Diode Circuits: Part 1

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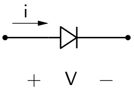
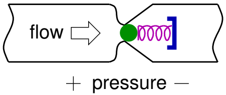
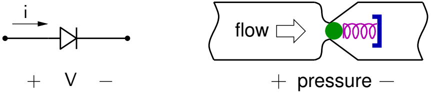

i
+ V −


flow
+ pressure −



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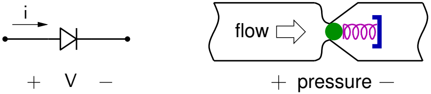

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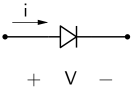

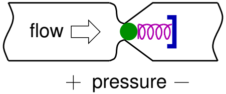

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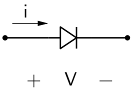

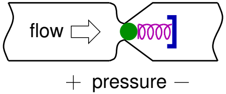

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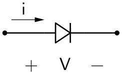
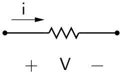
* A check valve presents a small resistance if the pressure $p > 0$, but blocks the flow (i.e., presents a large resistance) if $p < 0$.
* Similarly, a diode presents a small resistance in the forward direction and a large resistance in the reverse direction.
* Note: In a practical diode, the resistance $R_D = V/i$ 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.

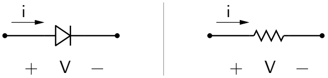
Simple models: $R_{\mathrm{on}}/R_{\mathrm{off}}$ model





$\mathrm{R} = \mathrm{R_{on}}$ if $\mathrm{V} > 0$

$\mathrm{R} = \mathrm{R_{off}}$ if $\mathrm{V} < 0$



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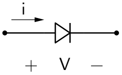

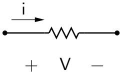

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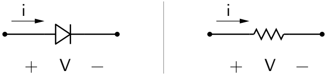

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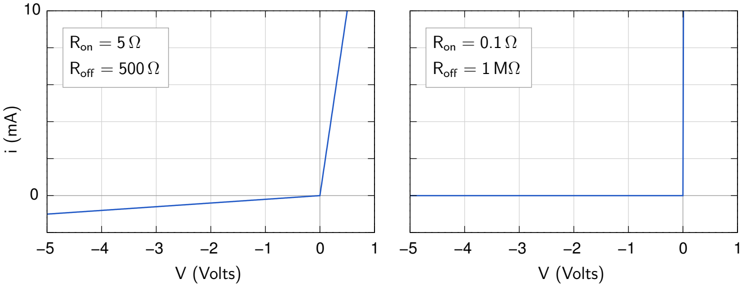
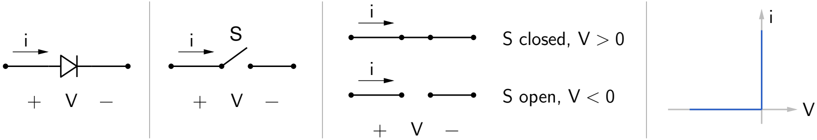
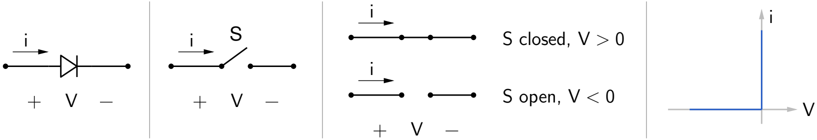
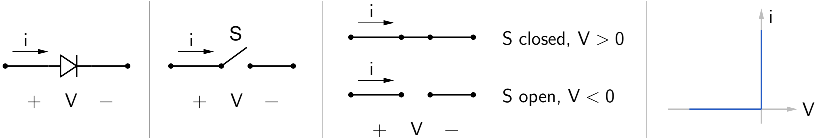


Simple models: ideal switch





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



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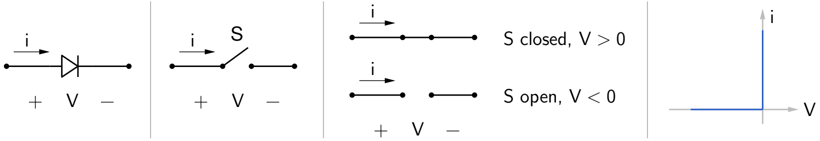

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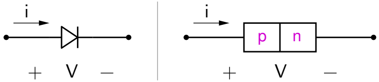
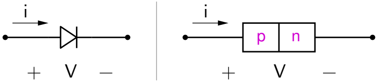
* The actual values of V and i for a diode in a circuit get determined by the i-V relationship of the diode *and* the constraints on V and i imposed by the circuit.

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 = 1.38×10^{-23} J/K.

q = electron charge = 1.602×10^{-19} Coul.

T = temperature in $^\circ K$.

$V_T \approx 25$ mV at room temperature (27 °C).

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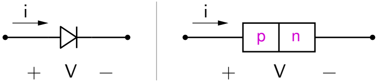

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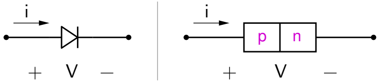

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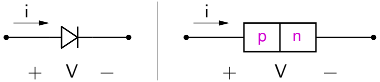

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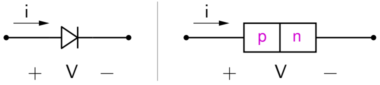

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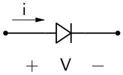
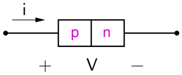
* The "turn-on" voltage (V_{on}) of a diode depends on the value of I_s. V_{on} may be defined as the voltage at which the diode starts carrying a substantial forward current (say, a few mA).
  For a silicon diode, $V_{on} \approx 0.7\ V$.
  For LEDs, V_{on} varies from about 1.8 V (red) to 3.3 V (blue).

Shockley diode equation





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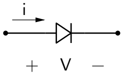

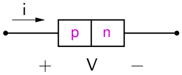

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0.2	7.74	0.229×10^{4}	0.229×10^{-9}
0.3	11.6	0.110×10^{6}	0.110×10^{-7}
0.4	15.5	0.525×10^{7}	0.525×10^{-6}
0.5	19.3	0.251×10^{9}	0.251×10^{-4}
0.6	23.2	0.120×10^{11}	0.120×10^{-2}
0.62	24.0	0.260×10^{11}	0.260×10^{-2}
0.64	24.8	0.565×10^{11}	0.565×10^{-2}
0.66	25.5	0.122×10^{12}	0.122×10^{-1}
0.68	26.3	0.265×10^{12}	0.265×10^{-1}
0.70	27.1	0.575×10^{12}	0.575×10^{-1}
0.72	27.8	0.125×10^{13}	0.125

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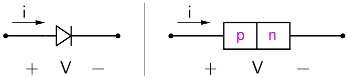

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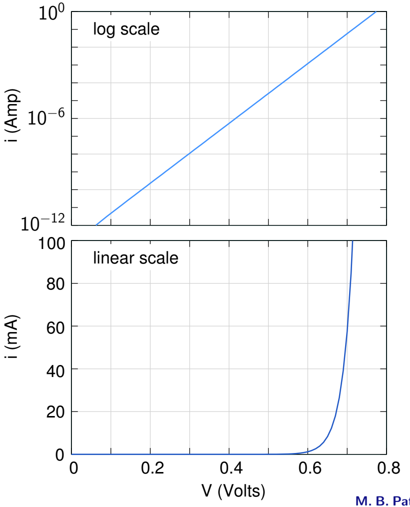
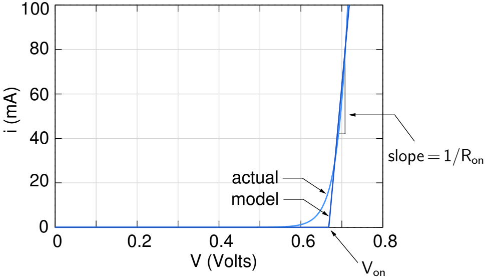
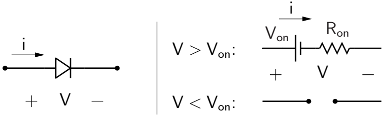


Diode circuit model





∗ 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.

