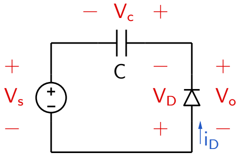
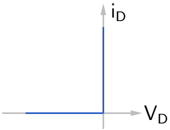
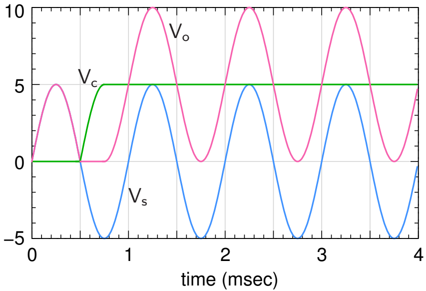
Clamper circuits

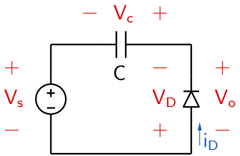


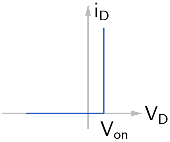


$V_s(t) = V_m \sin \omega t$
$V_c(0) = 0\,\text{V}$
$V_{on} = 0\,\text{V}$
$R_{on} \rightarrow 0\,\Omega$
$R_{off} \rightarrow \infty\,\Omega$



* When D conducts, the capacitor charges instantaneously since R_{on} is small. In this phase, $V_D = 0 \rightarrow V_c + V_s = 0 \rightarrow V_c = -V_s$.
* V_c can only increase since a decrease in V_c would require the diode to conduct in the reverse direction.
* After V_c reaches its maximum value (V_m), it cannot change any more. We then have $V_o(t) = V_s(t) + V_c(t) = V_s(t) + V_m$, i.e., a positive level shift.
* Note that we are generally interested only in the steady-state behaviour and not in the transient at the beginning.





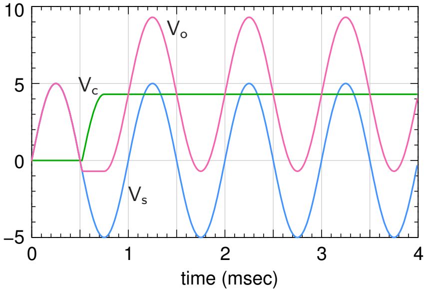
$V_s(t) = V_m \sin \omega t$

$V_c(0) = 0\,\text{V}$

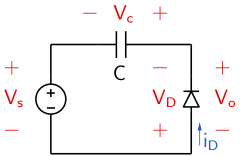
$V_{on} = 0.7\,\text{V}$

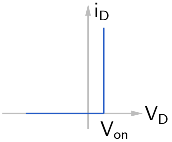
$R_{on} \rightarrow 0\,\Omega$

$R_{off} \rightarrow \infty\,\Omega$



Clamper circuits





$V_s(t) = V_m \sin \omega t$

$V_c(0) = 0\,\mathrm{V}$

$V_{on} = 0.7\,\mathrm{V}$

$R_{on} \rightarrow 0\,\Omega$

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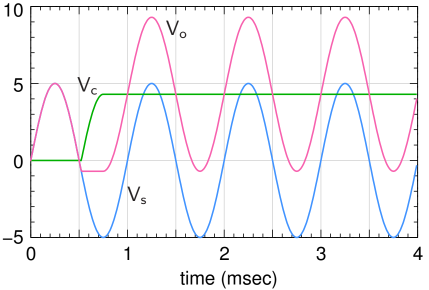
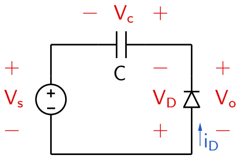
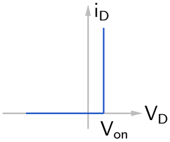


* When D conducts, the capacitor charges instantaneously since R_{on} is small (as in the last circuit).
  In this phase,
  $V_c + V_s + V_{on} = 0 \rightarrow V_c = -V_s - V_{on}$.





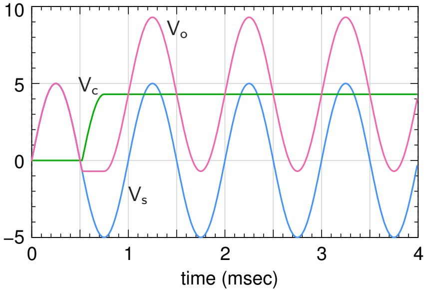
$V_s(t) = V_m \sin \omega t$

$V_c(0) = 0\,V$

$V_{on} = 0.7\,V$

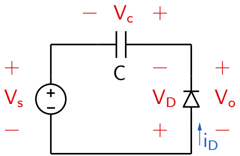
$R_{on} \rightarrow 0\,\Omega$

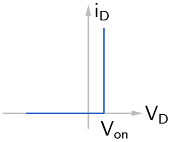
$R_{off} \rightarrow \infty\,\Omega$



* When D conducts, the capacitor charges instantaneously since R_{on} is small (as in the last circuit).
  In this phase,
  $V_c + V_s + V_{on} = 0 \rightarrow V_c = -V_s - V_{on}$.
* V_c can only increase since a decrease in V_c would require the diode to conduct in the reverse direction.

Clamper circuits





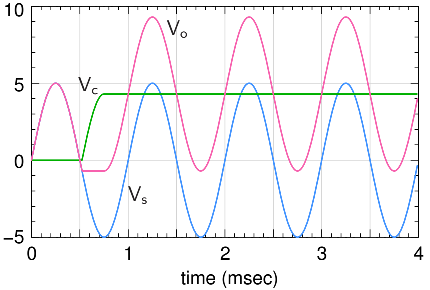
$V_s(t) = V_m \sin \omega t$

$V_c(0) = 0\,\text{V}$

$V_{on} = 0.7\,\text{V}$

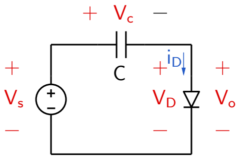
$R_{on} \rightarrow 0\,\Omega$

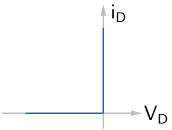
$R_{off} \rightarrow \infty\,\Omega$



* When D conducts, the capacitor charges instantaneously since R_{on} is small (as in the last circuit).
  In this phase,
  $V_c + V_s + V_{on} = 0 \rightarrow V_c = -V_s - V_{on}$.
* V_c can only increase since a decrease in V_c would require the diode to conduct in the reverse direction.
* After V_c reaches its maximum value $(V_m - V_{on})$, it cannot change any more. We then have
  $V_o(t) = V_s(t) + V_c(t) = V_s(t) + V_m - V_{on}$. In this case, V_o gets clamped at $-0.7\,\text{V}$.

Clamper circuits





$$V_s(t) = V_m \sin \omega t$$
$$V_c(0) = 0\,\text{V}$$
$$V_{on} = 0\,\text{V}$$
$$R_{on} \to 0\,\Omega$$
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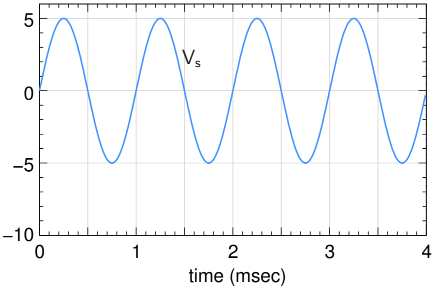
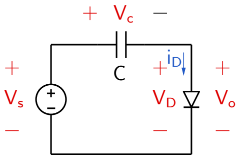
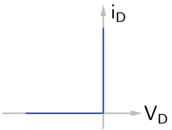


Clamper circuits





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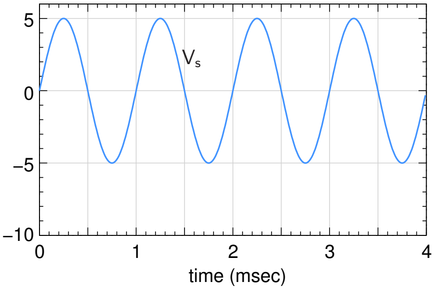
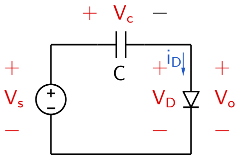
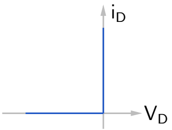


* When D conducts, the capacitor charges instantaneously since R_{on} is small. In this phase, $V_D = 0 \rightarrow V_c - V_s = 0 \rightarrow V_c = V_s$.

Clamper circuits





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$R_{on} \rightarrow 0\,\Omega$

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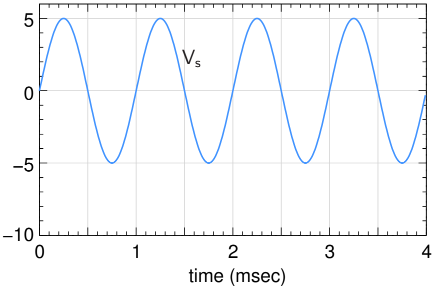
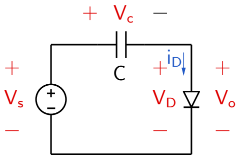
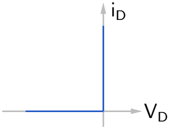


* When D conducts, the capacitor charges instantaneously since R_{on} is small. In this phase, $V_D = 0 \rightarrow V_c - V_s = 0 \rightarrow V_c = V_s$.
* V_c can only increase since a decrease in V_c would require the diode to conduct in the reverse direction.

Clamper circuits





$V_s(t) = V_m \sin \omega t$
$V_c(0) = 0\,V$
$V_{on} = 0\,V$
$R_{on} \to 0\,\Omega$
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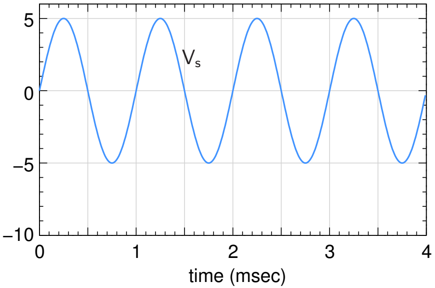
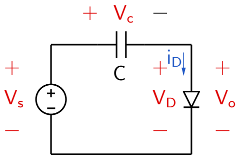
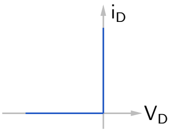


* When D conducts, the capacitor charges instantaneously since R_{on} is small. In this phase, $V_D = 0 \to V_c - V_s = 0 \to V_c = V_s$.
* V_c can only increase since a decrease in V_c would require the diode to conduct in the reverse direction.
* After V_c reaches its maximum value (V_m), it cannot change any more. We then have $V_o(t) = V_s(t) - V_c(t) = V_s(t) - V_m$, i.e., a negative level shift.

Clamper circuits





$V_s(t) = V_m \sin \omega t$
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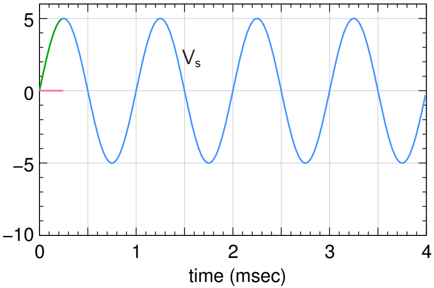

* When D conducts, the capacitor charges instantaneously since R_{on} is small. In this phase, $V_D = 0 \to V_c - V_s = 0 \to V_c = V_s$.
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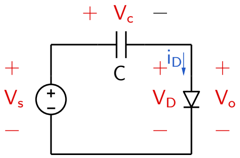
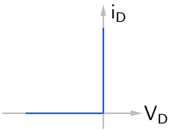
Clamper circuits





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$R_{on} \rightarrow 0\,\Omega$

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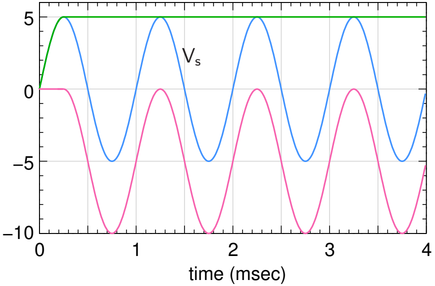

* When D conducts, the capacitor charges instantaneously since R_{on} is small. In this phase, $V_D = 0 \rightarrow V_c - V_s = 0 \rightarrow V_c = V_s$.
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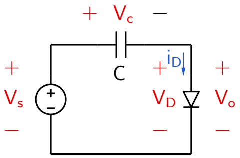
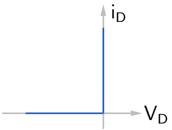
Clamper circuits





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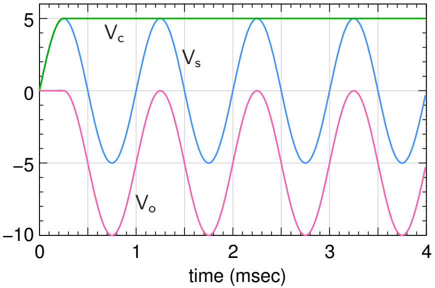

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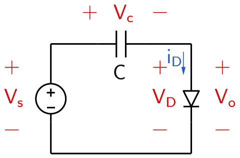
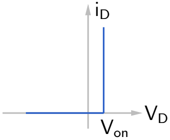




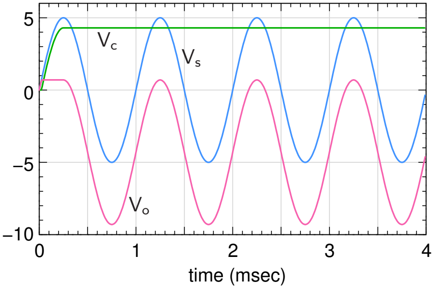
$V_s(t) = V_m \sin \omega t$

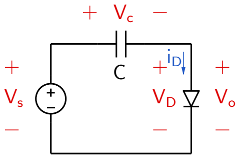
$V_c(0) = 0\,V$

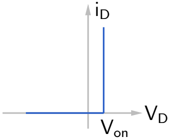
$V_{on} = 0.7\,V$

$R_{on} \to 0\,\Omega$

$R_{off} \to \infty\,\Omega$







$V_s(t) = V_m \sin \omega t$

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$V_{on} = 0.7\,V$

$R_{on} \rightarrow 0\,\Omega$

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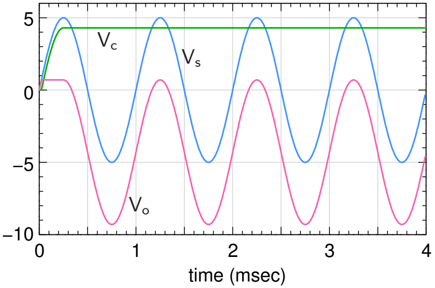
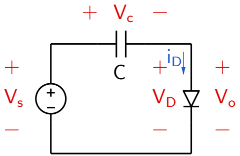
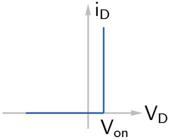


* When D conducts, the capacitor charges instantaneously since R_{on} is small (as in the last circuit). In this phase, $V_c + V_{on} - V_s = 0 \rightarrow V_c = V_s - V_{on}$.

Clamper circuits





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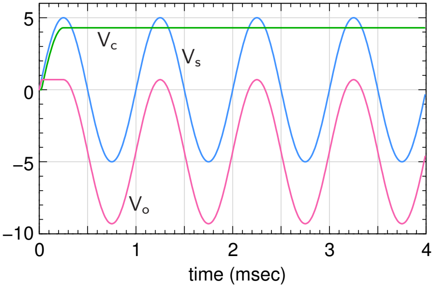
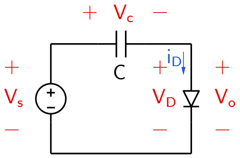
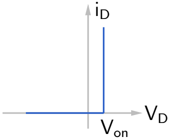
$R_{on} \rightarrow 0\,\Omega$

$R_{off} \rightarrow \infty\,\Omega$



* When D conducts, the capacitor charges instantaneously since R_{on} is small (as in the last circuit).
  In this phase,
  $V_c + V_{on} - V_s = 0 \rightarrow V_c = V_s - V_{on}$.
* V_c can only increase since a decrease in V_c would require the diode to conduct in the reverse direction.