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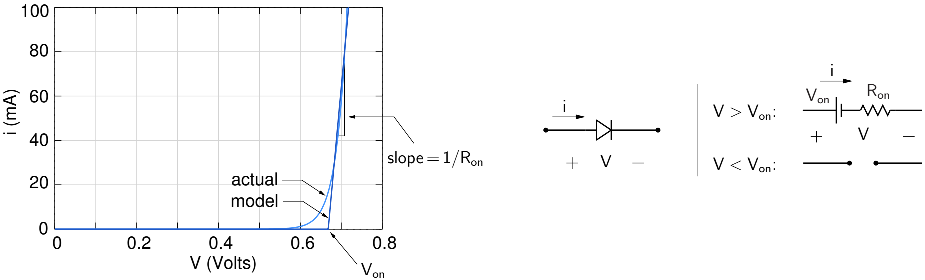

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* Note that the "battery" shown in the above model is not a "source" of power! It can only absorb power (see the direction of the current), causing heat dissipation.

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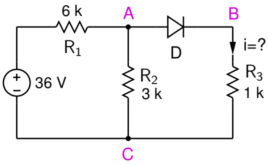
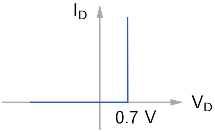
* In transient analysis, we need to find the time points at which a diode turns on or off, and analyse the circuit in intervals between these time points.
* In some diode circuits, the exponential nature of the diode I-V relationship (the Shockley model) is made use of. For these circuits, computation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

Diode circuit example





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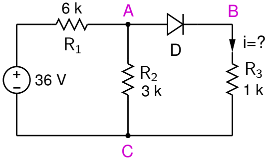
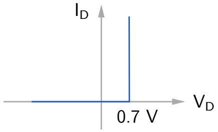
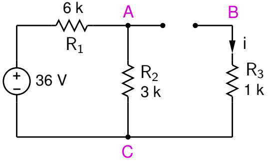




Case 1: D is off.



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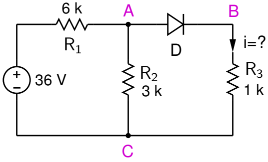

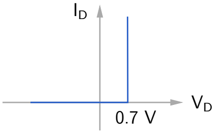

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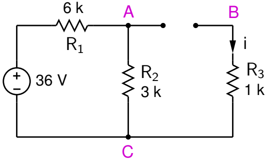

$$V_{AB} = V_{AC} = \frac{3}{9} \times 36 = 12\ \text{V}\,,$$

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

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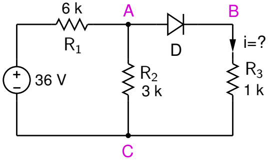

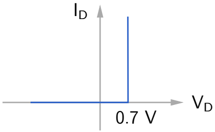

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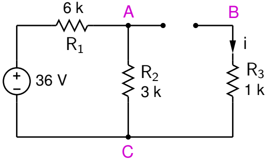

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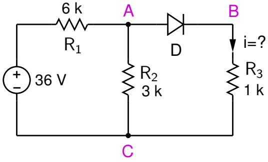
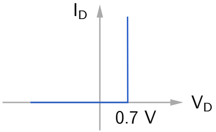
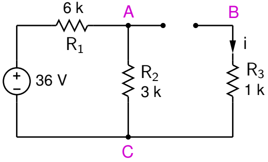
$\rightarrow$ D must be on.

Diode circuit example





Case 1: D is off.

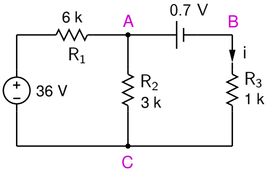


$$V_{AB} = V_{AC} = \frac{3}{9} \times 36 = 12\ \text{V},$$

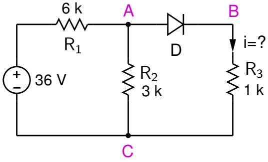
which is not consistent with our assumption of D being off.

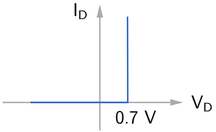
$\rightarrow$ D must be on.

Case 2: D is on.

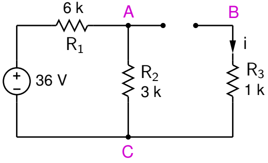


Diode circuit example





Case 1: D is off.

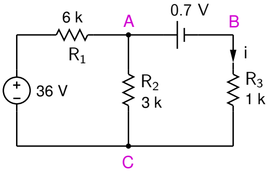


$$V_{AB} = V_{AC} = \frac{3}{9} \times 36 = 12 \text{ V}\,,$$

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

$\rightarrow$ D must be on.

Case 2: D is on.

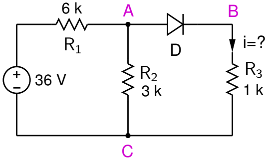


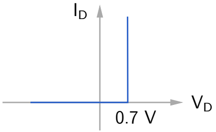
Taking $V_C = 0$ V,

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

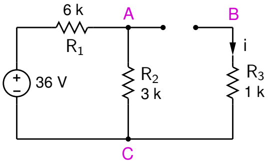
$\rightarrow$ $V_A = 4.47$ V, $i = 3.77$ mA.

Diode circuit example





Case 1: D is off.

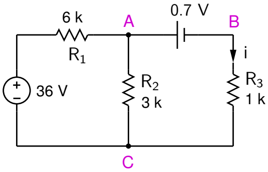


$$V_{AB} = V_{AC} = \frac{3}{9} \times 36 = 12 \text{ V},$$

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

$\rightarrow$ D must be on.

Case 2: D is on.

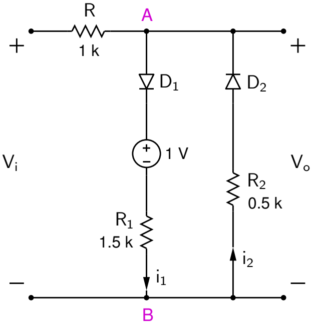


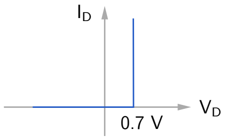
Taking $V_C = 0$ V,

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

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

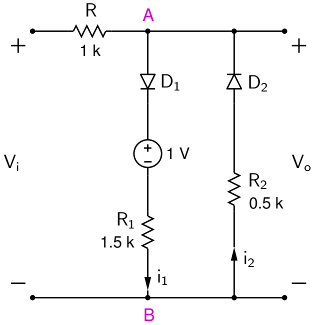
Remark: Often, we can figure out by inspection if a diode is on or off.

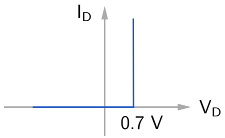




(a) Plot V_o versus V_i for $-5\ \text{V} < V_i < 5\ \text{V}$.

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





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

(b) Plot $V_o(t)$ for a triangular input:
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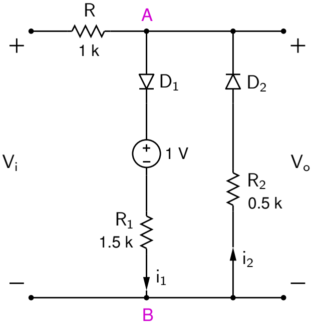
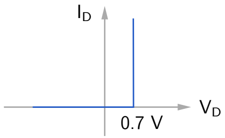
First, let us show that D_1 on $\Rightarrow$ D_2 off, and D_2 on $\Rightarrow$ D_1 off.



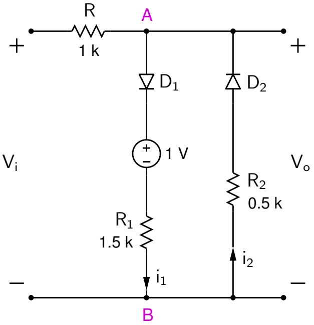


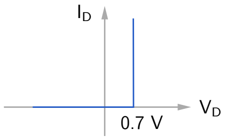
(a) Plot V_o versus V_i for $-5\text{ V} < V_i < 5\text{ V}$.

(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 $\rightarrow$ $V_{AB} = 0.7 + 1 + i_1 R_1$.





(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.

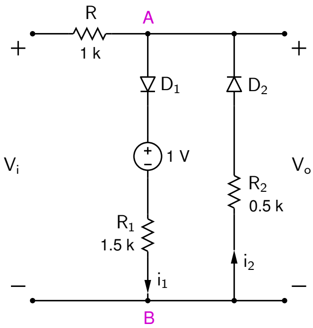
First, let us show that D_1 on $\Rightarrow$ D_2 off, and D_2 on $\Rightarrow$ D_1 off.

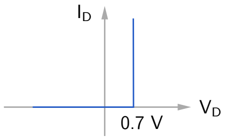
Consider D_1 to be on $\rightarrow$ $V_{AB} = 0.7 + 1 + i_1 R_1$.

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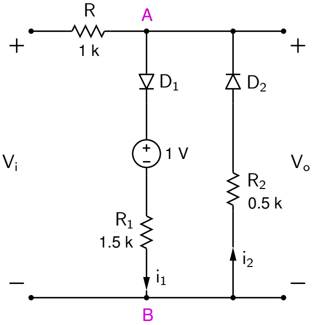
First, let us show that D_1 on $\Rightarrow$ D_2 off, and D_2 on $\Rightarrow$ D_1 off.

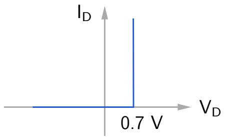
Consider D_1 to be on $\rightarrow$ $V_{AB} = 0.7 + 1 + i_1 R_1$.

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.





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

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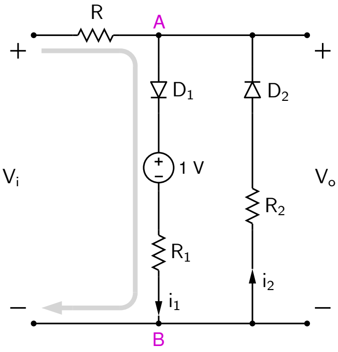
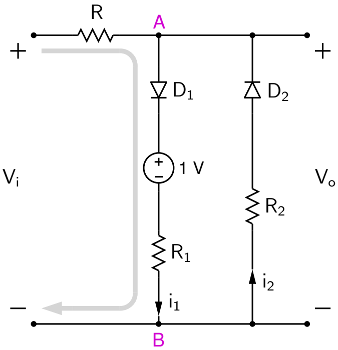
Similarly, if D_2 is on, $V_{BA} > 0.7\ V$, i.e., $V_{AB} < -0.7\ V \Rightarrow D_1$ cannot conduct.

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

Diode circuit example



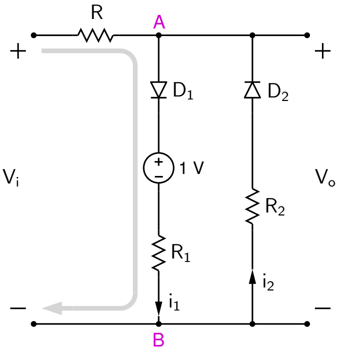
Diode circuit example



D_1 on:

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

Diode circuit example

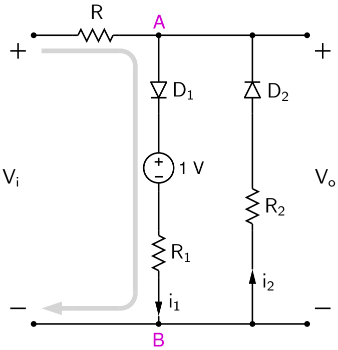


D_1 on:

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

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

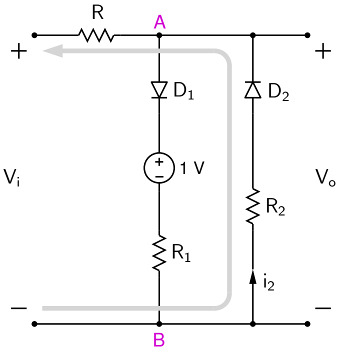
Diode circuit example



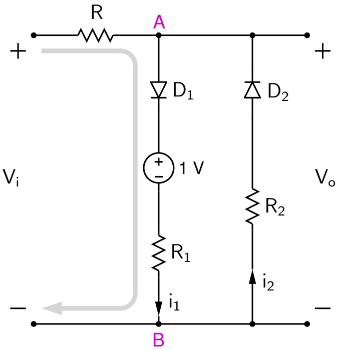
D$_1$ on:

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

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



Diode circuit example



D_1 on:

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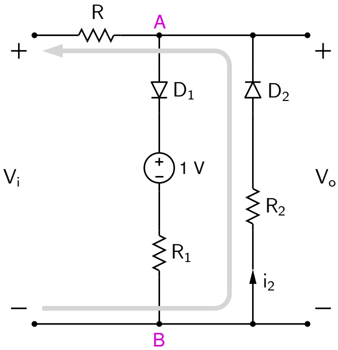
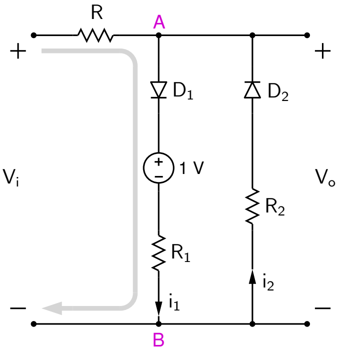
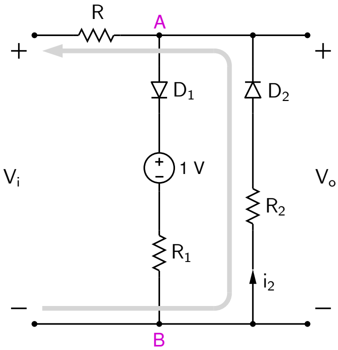


D_2 on:

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

Diode circuit example





D_1 on:

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

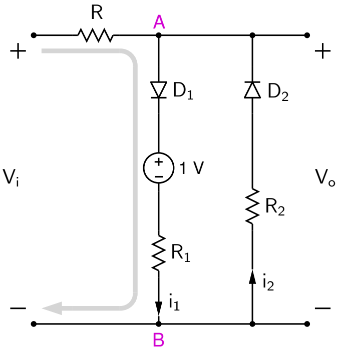
Since $i_1 > 0$, $\boxed{V_i > 1.7\,\text{V}}$

D_2 on:

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

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

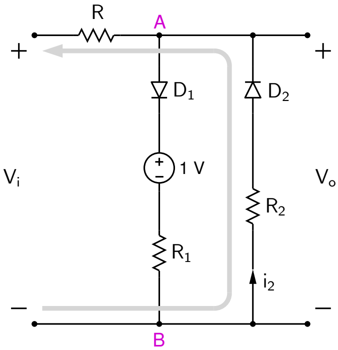
Diode circuit example



D_1 on:

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

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



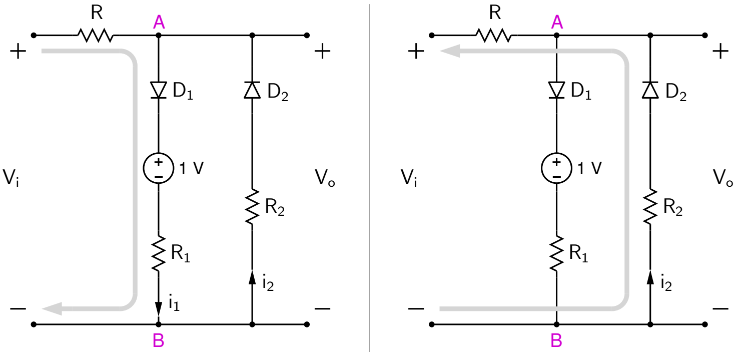
D_2 on:

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

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

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

D_2 on:

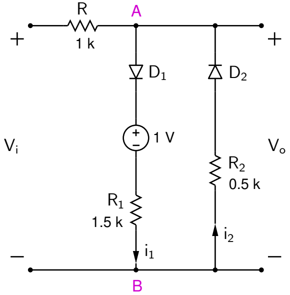
$$i_2(R + R_2) + 0.7 + V_i = 0$$

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

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

For $-0.7\,\text{V} < V_i < 1.7\,\text{V}$, 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)