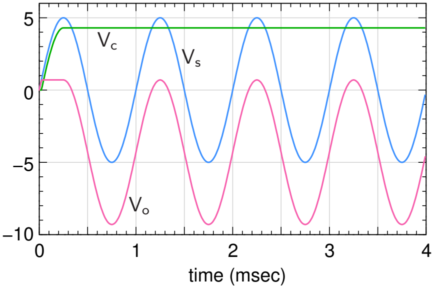
$V_s(t) = V_m \sin \omega t$

$V_c(0) = 0\,V$

$V_{on} = 0.7\,V$

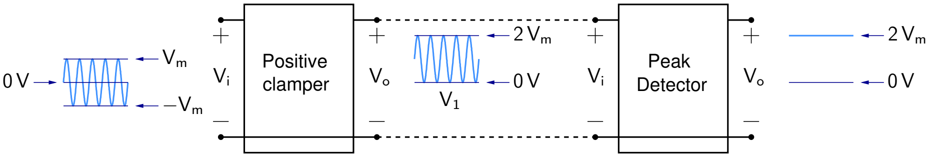
$R_{on} \rightarrow 0\,\Omega$

$R_{off} \rightarrow \infty\,\Omega$

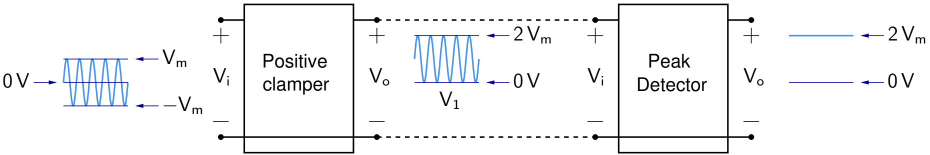


* When D conducts, the capacitor charges instantaneously since R_{on} is small (as in the last circuit). In this phase,
  $V_c + V_{on} - V_s = 0 \rightarrow V_c = V_s - V_{on}$.
* V_c can only increase since a decrease in V_c would require the diode to conduct in the reverse direction.
* After V_c reaches its maximum value $(V_m - V_{on})$, it cannot change any more. We then have $V_o(t) = V_s(t) - V_c(t) = V_s(t) - V_m + V_{on}$. In this case, V_o gets clamped at $0.7\,V$.

Voltage doubler (peak-to-peak detector)

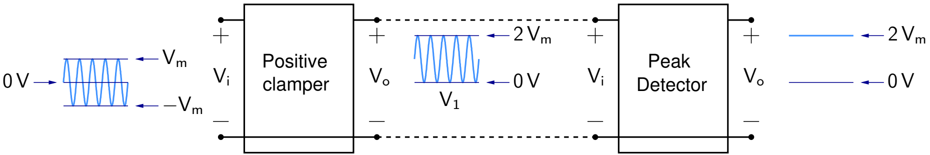


Voltage doubler (peak-to-peak detector)



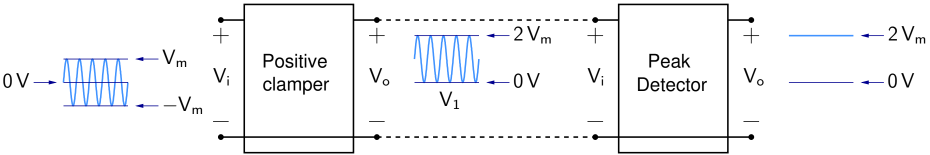
* Input voltage: $-V_m$ to V_m

Voltage doubler (peak-to-peak detector)



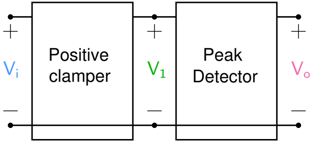
* Input voltage: $-V_m$ to V_m
* Output of positive clamper (V_1): 0 to 2 V_m

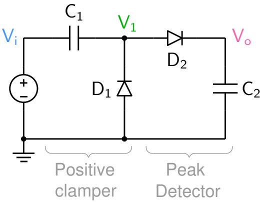
Voltage doubler (peak-to-peak detector)



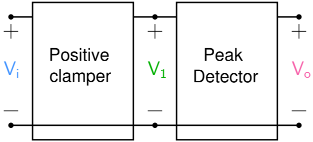
* Input voltage: $-V_m$ to V_m
* Output of positive clamper (V_1): 0 to 2 V_m
* The peak detector detects the peak of $V_1(t)$, i.e., 2 V_m (dc).

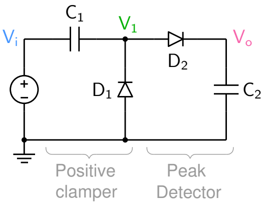
Voltage doubler (peak-to-peak detector)

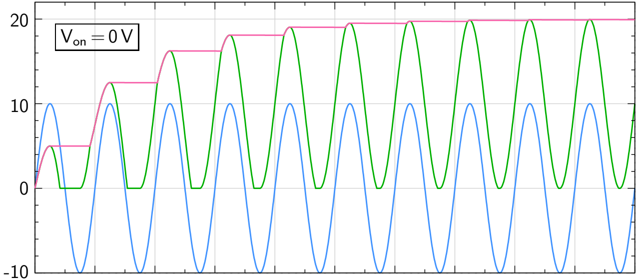




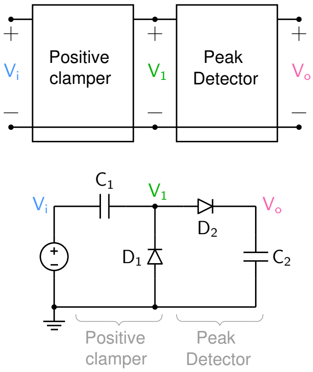
Voltage doubler (peak-to-peak detector)

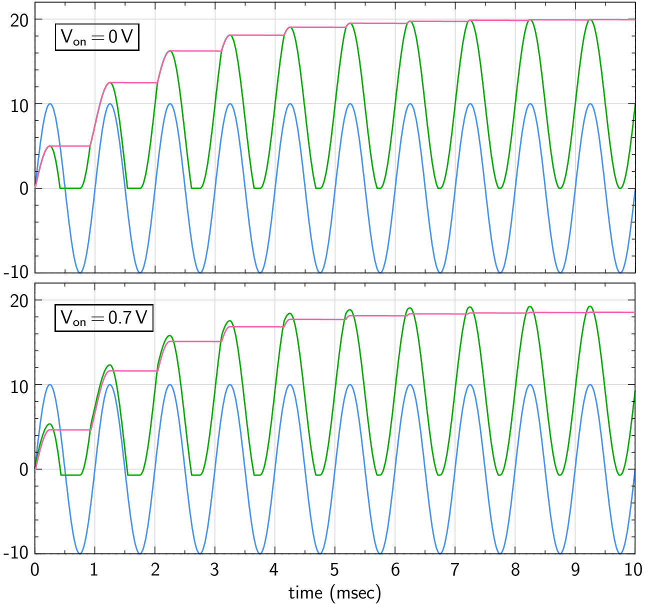




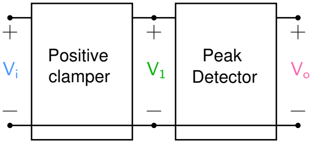


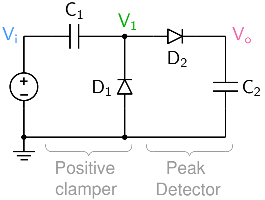
Voltage doubler (peak-to-peak detector)



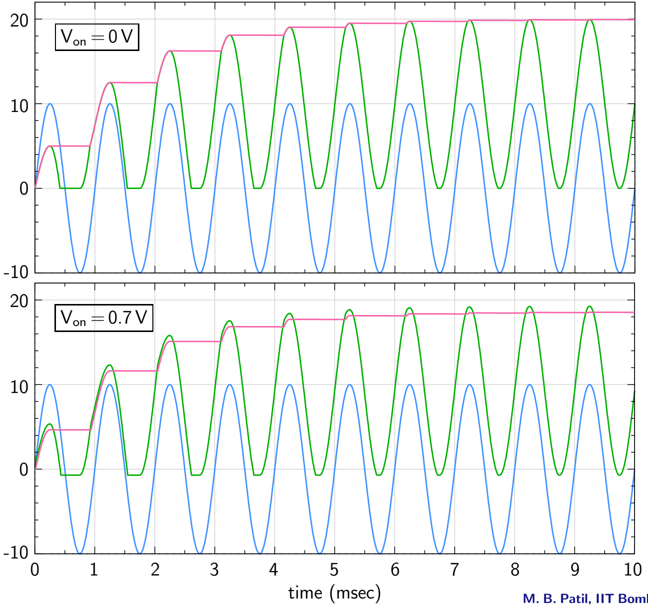


Voltage doubler (peak-to-peak detector)

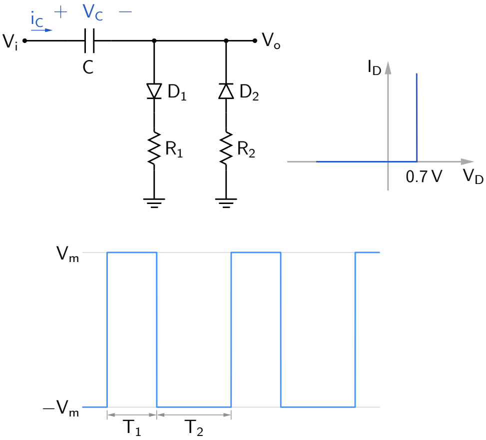




SEQUEL file: `ee101_voltage_doubler.sqproj`

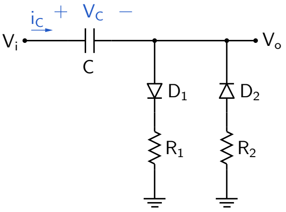


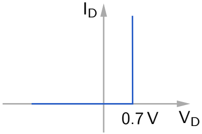
Diode circuit example

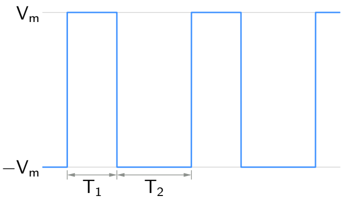


Assuming R_1C and R_2C to be large compared to T, find $V_o(t)$ in steady state.

Diode circuit example



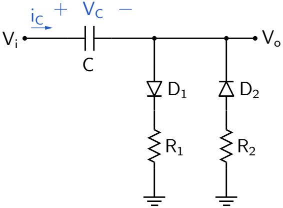


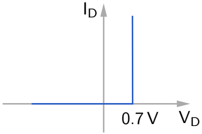


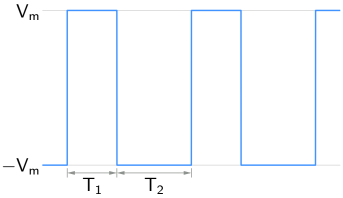
Assuming R_1C and R_2C to be large compared to T, find $V_o(t)$ in steady state.

* Charging time constant $\tau_1 = R_1C$.

Diode circuit example



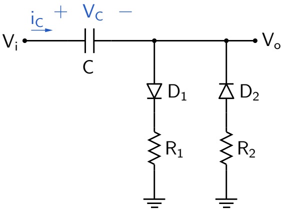


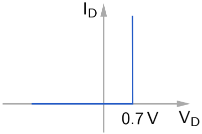


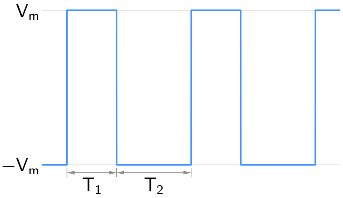
Assuming R_1C and R_2C to be large compared to T, find $V_o(t)$ in steady state.

* Charging time constant $\tau_1 = R_1C$.
* Discharging time constant $\tau_2 = R_2C$.

Diode circuit example

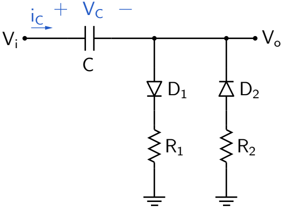


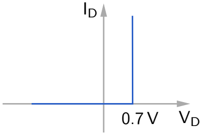


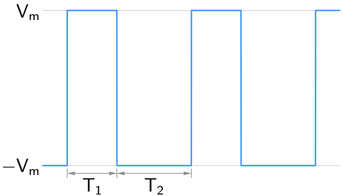


Assuming $R_1 C$ and $R_2 C$ to be large compared to T, find $V_o(t)$ in steady state.

* Charging time constant $\tau_1 = R_1 C$.
* Discharging time constant $\tau_2 = R_2 C$.
* Since $\tau_1 \gg T$ and $\tau_2 \gg T$, we expect V_C to be nearly constant in steady state,
  i.e., $V_C(t) \approx \text{constant} \equiv V_C^0$.



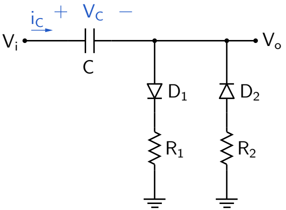


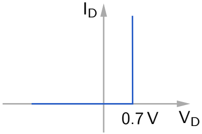


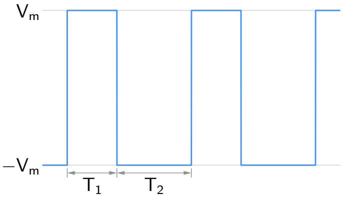
Assuming $R_1 C$ and $R_2 C$ to be large compared to T, find $V_o(t)$ in steady state.

* Charging time constant $\tau_1 = R_1 C$.
* Discharging time constant $\tau_2 = R_2 C$.
* Since $\tau_1 \gg T$ and $\tau_2 \gg T$, we expect V_C to be nearly constant in steady state, i.e., $V_C(t) \approx \text{constant} \equiv V_C^0$.
* $V_o(t) = V_i(t) - V_C(t) \approx V_i(t) - V_C^0$.

Diode circuit example



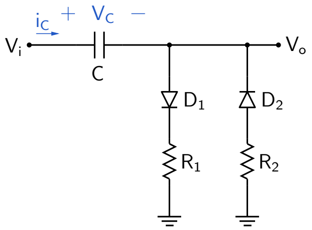




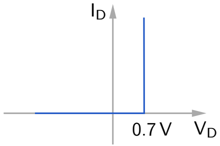
Assuming $R_1 C$ and $R_2 C$ to be large compared to T, find $V_o(t)$ in steady state.

* Charging time constant $\tau_1 = R_1 C$.
* Discharging time constant $\tau_2 = R_2 C$.
* Since $\tau_1 \gg T$ and $\tau_2 \gg T$, we expect V_C to be nearly constant in steady state,
  i.e., $V_C(t) \approx \text{constant} \equiv V_C^0$.
* $V_o(t) = V_i(t) - V_C(t) \approx V_i(t) - V_C^0$.

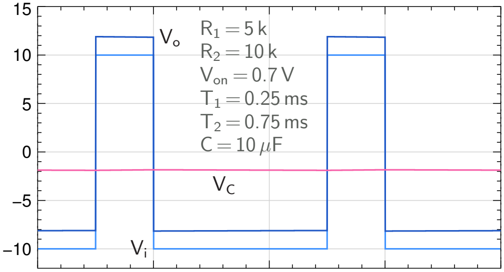
Let us look at an example.



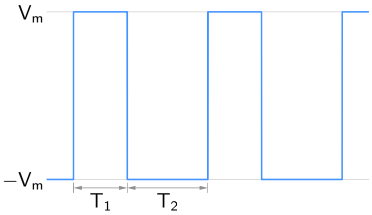
i_C
+ V_C −
V_i
V_o
C
D_1
D_2
R_1
R_2



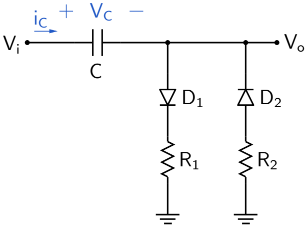
I_D
0.7 V
V_D

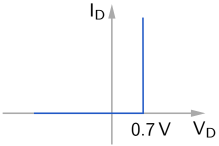


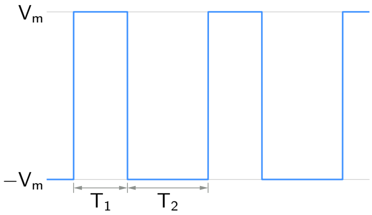
15
10
5
0
−5
−10
V_o
V_i
V_C
$R_1 = 5$ k
$R_2 = 10$ k
$V_{on} = 0.7$ V
$T_1 = 0.25$ ms
$T_2 = 0.75$ ms
$C = 10\ \mu$F

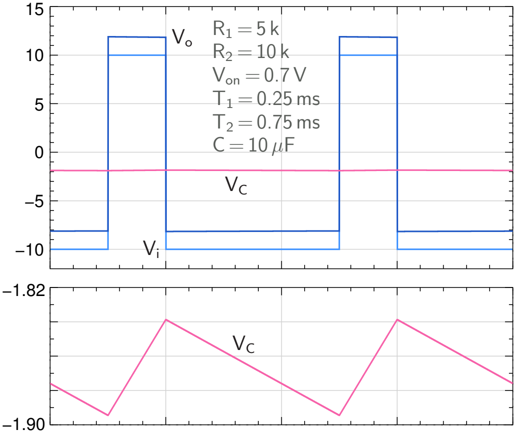


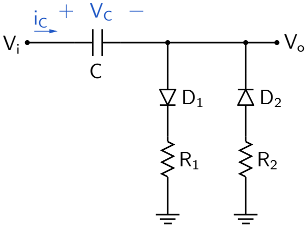
V_m
$-V_m$
T_1
T_2

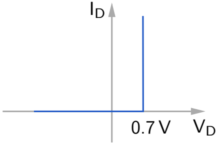

i_C
+ V_C −
V_i
C
V_o
D_1
D_2
R_1
R_2

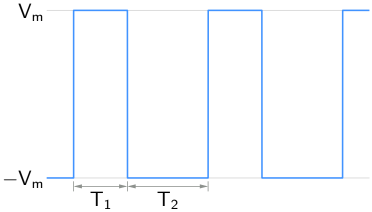

I_D
0.7 V
V_D


V_m
$-V_m$
T_1
T_2


15
10
5
0
−5
−10
V_o
$R_1 = 5\,k$
$R_2 = 10\,k$
$V_{on} = 0.7\,V$
$T_1 = 0.25\,ms$
$T_2 = 0.75\,ms$
$C = 10\,\mu F$
V_C
V_i
−1.82
−1.90
V_C







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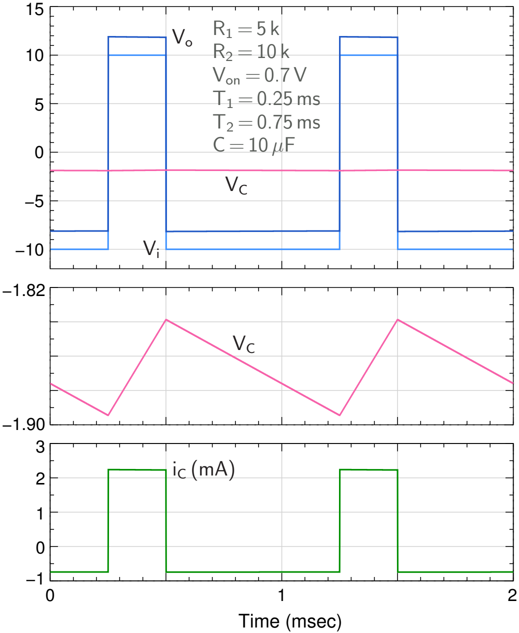
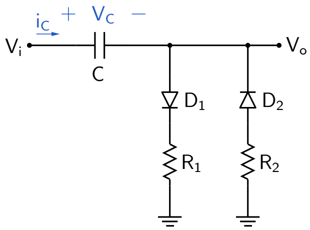
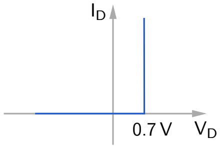
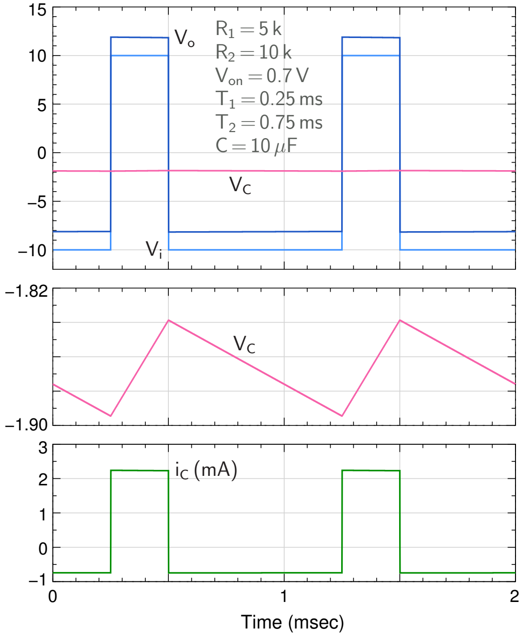
`ee101_diode_circuit_13.sqproj`

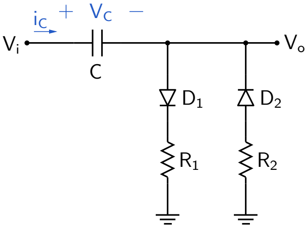


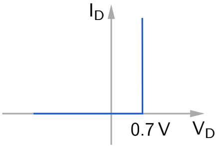


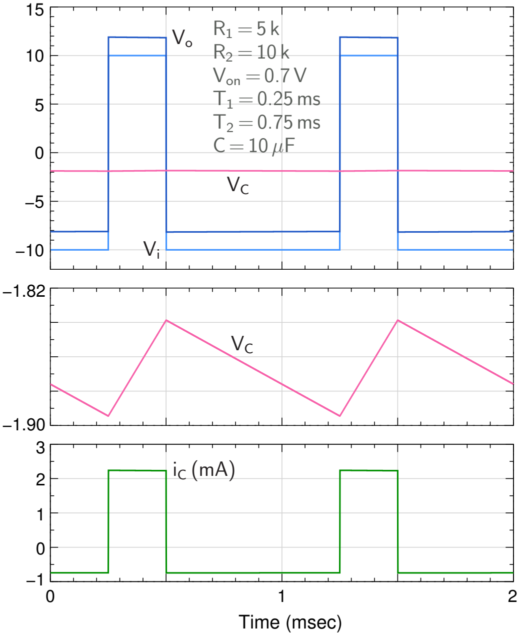




Charge conservation:

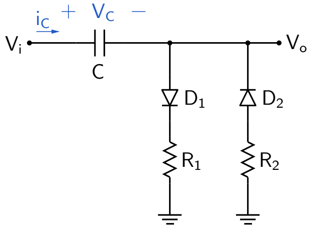


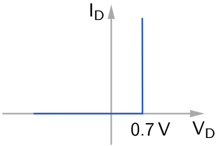




Charge conservation:

$$\Delta Q = \int_0^T i_C\, dt = \int_0^{T_1} i_C\, dt + \int_{T_1}^{T_1+T_2} i_C\, dt = 0.$$

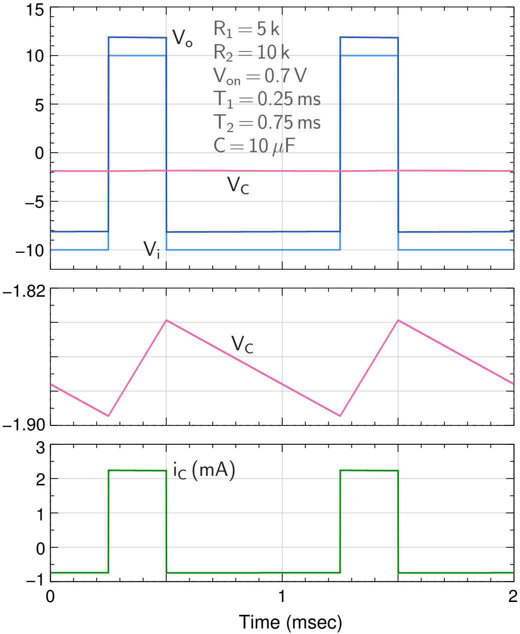


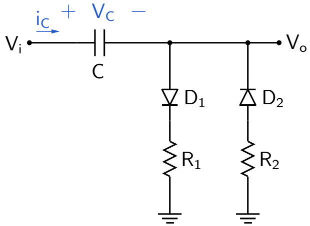


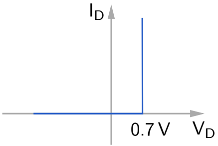
Charge conservation:

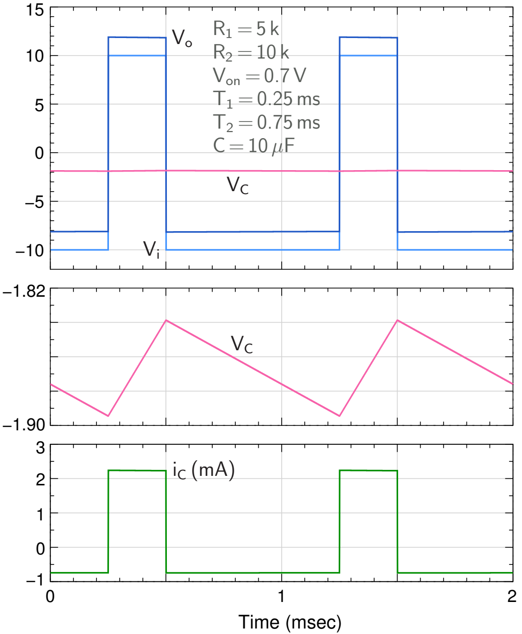
$$\Delta Q = \int_0^T i_C\, dt = \int_0^{T_1} i_C\, dt + \int_{T_1}^{T_1+T_2} i_C\, dt = 0.$$

$$T_1 \left(\frac{V_m - V_C - V_{on}}{R_1} \right) - T_2 \left(\frac{0 - (-V_m - V_C) - V_{on}}{R_2} \right) = 0.$$







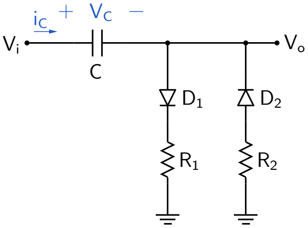


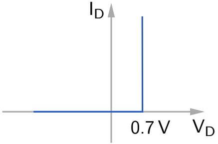
Charge conservation:

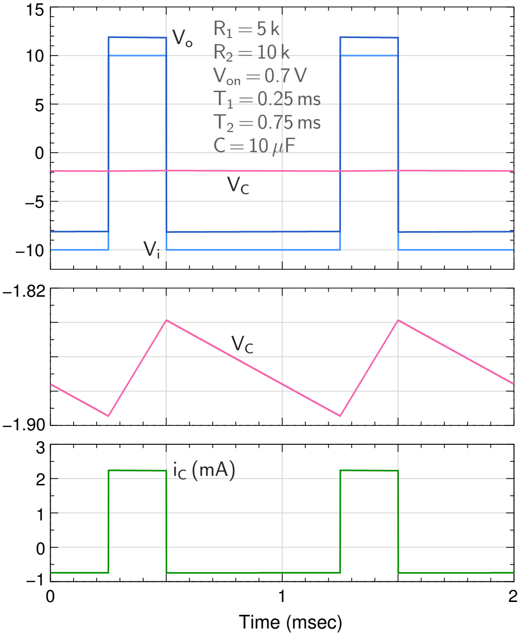
$$\Delta Q = \int_0^T i_C\,dt = \int_0^{T_1} i_C\,dt + \int_{T_1}^{T_1+T_2} i_C\,dt = 0.$$

$$T_1\left(\frac{V_m - V_C - V_{on}}{R_1}\right) - T_2\left(\frac{0 - (-V_m - V_C) - V_{on}}{R_2}\right) = 0.$$

$$\left(\frac{T_1}{R_1} - \frac{T_2}{R_2}\right)(V_m - V_{on}) = V_C\left(\frac{T_1}{R_1} + \frac{T_2}{R_2}\right).$$







Charge conservation:

$$\Delta Q = \int_0^T i_C\, dt = \int_0^{T_1} i_C\, dt + \int_{T_1}^{T_1+T_2} i_C\, dt = 0.$$

$$T_1 \left(\frac{V_m - V_C - V_{on}}{R_1} \right) - T_2 \left(\frac{0 - (-V_m - V_C) - V_{on}}{R_2} \right) = 0.$$

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$$\rightarrow V_C = \frac{\left(\frac{T_1}{R_1} - \frac{T_2}{R_2} \right)}{\left(\frac{T_1}{R_1} + \frac{T_2}{R_2} \right)} (V_m - V_{on}) = -1.86\,V.$$

Rectifiers

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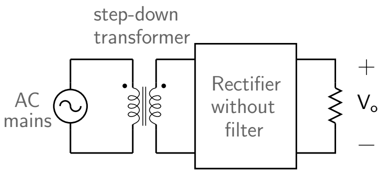
Rectifiers



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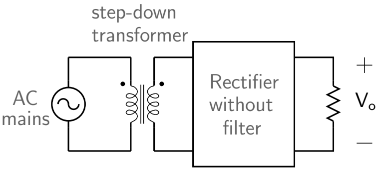

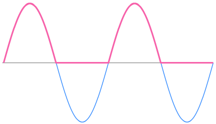

half-wave rectifier

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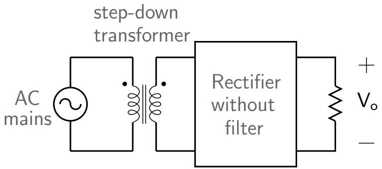
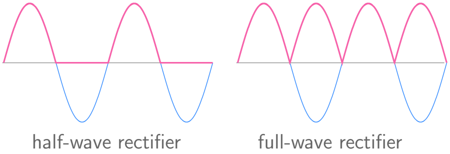
Rectifiers





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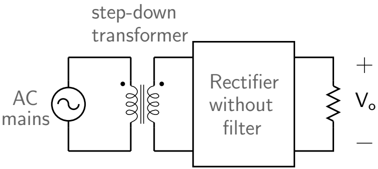

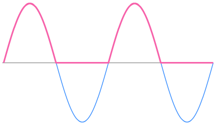

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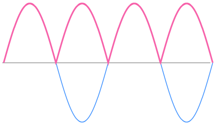
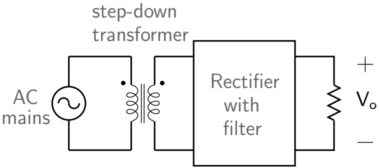


full-wave rectifier



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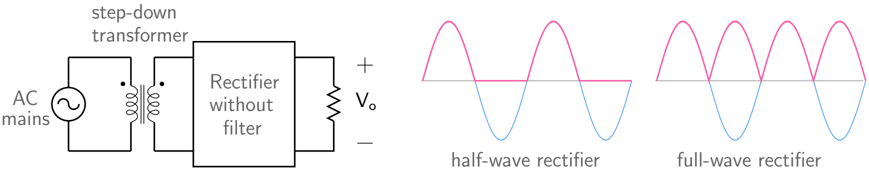
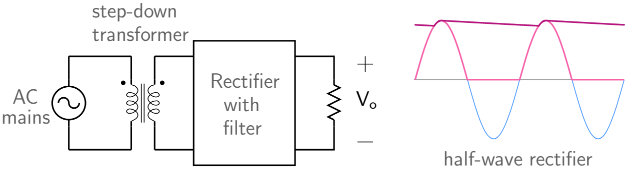
Rectifiers