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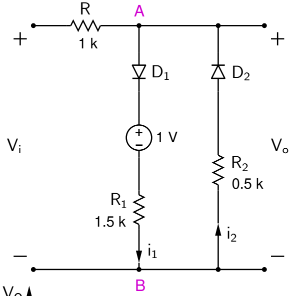
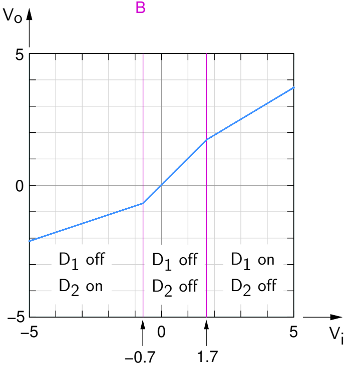




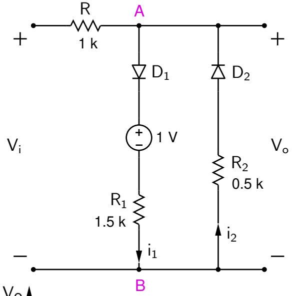
* For $-0.7\ V < V_i < 1.7\ V$, both D_1 and D_2 are off.
  $\rightarrow$ no drop across R, and $V_o = V_i$. (1)

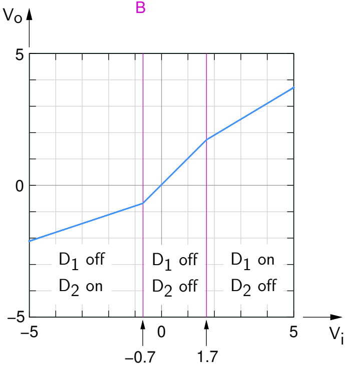
* For $V_i < -0.7\ V$, D_2 conducts. $\rightarrow V_o = -0.7 - i_2 R_2$.
  Use KVL to get i_2: $V_i + i_2 R_2 + 0.7 + R i_2 = 0$.

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

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

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

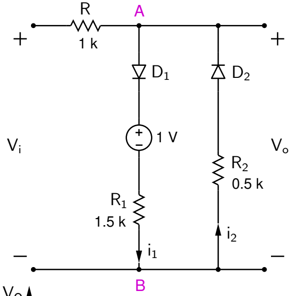


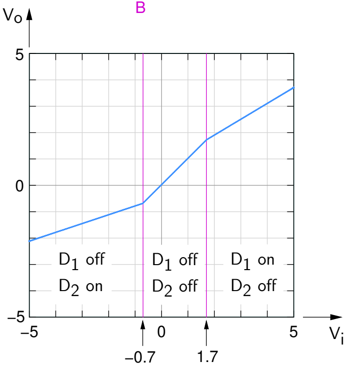


* For $-0.7\ V < V_i < 1.7\ V$, both D_1 and D_2 are off.
  $\rightarrow$ no drop across R, and $V_o = V_i$. (1)

* 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
  $$V_o = -0.7 - R_2 i_2 = \frac{R_2}{R + R_2}\, V_i - 0.7\, \frac{R}{R + R_2} \, . \qquad (2)$$
  $$\text{Slope } \frac{dV_o}{dV_i} = \frac{R_2}{R + R_2} = \frac{0.5\,\text{k}}{1\,\text{k} + 0.5\,\text{k}} = \frac{1}{3} \, .$$

* 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: $-V_i + i_1 R + 0.7 + 1 + i_1 R_1 = 0$.
  $\rightarrow i_1 = \dfrac{V_i - 1.7}{R + R_1}$, and
  $$V_o = 1.7 + R_1 i_1 = \frac{R_1}{R + R_1}\, V_i + 1.7\, \frac{R}{R + R_1} \, . \qquad (3)$$
  $$\text{Slope } \frac{dV_o}{dV_i} = \frac{R_1}{R + R_1} = \frac{1.5\,\text{k}}{1\,\text{k} + 1.5\,\text{k}} = \frac{3}{5} \, .$$





* 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: $V_i + i_2 R_2 + 0.7 + R i_2 = 0$.

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

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

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

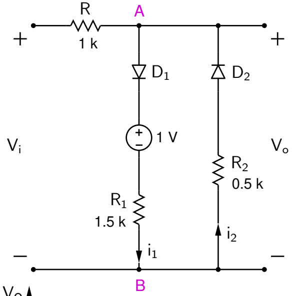
* For $V_i > 1.7\ V$, D_1 conducts. $\rightarrow V_o = 0.7 + 1 + i_1 R_1$.
Use KVL to get i_1: $-V_i + i_1 R + 0.7 + 1 + i_1 R_1 = 0$.

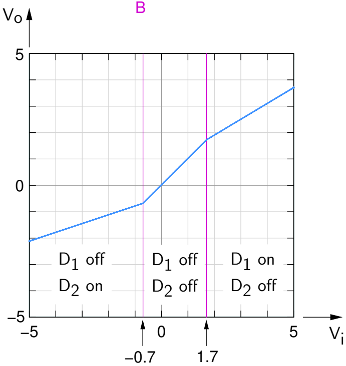
$$\rightarrow i_1 = \frac{V_i - 1.7}{R + R_1}\text{ , and}$$

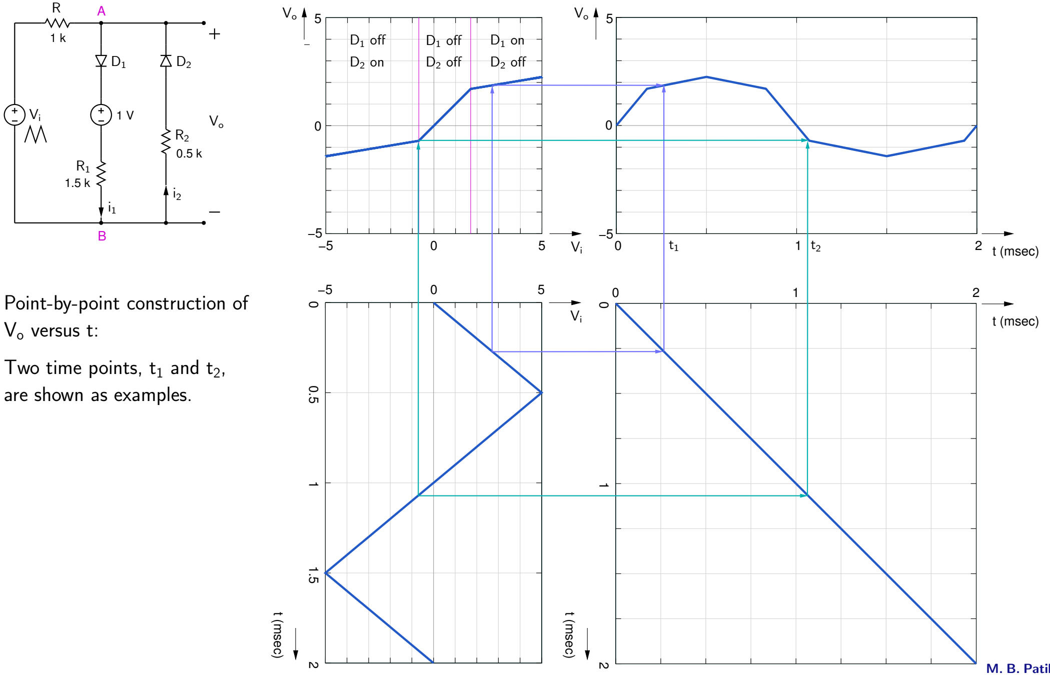
$$V_o = 1.7 + R_1 i_1 = \frac{R_1}{R + R_1} V_i + 1.7 \frac{R}{R + R_1} \ . \qquad (3)$$

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

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



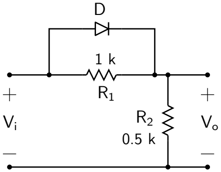


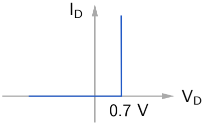


Point-by-point construction of V_o versus t:

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

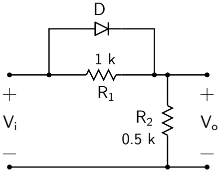
Diode circuit example

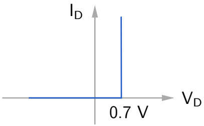




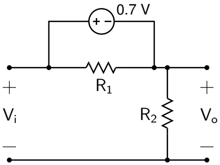
Plot V_o versus V_i for -5 V $< V_i <$ 5 V .

Diode circuit example





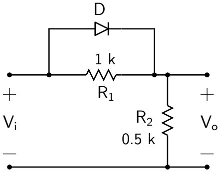
Plot V_o versus V_i for $-5\ \text{V} < V_i < 5\ \text{V}$.

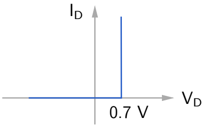


D on

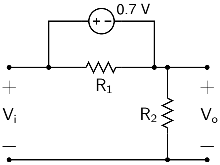
$V_o = V_i - 0.7$

Diode circuit example



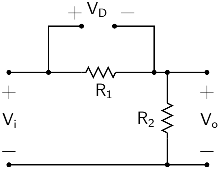


Plot V_o versus V_i for $-5\text{ V} < V_i < 5\text{ V}$.



D on

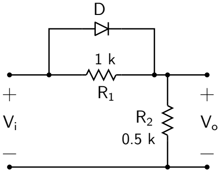
$$V_o = V_i - 0.7$$

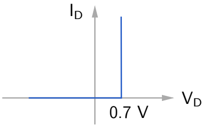


D off

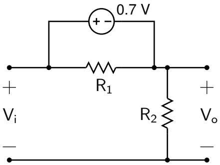
$$V_o = \frac{R_2}{R_1 + R_2} V_i$$

Diode circuit example



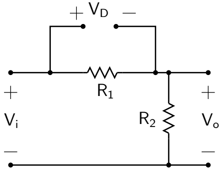


Plot V_o versus V_i for $-5\ V < V_i < 5\ V$.



D on

$$V_o = V_i - 0.7$$

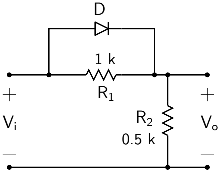


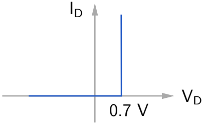
D off

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

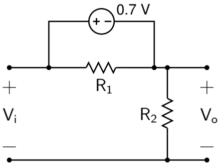
At what value of V_i will the diode turn on?

Diode circuit example



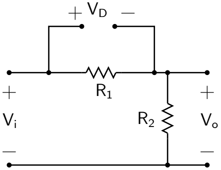


Plot V_o versus V_i for $-5\text{ V} < V_i < 5\text{ V}$.



D on

$V_o = V_i - 0.7$



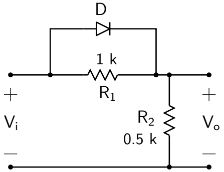
D off

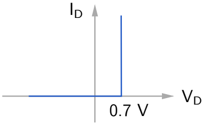
$$V_o = \frac{R_2}{R_1 + R_2} V_i$$

At what value of V_i will the diode turn on?

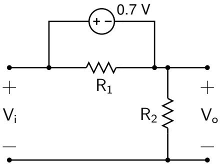
In the off state, $V_D = \dfrac{R_1}{R_1 + R_2}\, V_i$.

Diode circuit example



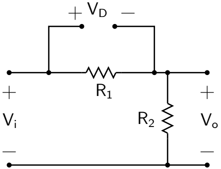


Plot V_o versus V_i for $-5\ V < V_i < 5\ V$.



D on

$V_o = V_i - 0.7$



D off

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

At what value of V_i will the diode turn on?

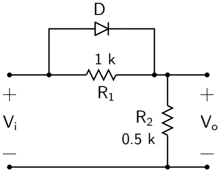
In the off state, $V_D = \dfrac{R_1}{R_1 + R_2}\, V_i$.

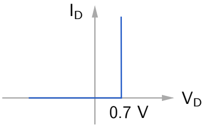
As V_i increases, V_D increases.

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

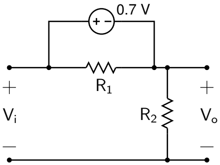
i.e., $V_i = \dfrac{R_1 + R_2}{R_1} \times 0.7 = 1.05\ V$.

Diode circuit example



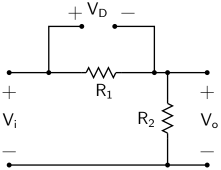


Plot V_o versus V_i for $-5\ V < V_i < 5\ V$.



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, $V_D = \dfrac{R_1}{R_1 + R_2}\, V_i$.

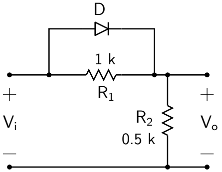
As V_i increases, V_D increases.

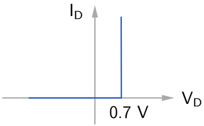
For D to turn on, we need $V_D = \ 0.7\ V$.

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

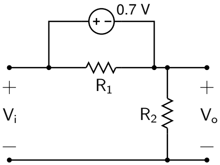
(SEQUEL file: `ee101_diode_circuit_2.sqproj`)

Diode circuit example



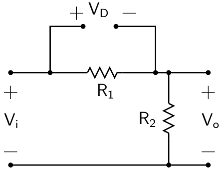


Plot V_o versus V_i for $-5\ V < V_i < 5\ V$.



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?

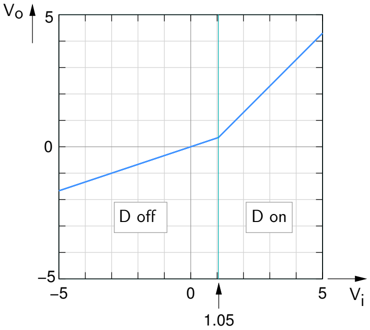
In the off state, $V_D = \dfrac{R_1}{R_1 + R_2} V_i$.

As V_i increases, V_D increases.

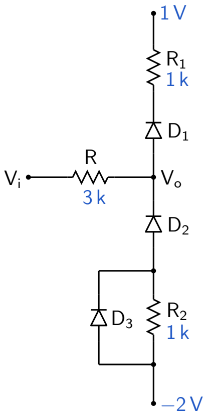
For D to turn on, we need $V_D =\ 0.7\ V$.

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

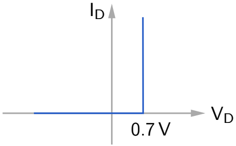
(SEQUEL file: `ee101_diode_circuit_2.sqproj`)

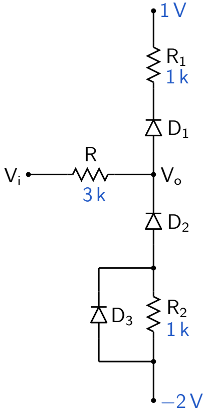


Diode circuit example

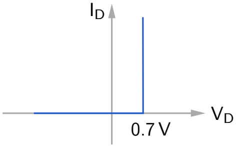


Plot V_o versus V_i (Ref: Sedra/Smith).



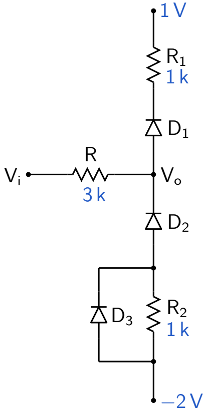


Plot V_o versus V_i (Ref: Sedra/Smith).

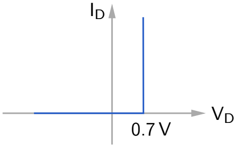


It is easier to find the status (on/off) of each diode w. r. t. V_o.