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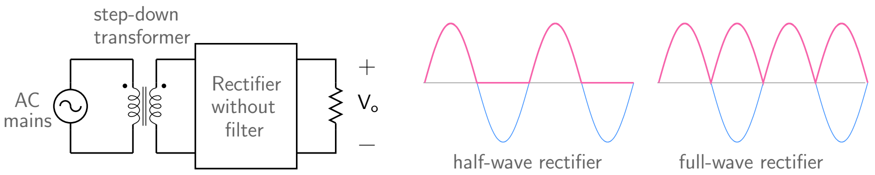
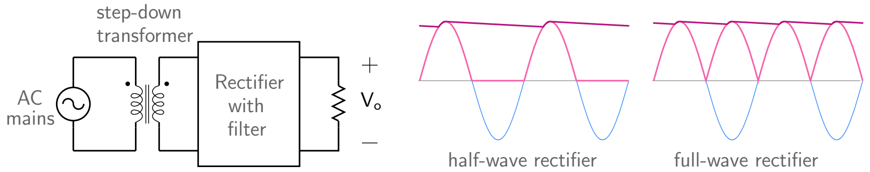
Rectifiers





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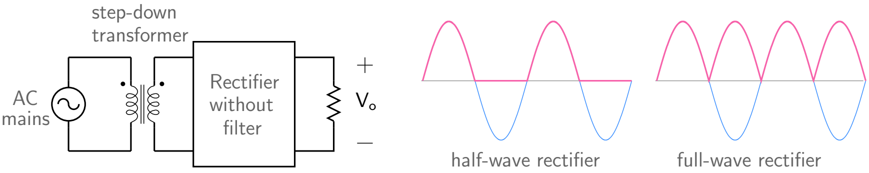

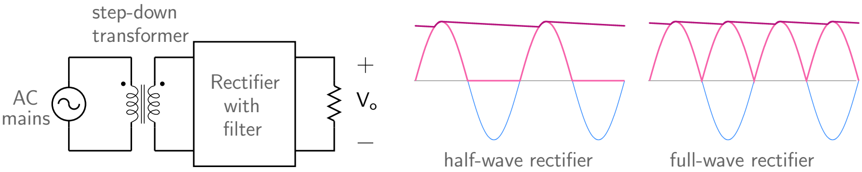

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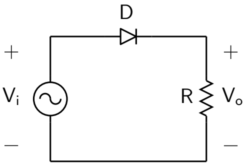
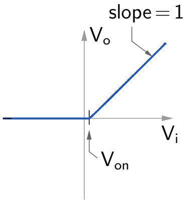
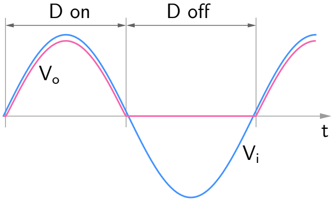
* A voltage regulator would be typically used to remove the ripple riding on the DC output.

Half-wave rectifier without filter







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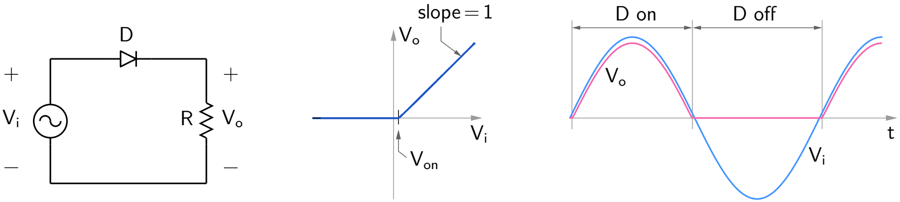

* D conducts only if $V_i > V_{\mathrm{on}}$, and in that case $V_o = V_i - V_{\mathrm{on}}$, a straight line with slope $= 1$.

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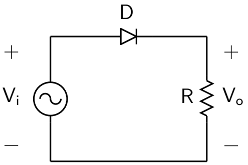
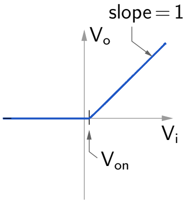
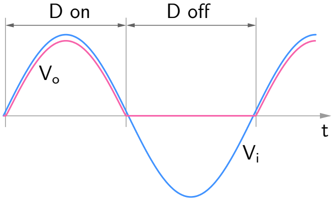
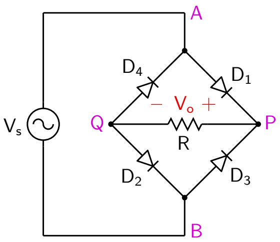






* D conducts only if $V_i > V_{\text{on}}$, and in that case $V_o = V_i - V_{\text{on}}$, a straight line with slope = 1.
* If $V_i < V_{\text{on}}$, D does not conduct $\rightarrow$ $V_o = 0$.

Full-wave (bridge) rectifier without filter



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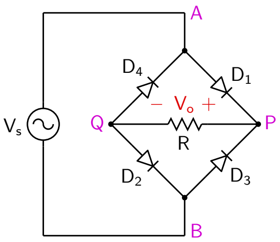

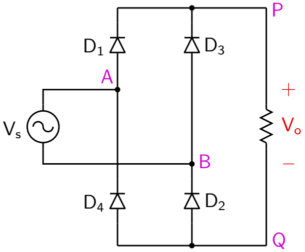

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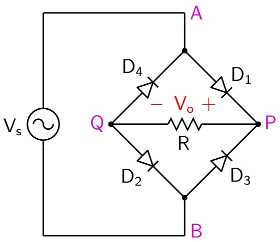

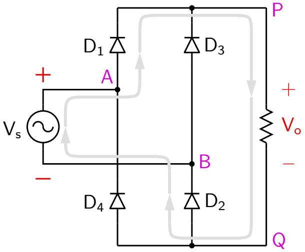

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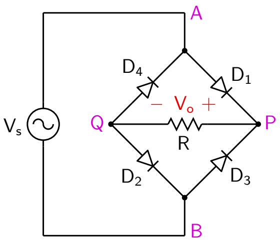

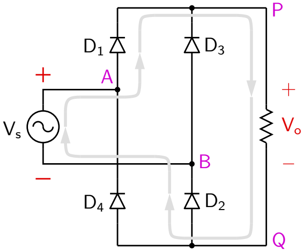

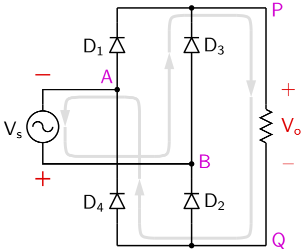

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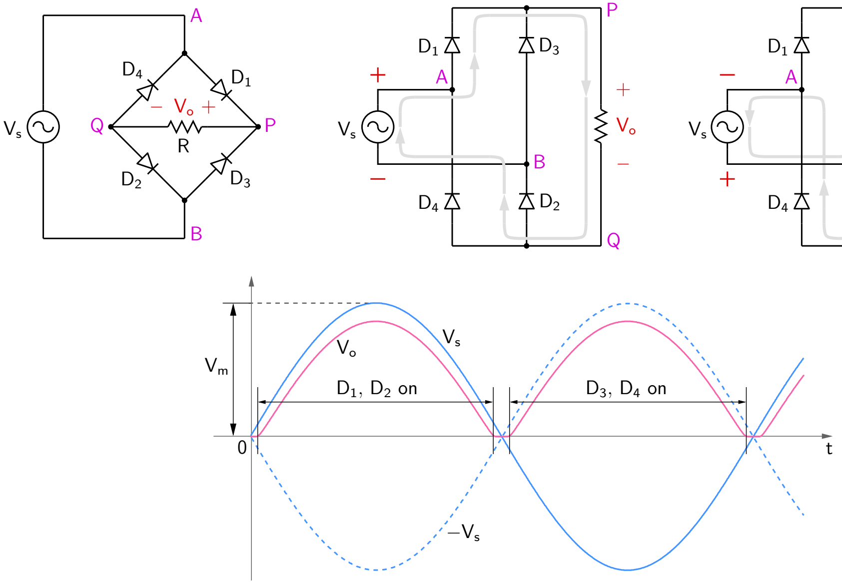
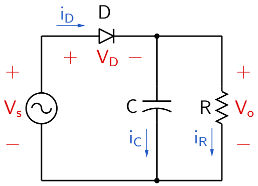


Half-wave rectifier with capacitor filter



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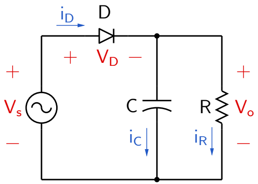

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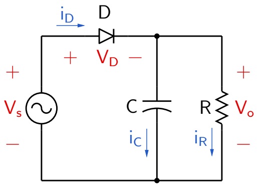

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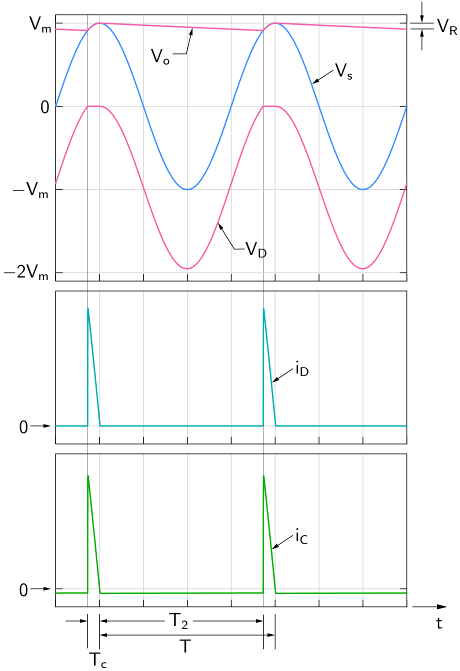

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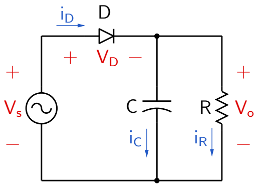

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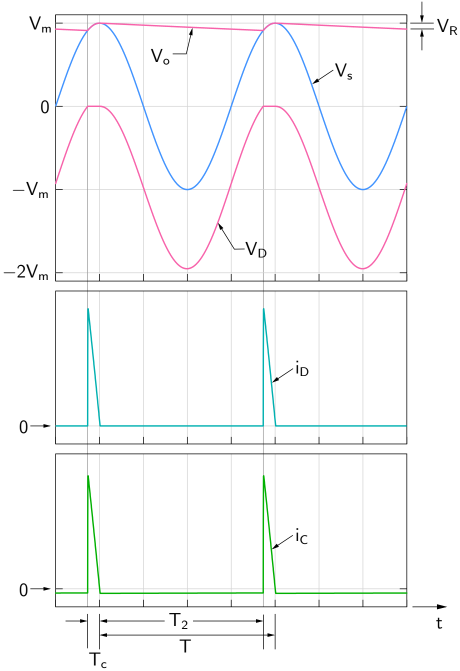

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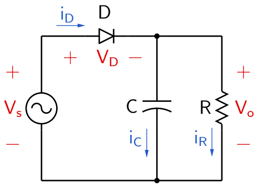

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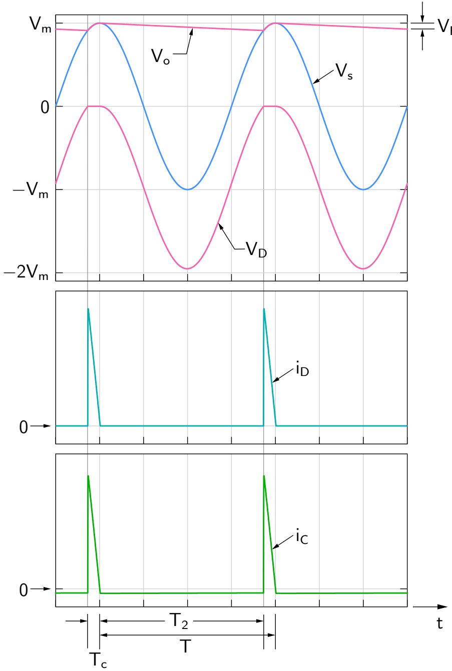

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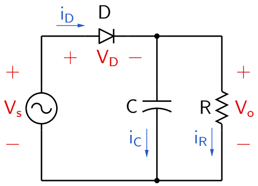

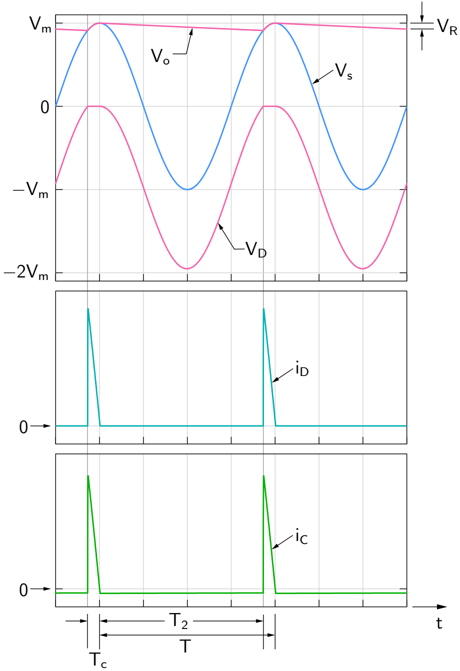

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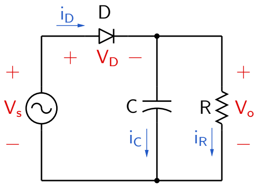
  → The maximum reverse bias ("Peak Inverse Voltage" or PIV) across the diode is 2 V_m.

Half-wave rectifier with capacitor filter



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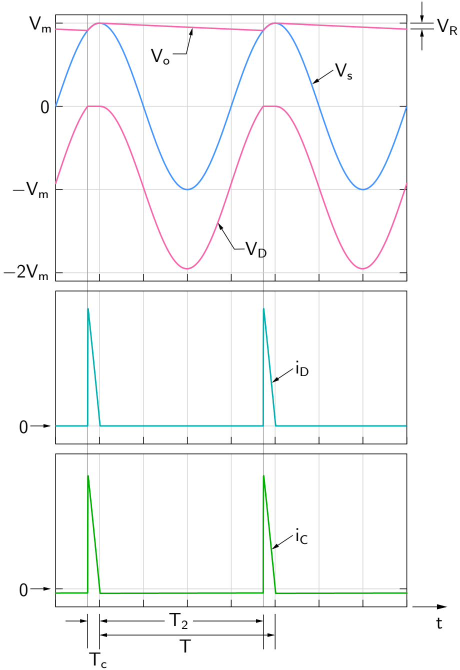

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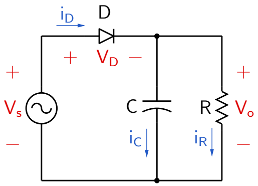

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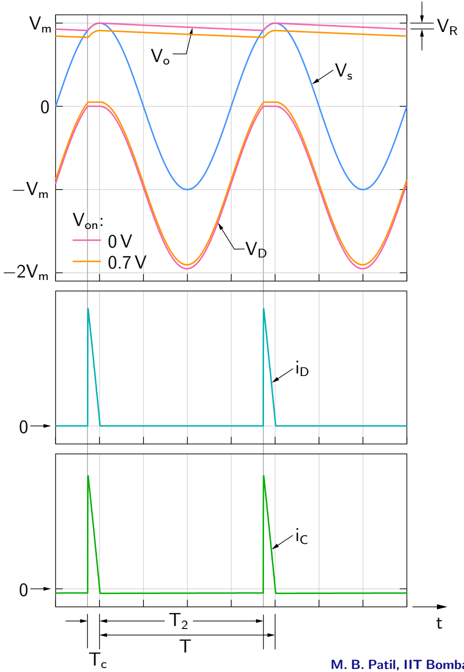
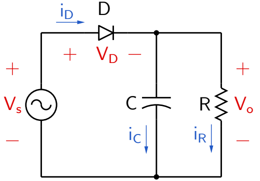


Half-wave rectifier with capacitor filter



$V_m = 16\,\text{V}$, $f = 50\,\text{Hz}$, $R = 100\,\Omega$. For a ripple voltage $V_R = 2\,\text{V}$, find (a) the filter capacitance C, (b) average and peak diode currents, (c) maximum reverse voltage across the diode.
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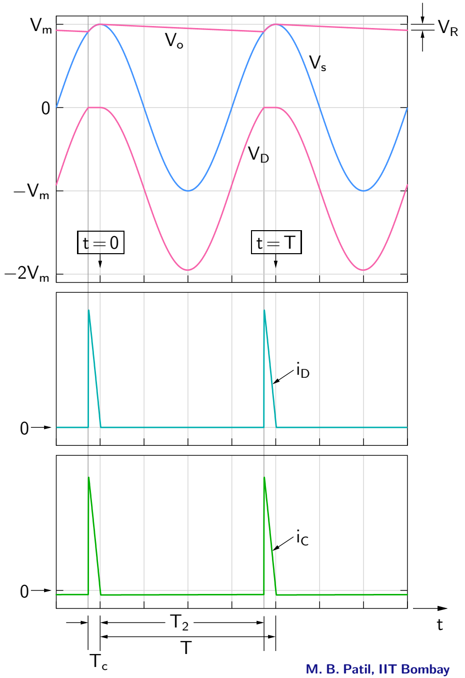
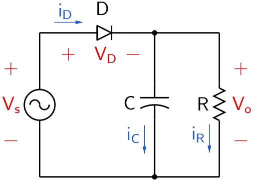


Half-wave rectifier with capacitor filter



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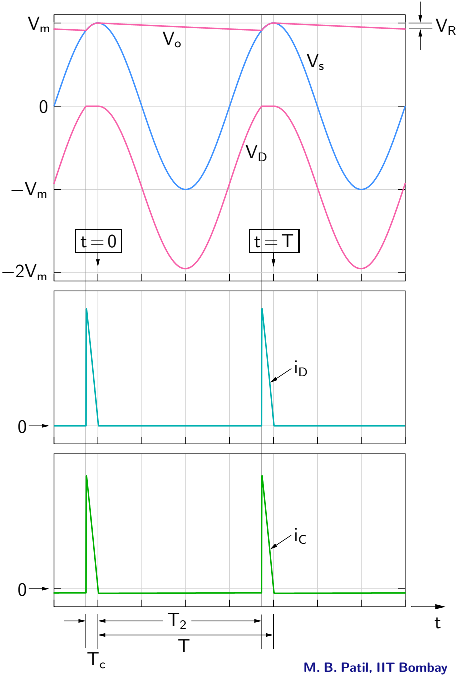
(a) filter capacitance

1. In the discharge phase,

$$V_o(t) = V_m e^{-t/\tau} \approx V_m \left(1 - \frac{t}{\tau}\right).$$



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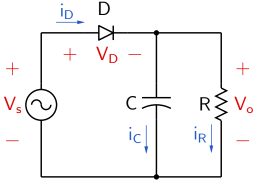
Half-wave rectifier with capacitor filter



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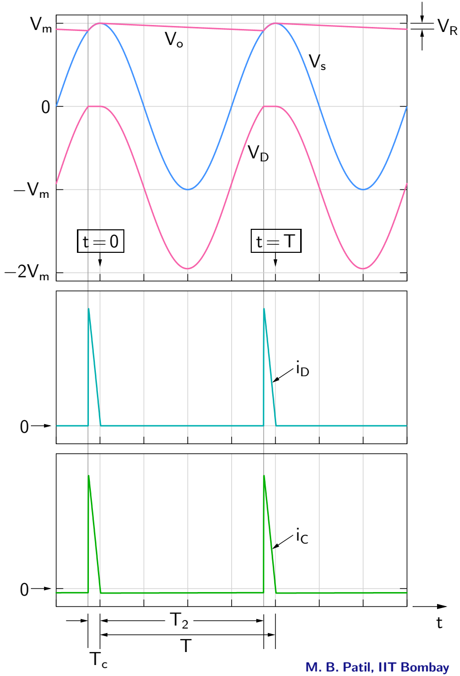
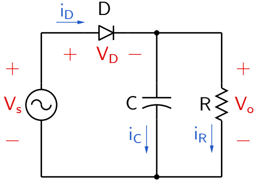
The drop in $V_o(t)$ is given by the second term.

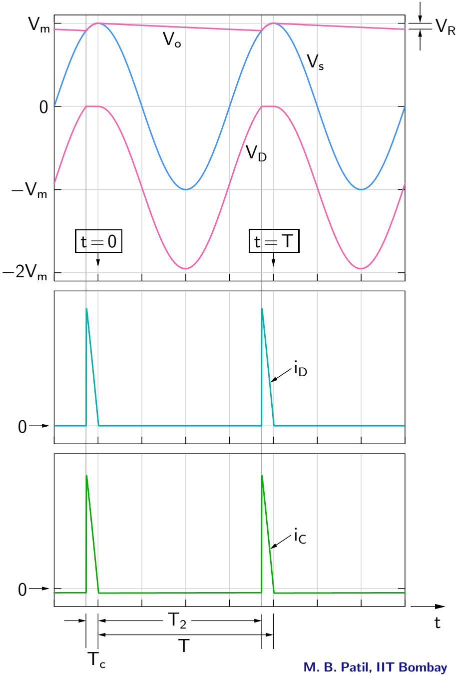
Using $T_2 \approx T$,

$$V_R = V_m \frac{T}{\tau} = V_m \frac{T}{RC}.$$



Half-wave rectifier with capacitor filter





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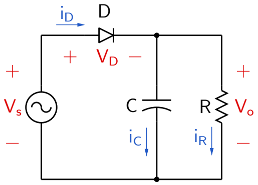
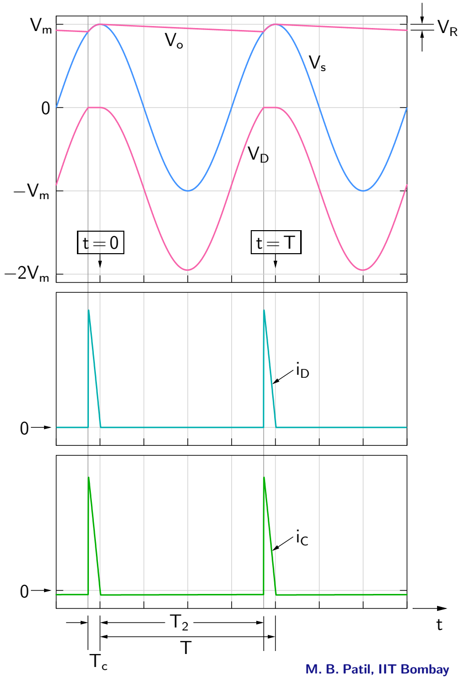
Half-wave rectifier with capacitor filter



(a) Ripple voltage V_R

2. Assuming $i_C = i_R = \dfrac{V_o}{R} \approx \dfrac{V_m}{R}$ in the discharge phase, we get

$$i_C = \frac{V_m}{R} = C\,\frac{\Delta V_o}{\Delta t} \approx C\,\frac{V_R}{T} \rightarrow V_R = V_m\,\frac{T}{RC}.$$



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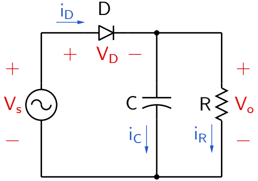
Half-wave rectifier with capacitor filter



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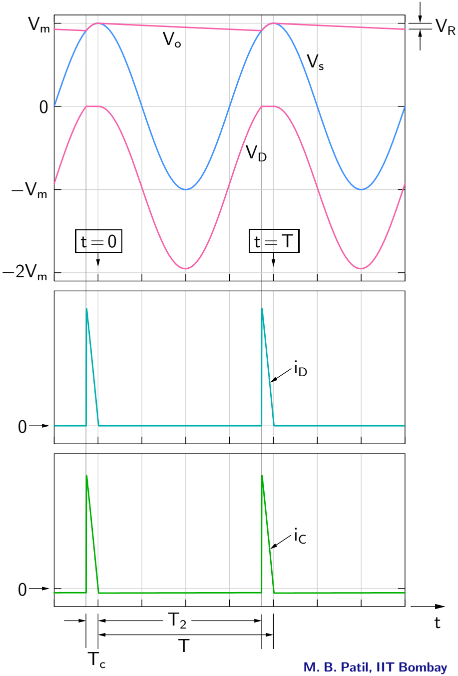
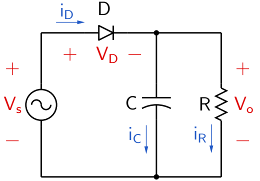
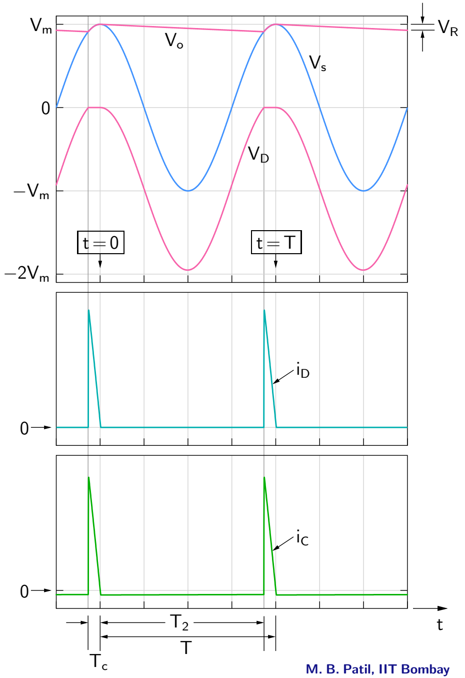
$$\rightarrow C = \frac{V_m}{V_R}\,\frac{T}{R} = \frac{16\,\text{V}}{2\,\text{V}}\,\frac{20\,\text{ms}}{100\,\Omega} = 1600\,\mu\text{F}.$$



Half-wave rectifier with capacitor filter



(b) Average diode current



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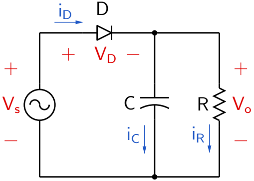
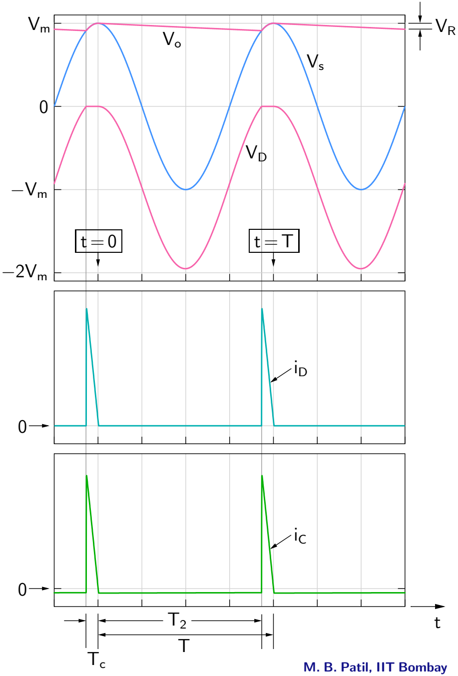
Half-wave rectifier with capacitor filter



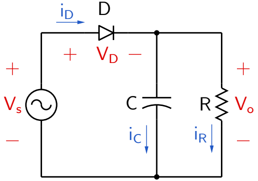
(b) Average diode current

Using charge balance,

$$\int_{T-T_c}^{T} (i_D - i_R)\, dt = \int_{0}^{T-T_c} i_R\, dt$$



Half-wave rectifier with capacitor filter



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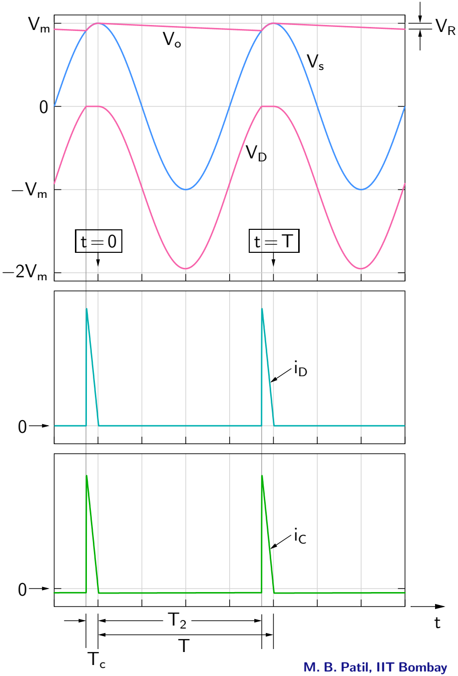
$$\rightarrow \int_{T-T_c}^{T} i_D\, dt = \int_0^{T} i_R\, dt.$$



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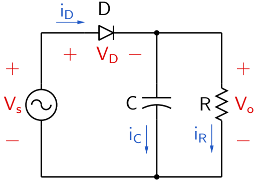
Half-wave rectifier with capacitor filter



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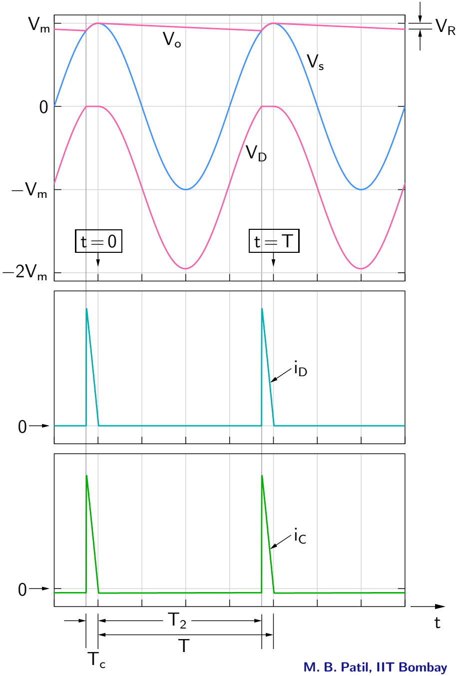
$$\int_{T-T_c}^{T} (i_D - i_R)\, dt = \int_0^{T-T_c} i_R\, dt$$

$$\rightarrow \int_{T-T_c}^{T} i_D\, dt = \int_0^{T} i_R\, dt.$$

$$i_D^{av} = \frac{1}{T}\int_0^{T} i_D\, dt = \frac{1}{T}\int_{T-T_c}^{T} i_D\, dt$$

$$= \frac{1}{T}\int_0^{T} i_R\, dt \approx \frac{V_m}{R}.$$



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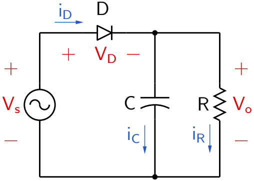
Half-wave rectifier with capacitor filter



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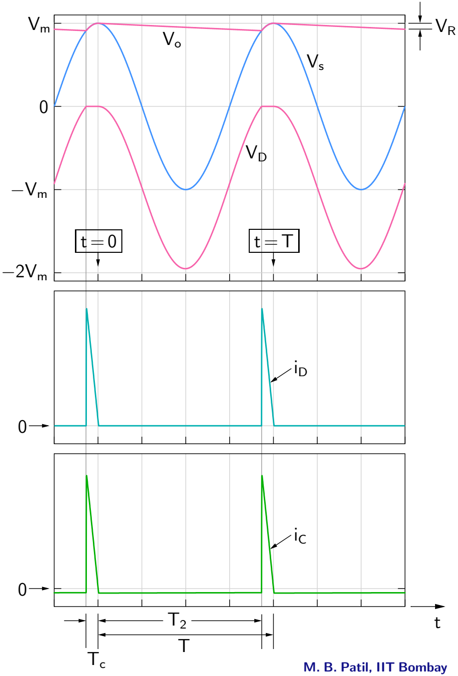
$$= \frac{1}{T}\int_0^T i_R\, dt \approx \frac{V_m}{R}.$$

$$i_D^{av} \approx \frac{16\,\text{V}}{100\,\Omega} = 160\,\text{mA}.$$



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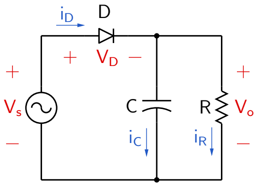
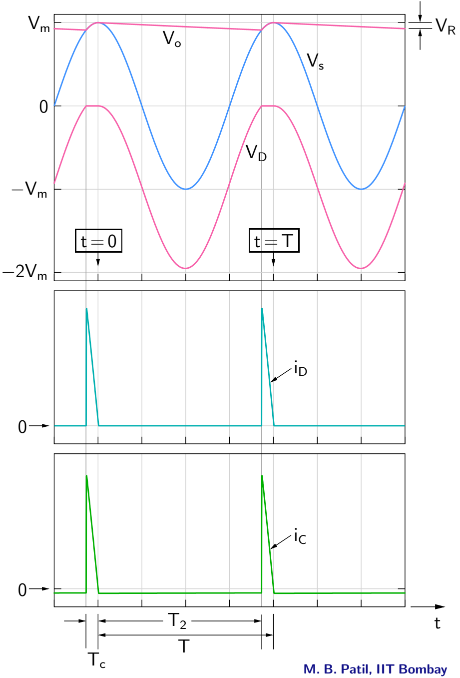