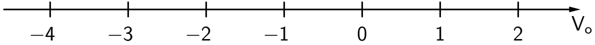
Diode circuit example



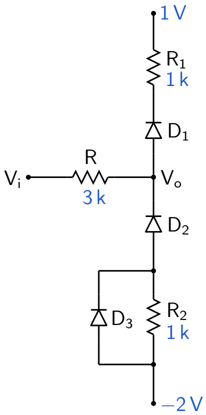
Plot V_o versus V_i (Ref: Sedra/Smith).



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



Diode circuit example



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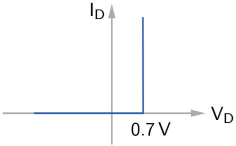

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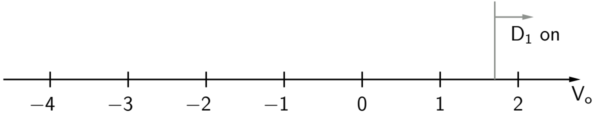
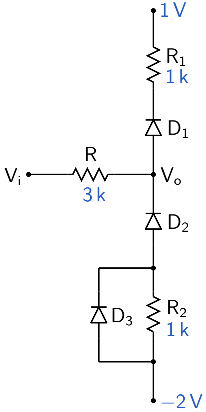
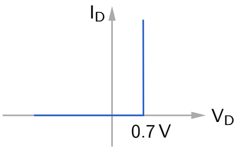
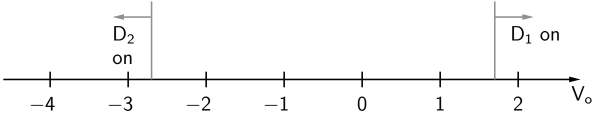




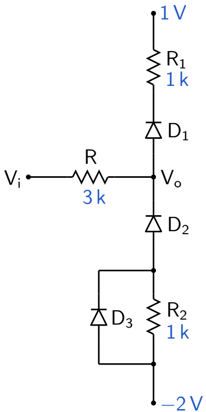
Plot V_o versus V_i (Ref: Sedra/Smith).



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



Diode circuit example



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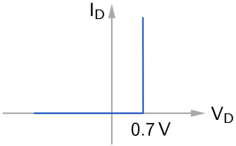
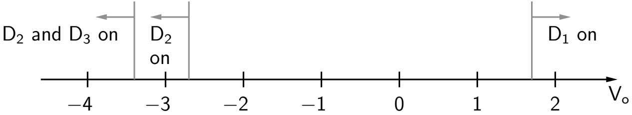
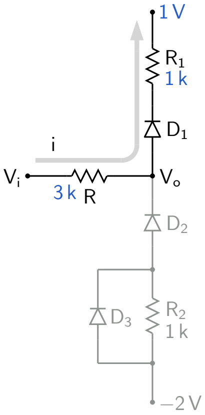
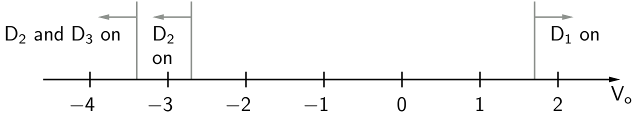
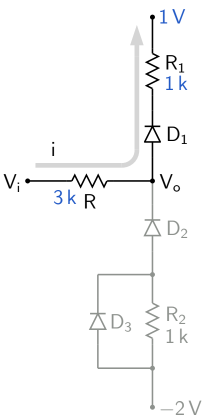


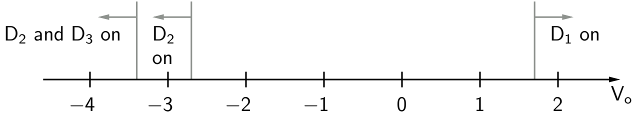
It is easier to find the status (on/off) of each diode w. r. t. V_o.




1 V
R1
1 k
D1
i
Vi
3 k
R
Vo
D2
D3
R2
1 k
−2 V

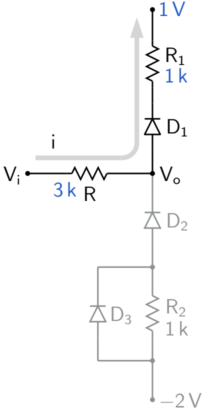

D2 and D3 on
D2
on
D1 on
−4
−3
−2
−1
0
1
2
Vo

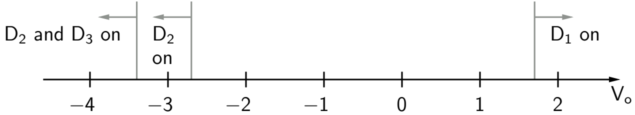




When D_1 just starts conducting,

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

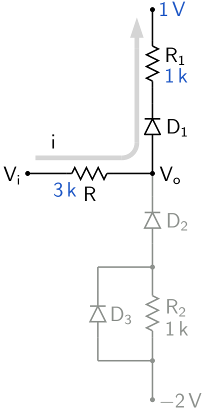


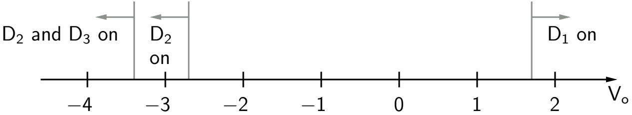


When D_1 just starts conducting,

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

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



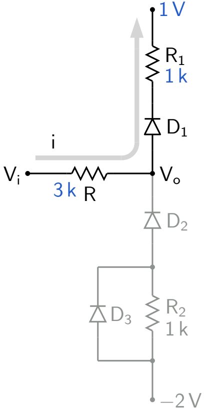


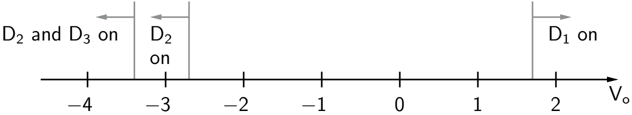
When D_1 just starts conducting,

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

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

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



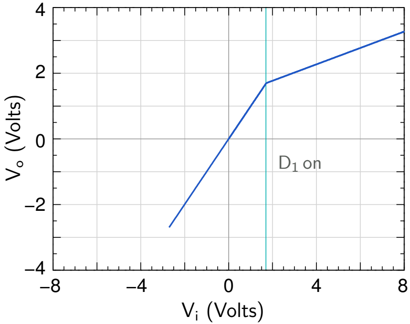


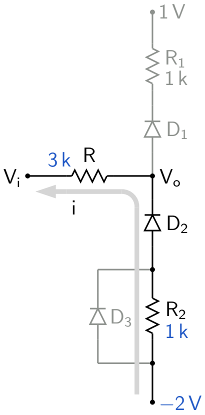
When D_1 just starts conducting,

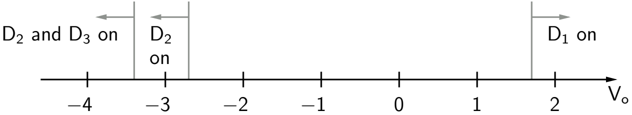
$$V_o = 1.7\,\text{V},\ i \approx 0 \rightarrow V_i = 1.7\,\text{V}$$

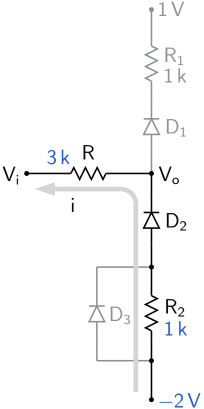
For $V_i > 1.7\,\text{V}$, $V_o = 1.7 + \left(\dfrac{V_i - 1.7}{R + R_1}\right) R_1$

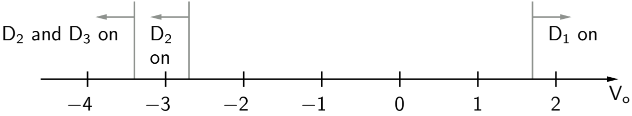
Slope $\dfrac{dV_o}{dV_i} = \dfrac{R_1}{R + R_1} = \dfrac{1}{4}$