(b) Peak diode current



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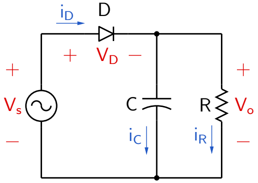
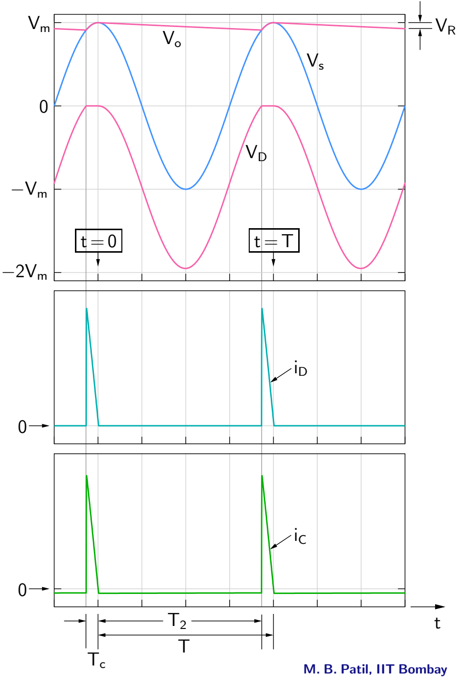
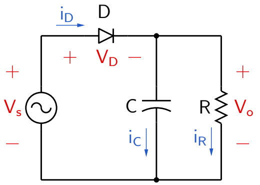


(b) Peak diode current

$$i_D^{\text{peak}} = C\,\frac{d}{dt}\,(V_m \cos\omega t)\Big|_{t=-T_c} + \frac{V_m}{R}$$



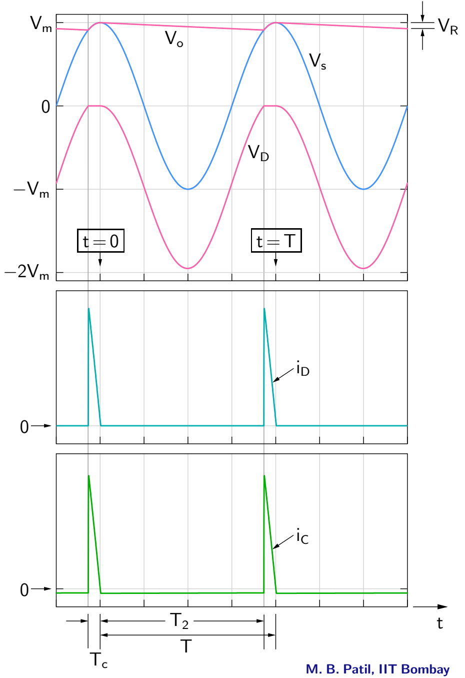


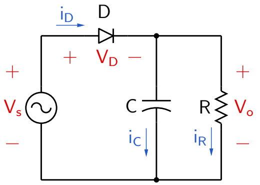
(b) Peak diode current

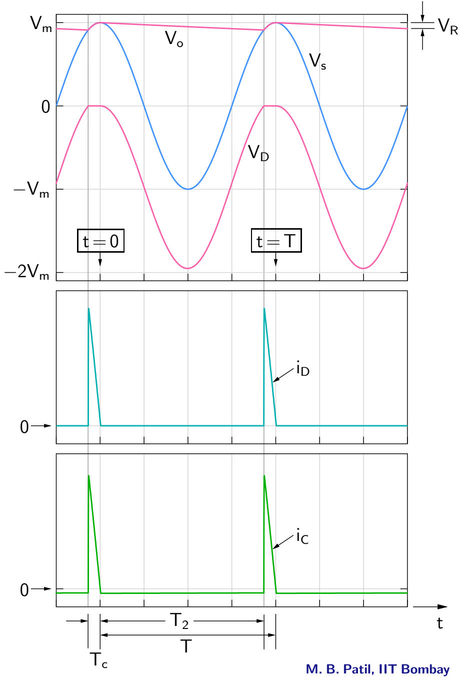
$$i_D^{\text{peak}} = C\,\frac{d}{dt}\,(V_m \cos\omega t)\Big|_{t=-T_c} + \frac{V_m}{R}$$

$$= -\omega C\, V_m \sin(-\omega T_c) + \frac{16\,\text{V}}{100\,\Omega}$$

$$= \omega C\, V_m \sin\omega T_c + 0.16$$







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$V_m\,\cos(-\omega T_c) = V_m - V_R,$ giving

$$\omega T_c = \cos^{-1}\left(1-\frac{V_R}{V_m}\right) = \cos^{-1}\left(1-\frac{2}{16}\right) = 29^\circ.$$

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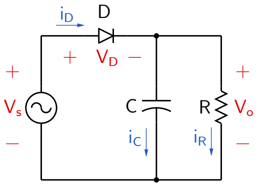

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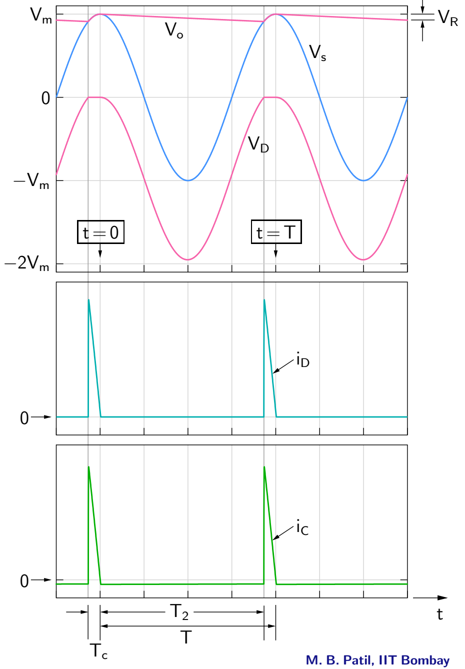
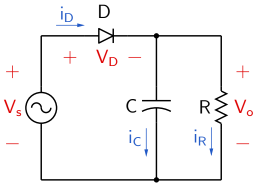
$$\omega T_c = \cos^{-1}\left(1 - \frac{V_R}{V_m}\right) = \cos^{-1}\left(1 - \frac{2}{16}\right) = 29^\circ.$$

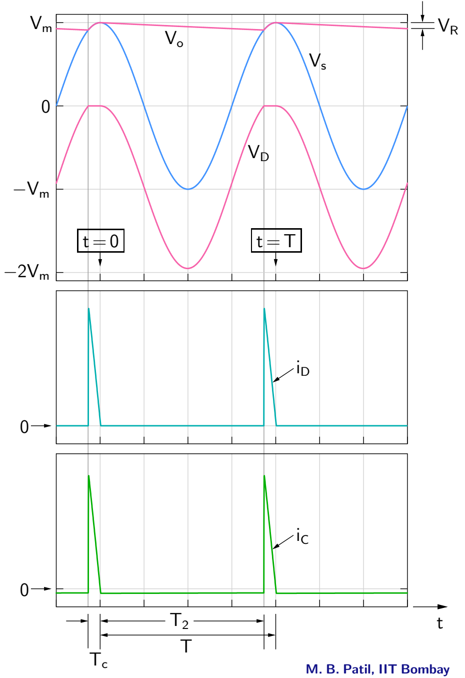
$$i_D^{\text{peak}} = 2\pi \times 50 \times 1600 \times 10^{-6} \times 16 \times \sin 29^\circ + 0.16$$

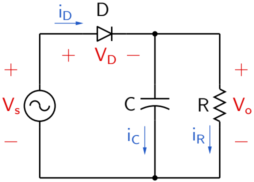
$$= 3.89 + 0.16 = 4.05\ \text{A}.$$





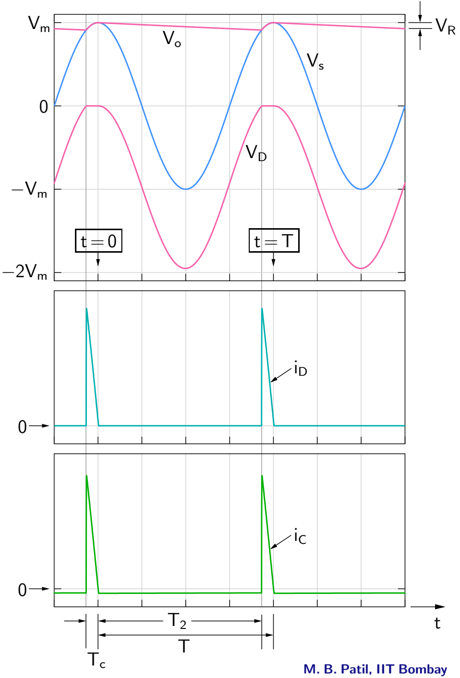
(b) Peak diode current: analytic expression

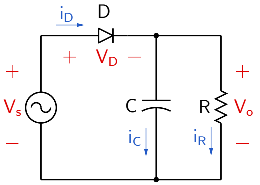




(b) Peak diode current: analytic expression

$$V_m \cos(-\omega T_c) = V_m - V_R \rightarrow \cos \omega T_c = 1 - \frac{V_R}{V_m} \equiv 1 - x$$





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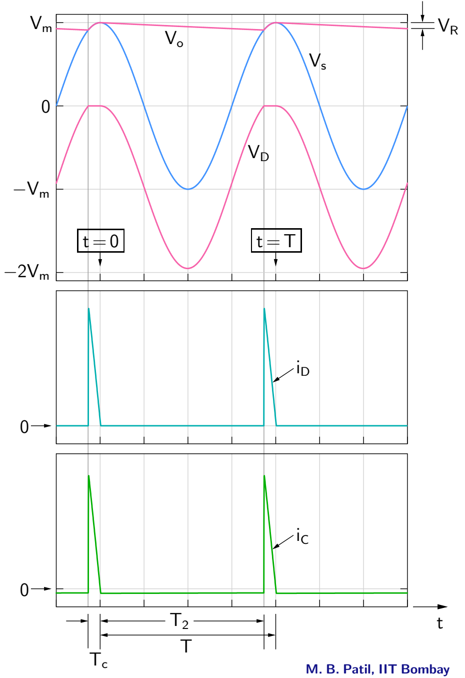
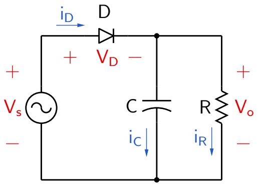
$$= \sqrt{1-(1-2x+x^2)} \approx \sqrt{2x} = \sqrt{\frac{2\,V_R}{V_m}}$$





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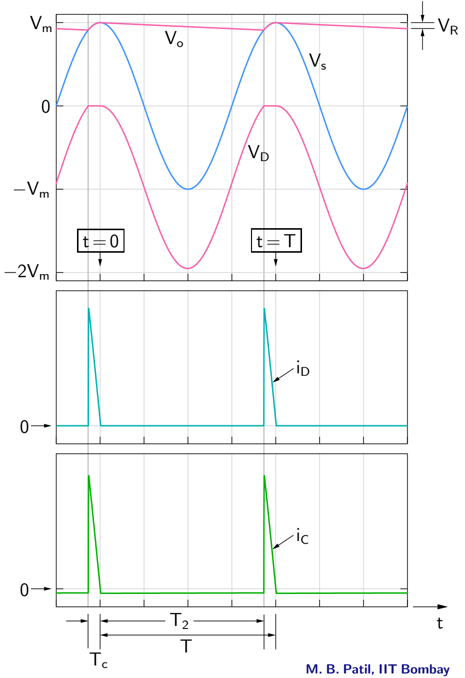

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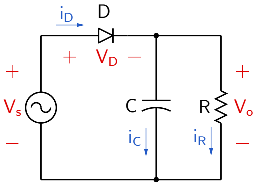

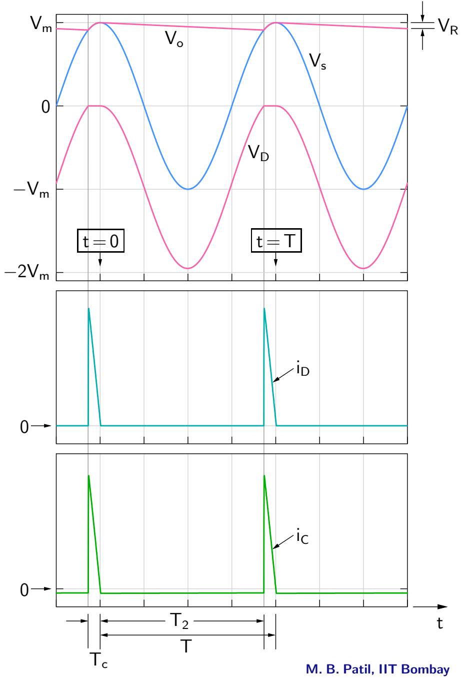

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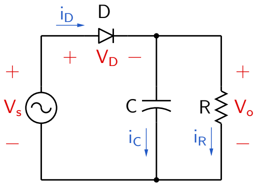
(c) Maximum reverse bias $\approx 2\,V_m = 32\,\text{V}$.