1 V
R1
1 k
D1
3 k
R
Vi
Vo
i
D2
D3
R2
1 k
−2 V

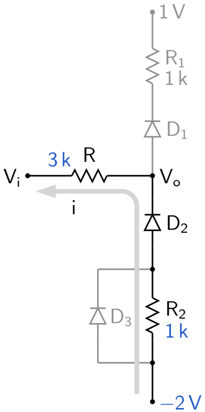

D2 and D3 on
D2 on
D1 on
−4
−3
−2
−1
0
1
2
Vo

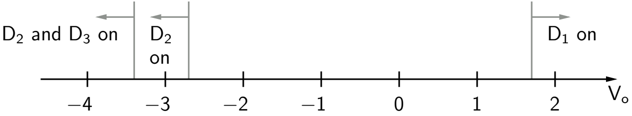




When D_2 just starts conducting,

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





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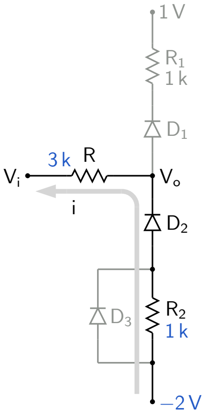

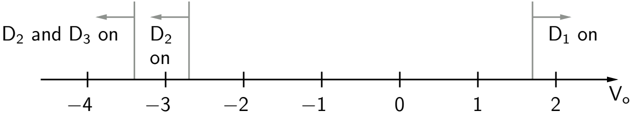

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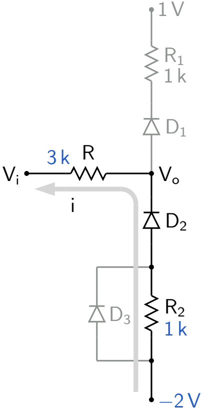
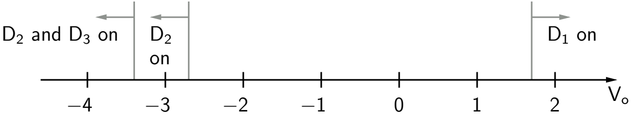
Slope $\dfrac{dV_o}{dV_i} = 1 - \dfrac{R}{R + R_2} = \dfrac{R_2}{R + R_2} = \dfrac{1}{4}$





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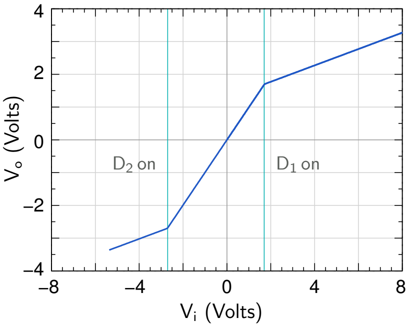
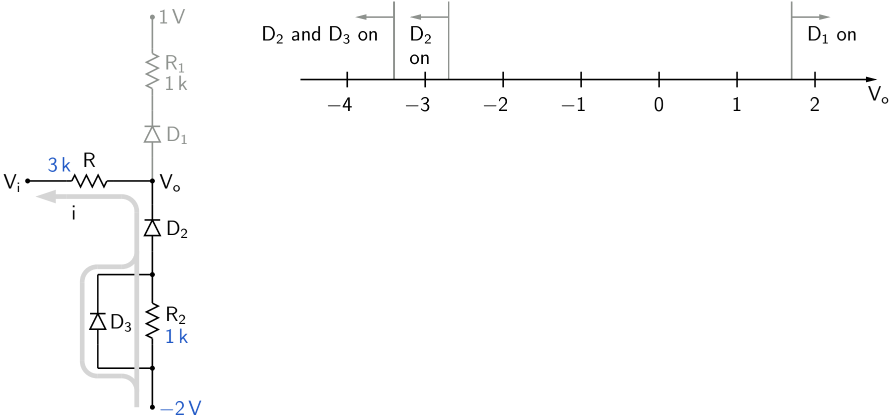
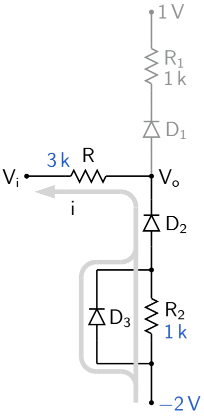
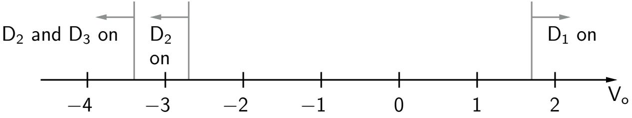




1 V
R1
1 k
D1
3 k
R
Vi
Vo
i
D2
D3
R2
1 k
−2 V
D2 and D3 on
D2 on
D1 on
−4
−3
−2
−1
0
1
2
Vo





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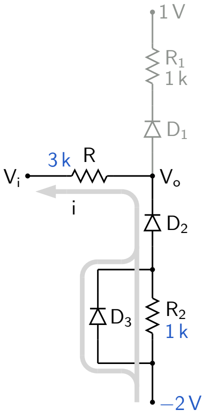

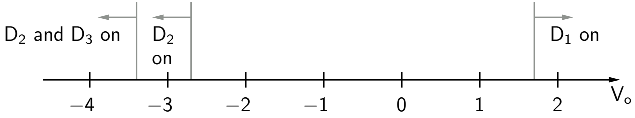

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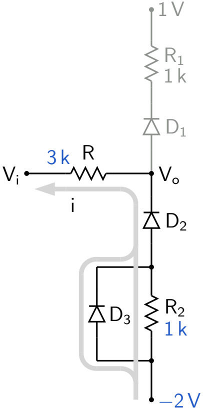

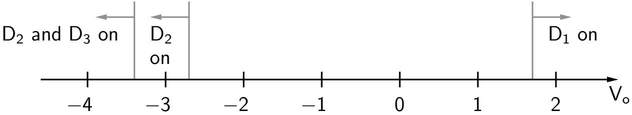

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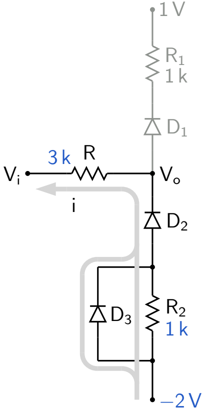

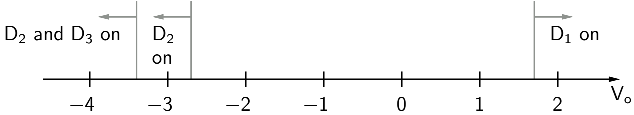

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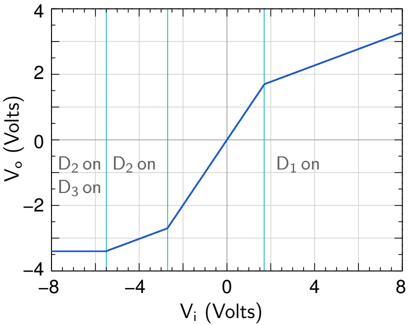

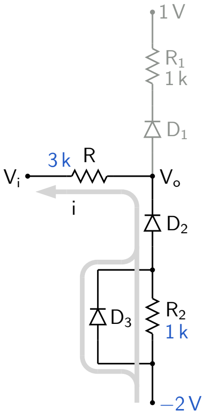

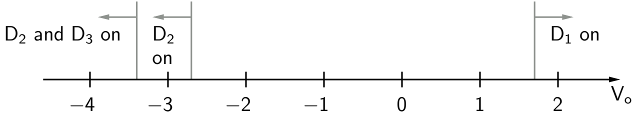

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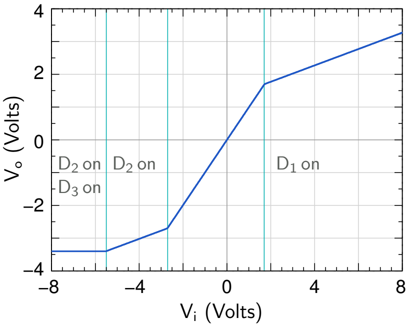
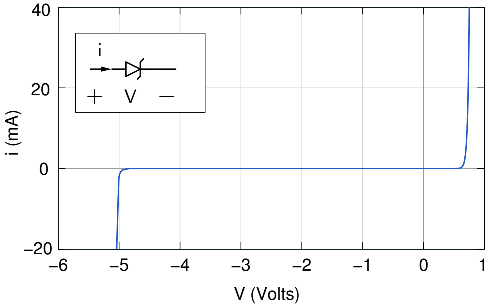
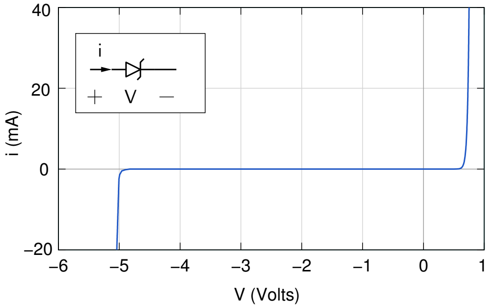