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$$i_D^{\text{peak}} = i_R + C\,\frac{d}{dt}\,(V_m \cos \omega t)\Big|_{t=-T_c}$$

$$= i_R + \omega C\, V_m \sin \omega T_c$$

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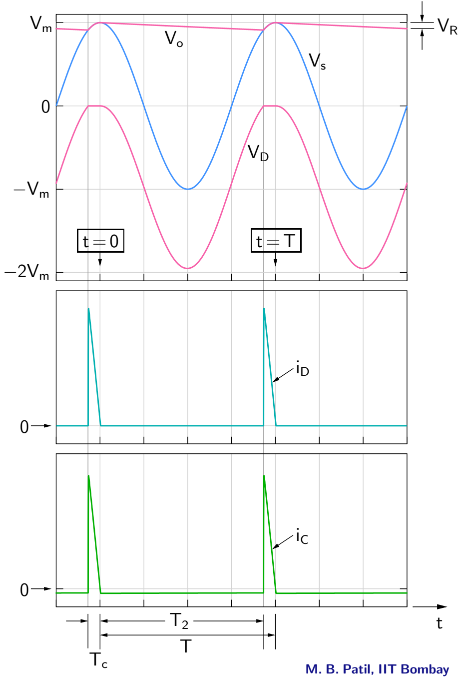
SEQUEL file: `ee101_half_rectifier.sqproj`



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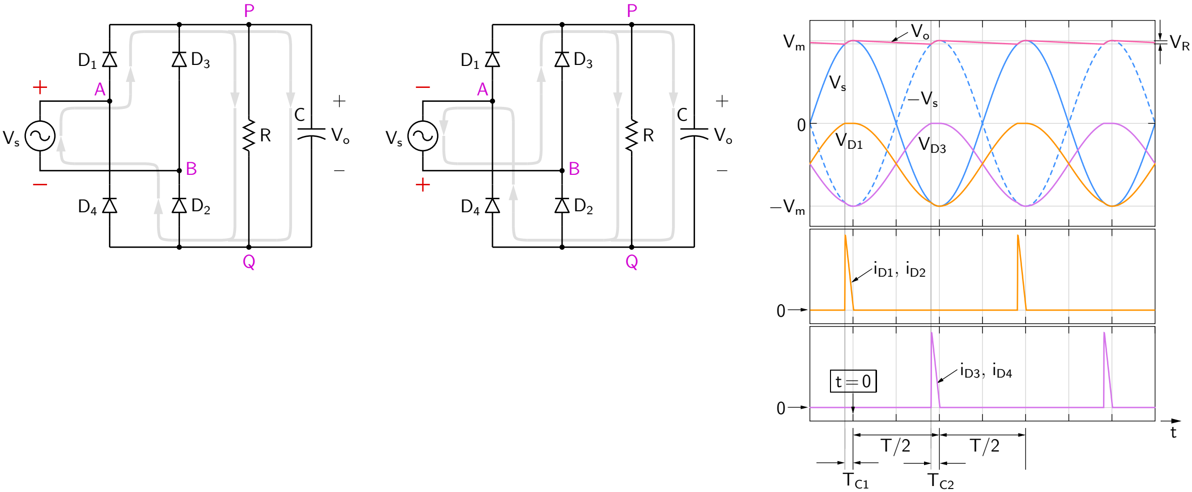
Full-wave (bridge) rectifier with capacitor filter



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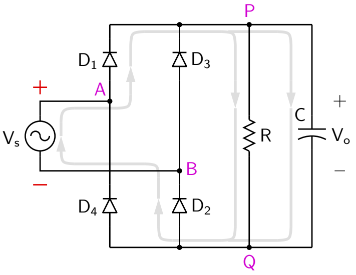
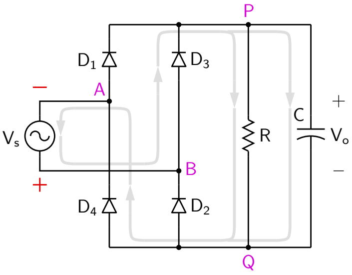
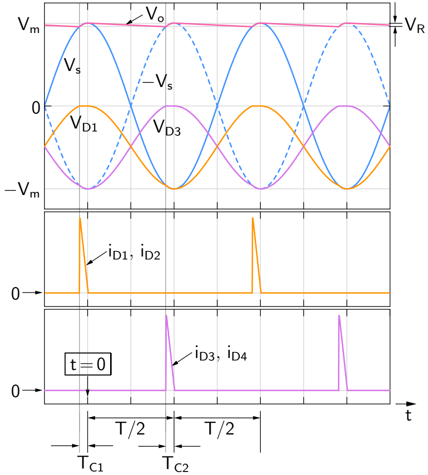
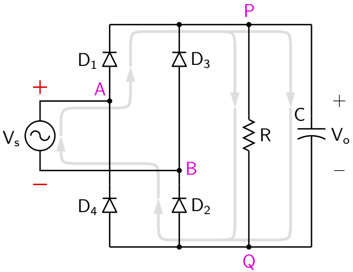


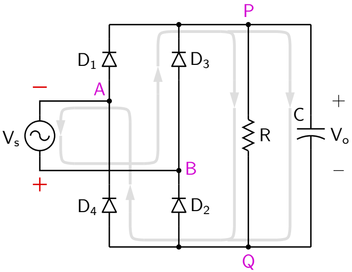


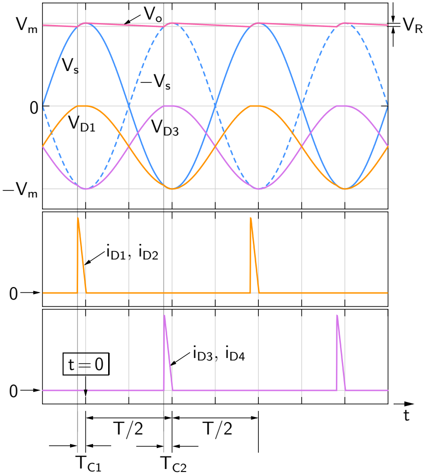


* As in the half-wave rectifier case, we have charging and discharging intervals, and $V_o \approx V_m$ is maintained.

Full-wave (bridge) rectifier with capacitor filter

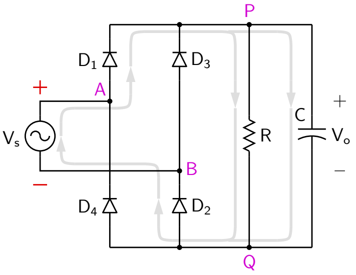


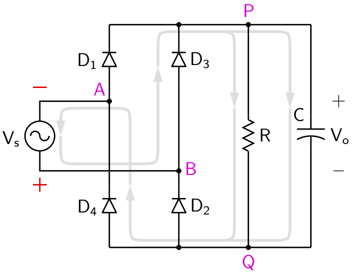


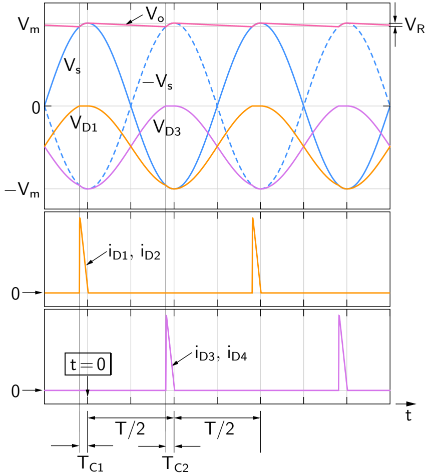


* As in the half-wave rectifier case, we have charging and discharging intervals, and $V_o \approx V_m$ is maintained.
* Charging through D_1, D_2 takes place when $V_o(t)$ falls below $V_s(t)$.

Full-wave (bridge) rectifier with capacitor filter

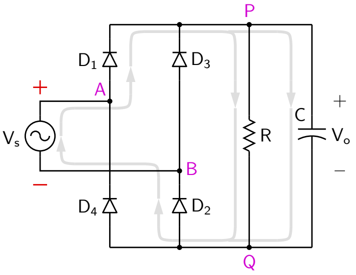


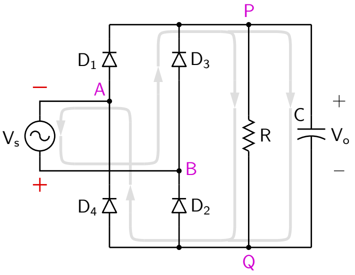


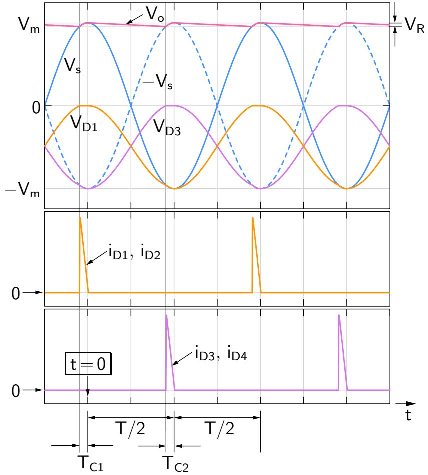


* As in the half-wave rectifier case, we have charging and discharging intervals, and $V_o \approx V_m$ is maintained.
* Charging through D_1, D_2 takes place when $V_o(t)$ falls below $V_s(t)$.
* Charging through D_3, D_4 takes place when $V_o(t)$ falls below $-V_s(t)$.

Full-wave (bridge) rectifier with capacitor filter

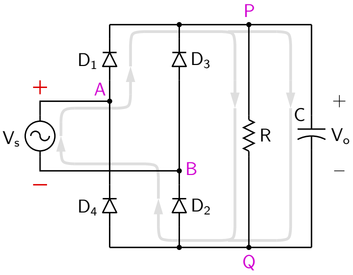


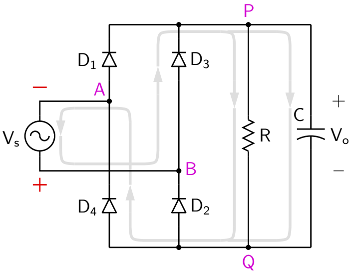


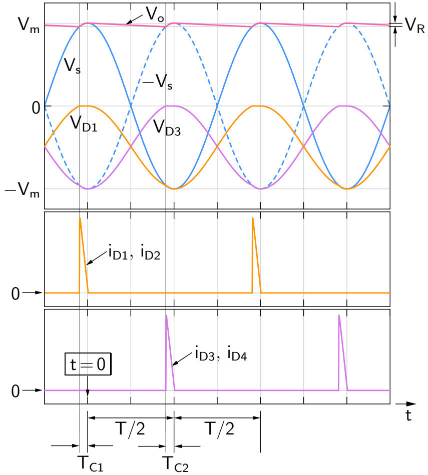


* As in the half-wave rectifier case, we have charging and discharging intervals, and $V_o \approx V_m$ is maintained.
* Charging through D_1, D_2 takes place when $V_o(t)$ falls below $V_s(t)$.
* Charging through D_3, D_4 takes place when $V_o(t)$ falls below $-V_s(t)$.
* The discharging interval is typically much longer than the charging intervals (T_{C1} and T_{C2}).

Full-wave (bridge) rectifier with capacitor filter







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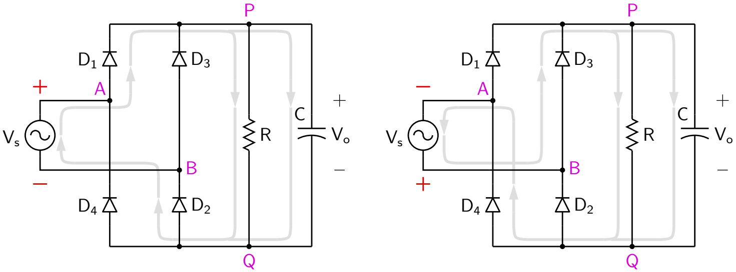
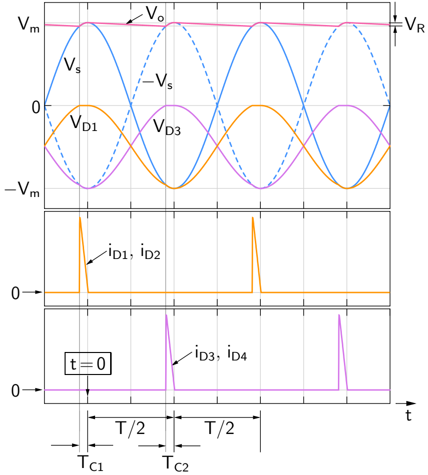
* Charging through D_3, D_4 takes place when $V_o(t)$ falls below $-V_s(t)$.
* The discharging interval is typically much longer than the charging intervals (T_{C1} and T_{C2}).
* The maximum reverse bias across any of the diodes is V_m.

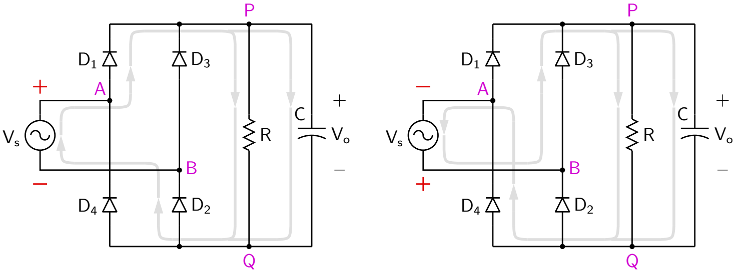
Full-wave rectifier with capacitor filter

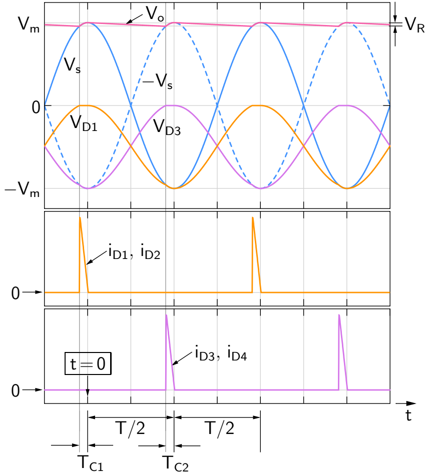




$V_m = 16\,\text{V}$, $f = 50\,\text{Hz}$, $R = 100\,\Omega$. For a ripple voltage $V_R = 2\,\text{V}$, find (a) the filter capacitance C, (b) average and peak diode currents, (c) maximum reverse voltage across the diode. (Let $V_{on} = 0\,\text{V}$.)

Full-wave rectifier with capacitor filter





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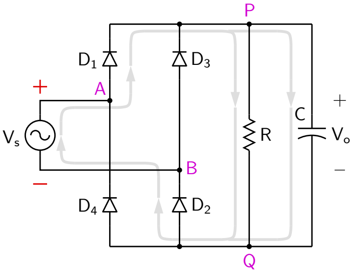
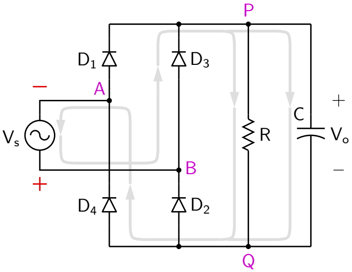
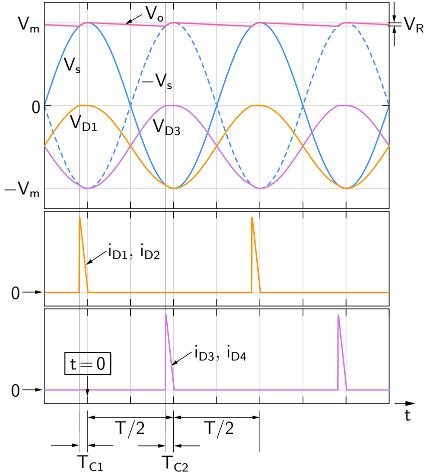
(a) filter capacitance:

Full-wave rectifier with capacitor filter







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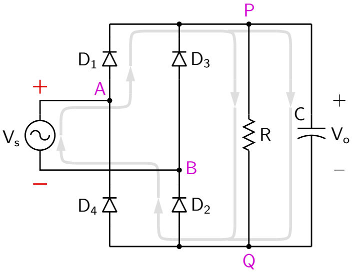
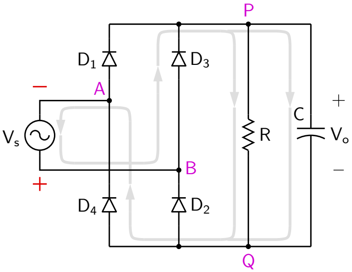
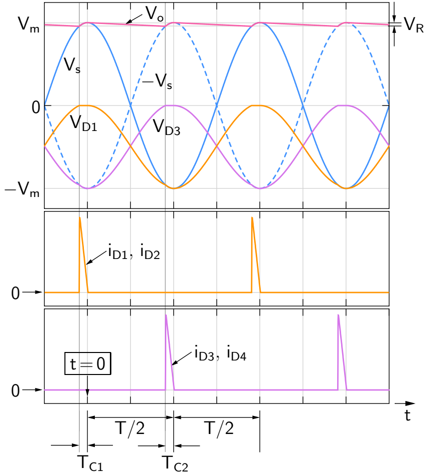
(a) filter capacitance:

Assuming $i_C = i_R = \dfrac{V_o}{R} \approx \dfrac{V_m}{R}$ in the discharge phase, we get

$$i_C = \frac{V_m}{R} = C\,\frac{\Delta V_o}{\Delta t} \approx C\,\frac{V_R}{T/2} \rightarrow V_R = V_m\,\frac{T}{2RC}.$$







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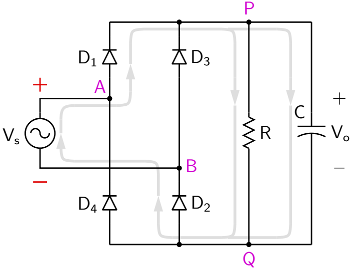
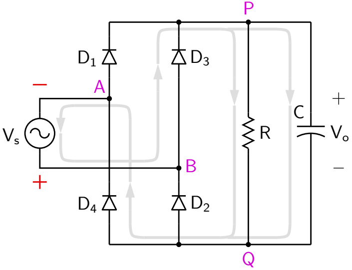
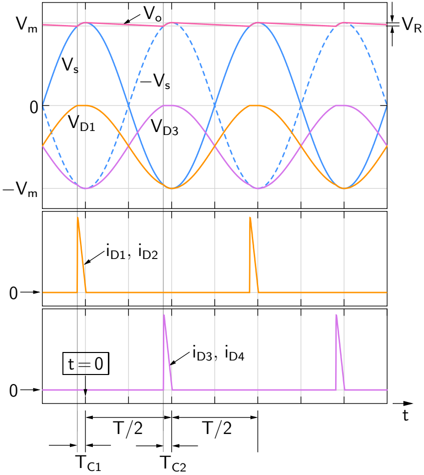
$$\rightarrow C = \frac{1}{2}\,\frac{V_m}{V_R}\,\frac{T}{R} = \frac{1}{2}\,\frac{16\,\text{V}}{2\,\text{V}}\,\frac{20\,\text{ms}}{100\,\Omega} = 800\,\mu\text{F}.$$

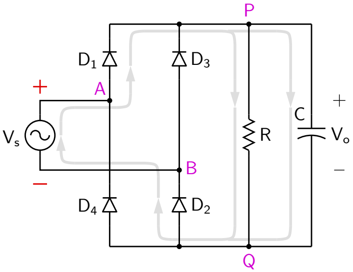
Full-wave rectifier with capacitor filter

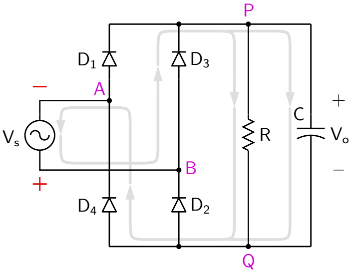


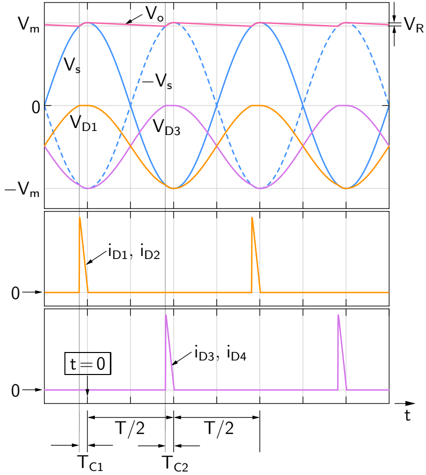


(b) Average diode current





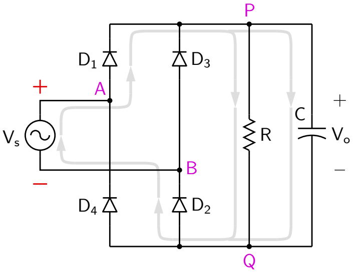


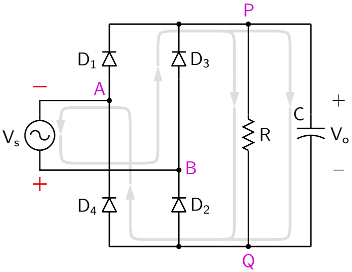


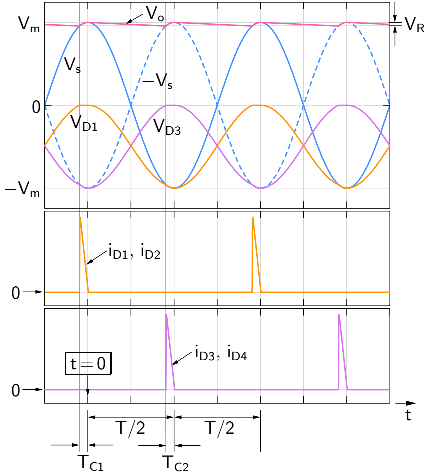
(b) Average diode current

Half of the charge lost by the capacitor is supplied by i_{D1} $(= i_{D2})$, and the other half by i_{D3} $(= i_{D4})$.

Full-wave rectifier with capacitor filter







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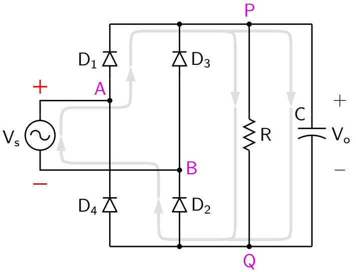
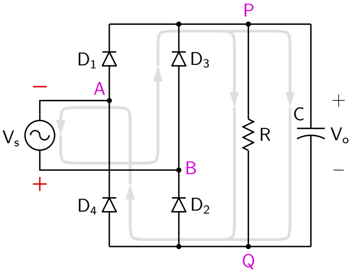
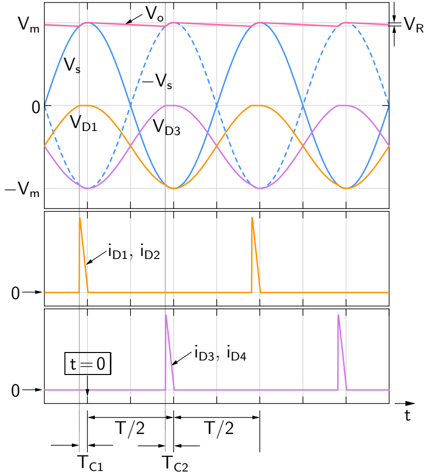
$$i_D^{av} = \frac{1}{T} \times \frac{1}{2} \times \text{(Charge lost in one cycle)}$$

Full-wave rectifier with capacitor filter







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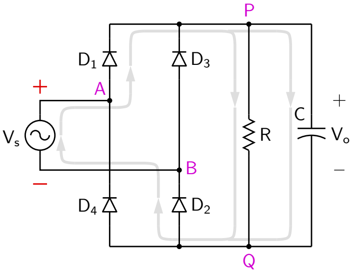
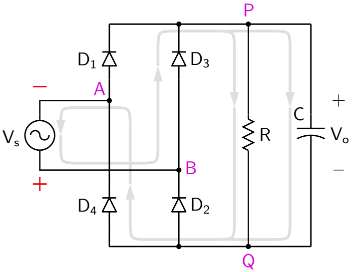
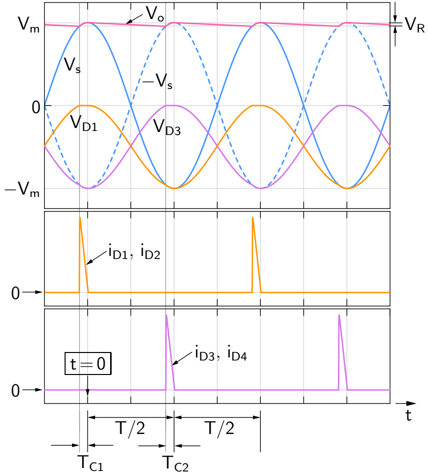
$$\approx \frac{1}{T} \times \frac{1}{2} \times \left(\frac{V_m}{R} \times T \right) = \frac{V_m}{2R} = \frac{16\,\text{V}}{2 \times 100\,\Omega} = 80\,\text{mA}.$$

Full-wave rectifier with capacitor filter

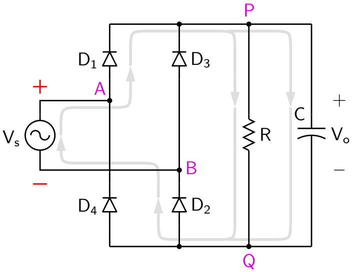


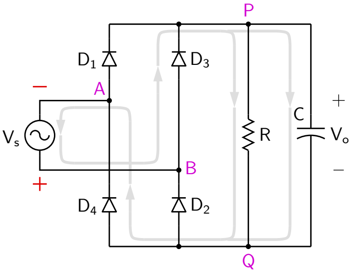


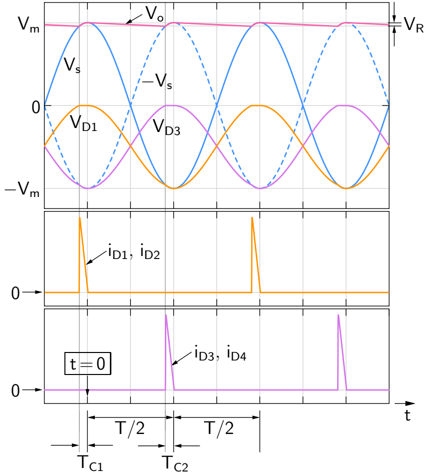
(b) Peak diode current



Full-wave rectifier with capacitor filter







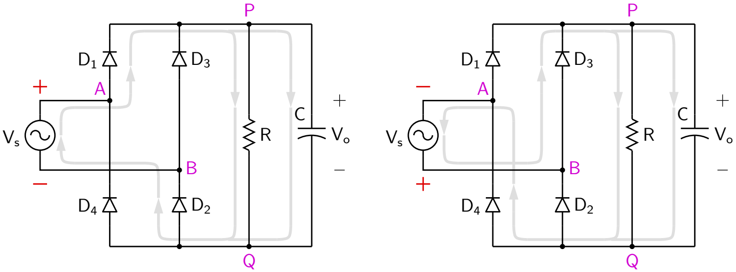
(b) Peak diode current

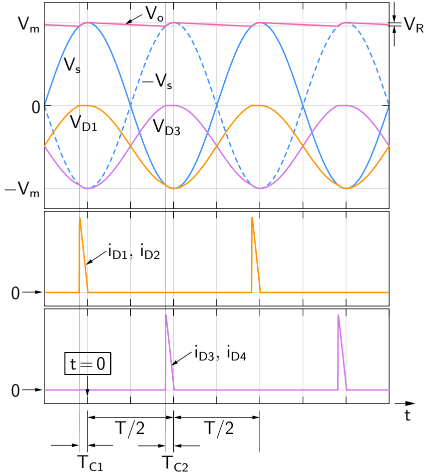
$$i_{D1}^{\text{peak}} = C\,\frac{d}{dt}\,(V_m \cos \omega t)\Big|_{t=-T_{C1}} + \frac{V_m}{R}$$

$$= -\omega C\, V_m \sin(-\omega T_{C1}) + \frac{16\,\text{V}}{100\,\Omega}$$

$$= \omega C\, V_m \sin \omega T_{C1} + 0.16$$

Full-wave rectifier with capacitor filter





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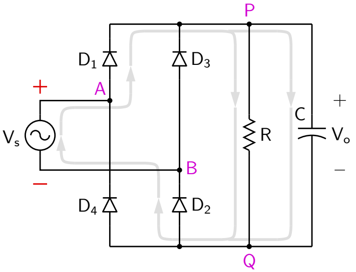
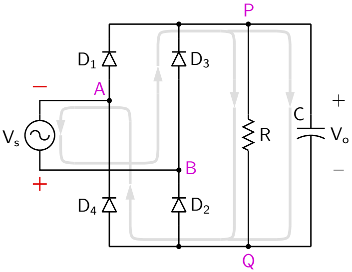
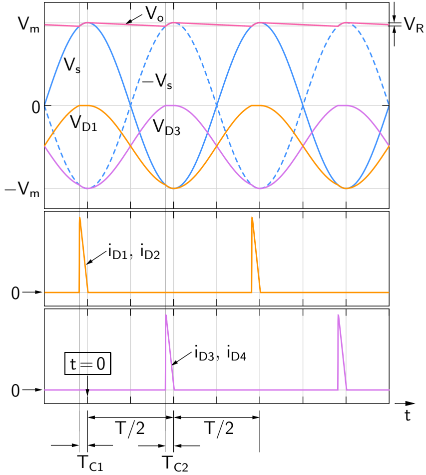
$$\omega T_{C1} = \cos^{-1}\left(1 - \frac{V_R}{V_m}\right) = \cos^{-1}\left(1 - \frac{2}{16}\right) = 29^\circ .$$

Full-wave rectifier with capacitor filter







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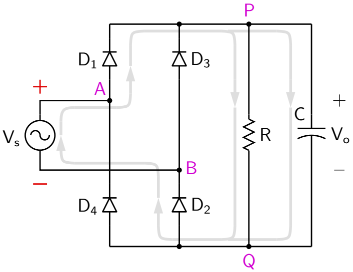
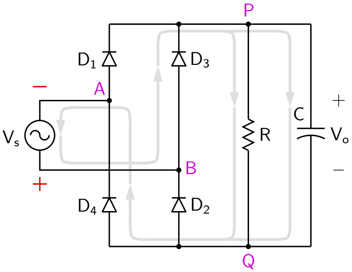
$$\omega T_{C1} = \cos^{-1}\left(1 - \frac{V_R}{V_m}\right) = \cos^{-1}\left(1 - \frac{2}{16}\right) = 29^\circ.$$

$$i_{D1}^{\text{peak}} = 2\pi \times 50 \times 800 \times 10^{-6} \times 16 \times \sin 29^\circ + 0.16$$

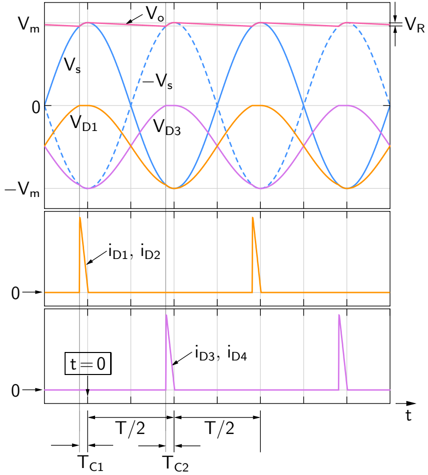
$$= 1.95 + 0.16 = 2.1\,\text{A}.$$

Full-wave rectifier with capacitor filter

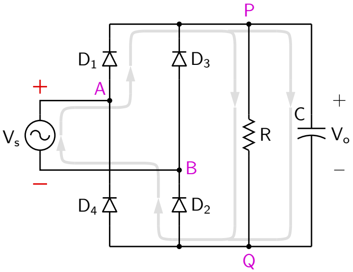


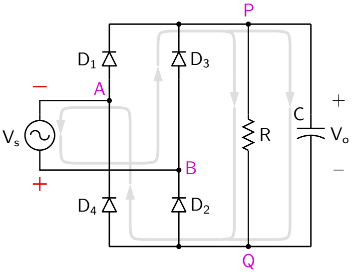


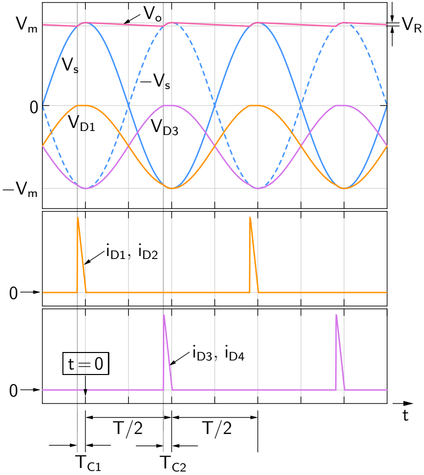
(c) Maximum reverse bias = $V_m = 16\,\text{V}$.



Full-wave rectifier with capacitor filter







(c) Maximum reverse bias $= V_m = 16\,\text{V}$.

SEQUEL file: `diode_rectifier_4.sqproj`

For the same source voltage ($V_m \sin \omega t$), load (R), and ripple voltage (V_R), compare the half-wave and full-wave rectifiers.

Comparison of half-wave and full-wave (bridge) rectifiers with capacitive filter

For the same source voltage ($V_m \sin \omega t$), load (R), and ripple voltage (V_R), compare the half-wave and full-wave rectifiers.

Parameter	Half-wave	Full-wave
Number of diodes	1	4
Filter capacitance	C	$C/2$
Average diode current	i_D^{av}	$i_D^{\text{av}}/2$
Peak diode current	i_D^{peak}	$i_D^{\text{peak}}/2$
Maximum reverse voltage	$2\,V_m$	V_m