SEQUEL file:

`ee101_diode_circuit_12.sqproj`

Reverse breakdown





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

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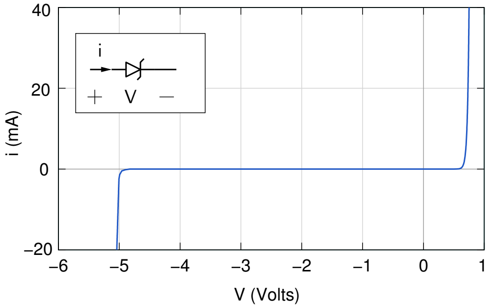

* In the reverse direction, an ideal diode presents a large resistance for *any* applied voltage.
* A real diode cannot withstand indefinitely large reverse voltages and "breaks down" at a certain voltage called the "breakdown voltage" (V_{BR}).

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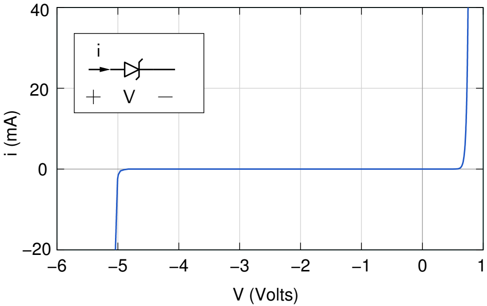
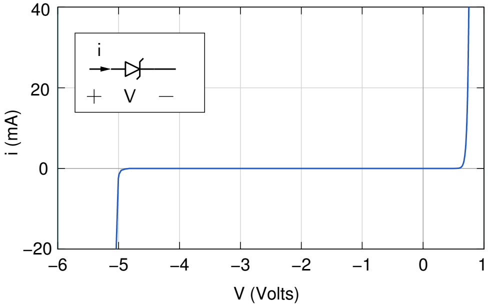
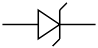
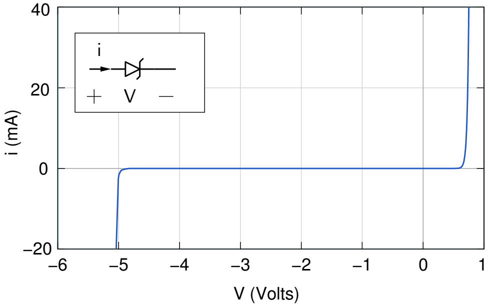


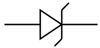
* In the reverse direction, an ideal diode presents a large resistance for *any* applied voltage.
* A real diode cannot withstand indefinitely large reverse voltages and "breaks down" at a certain voltage called the "breakdown voltage" (V_{BR}).
* When the reverse bias $V_R > V_{\mathrm{BR}}$ (i.e., $V < -V_{\mathrm{BR}}$), the diode allows a large amount of current. If the current is not constrained by the external circuit, the diode would get damaged.





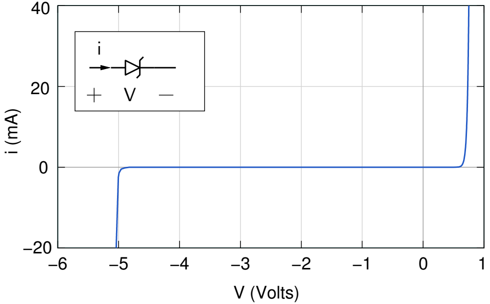
Symbol for a Zener diode

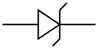




Symbol for a Zener diode

* 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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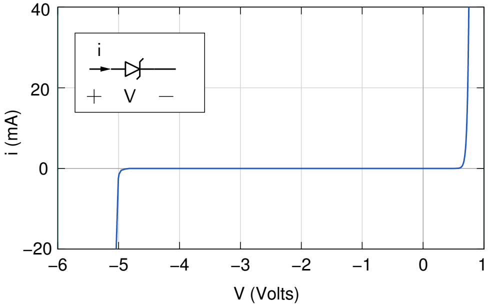
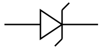
* Diodes with high V_{BR} are generally used in power electronics applications and are therefore also designed to carry a large forward current (tens or hundreds of Amps).

Reverse breakdown





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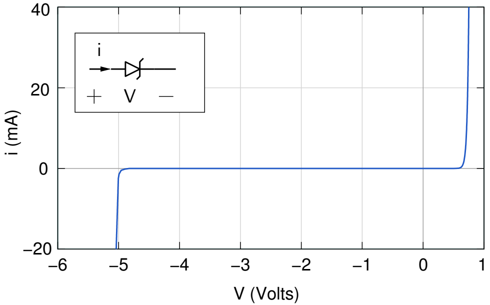

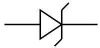

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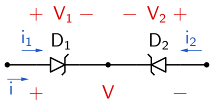
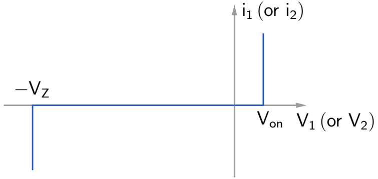
* Typically, circuits are designed so that the reverse bias across any diode is less than the V_{BR} rating for that diode.
* "Zener" diodes typically have V_{BR} of a few Volts, which is denoted by V_Z. They are often used to limit the voltage swing in electronic circuits.

Two Zener diodes connected "back-to-back"





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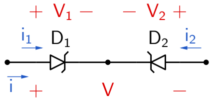

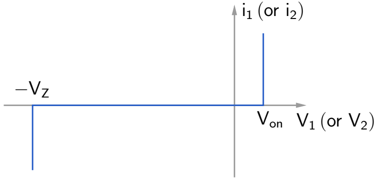

* $i > 0 \rightarrow D_1$ in forward conduction, D_2 in reverse conduction

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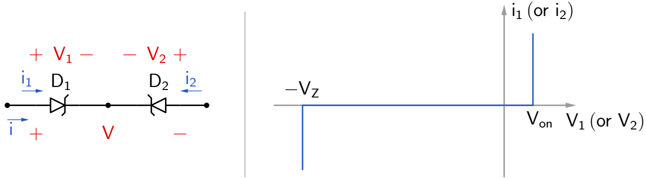

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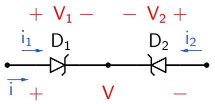

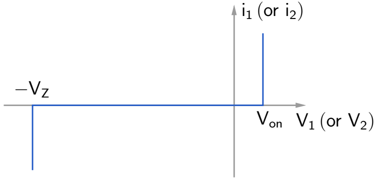

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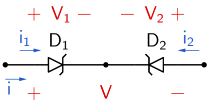

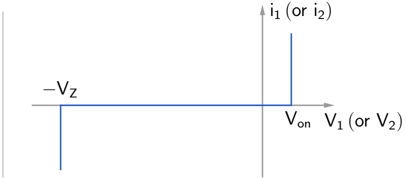

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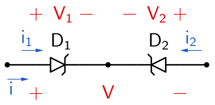

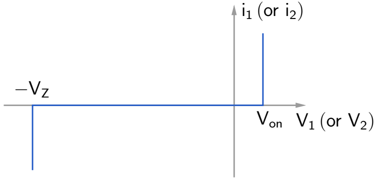

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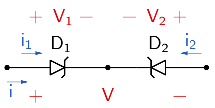

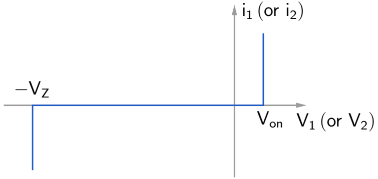

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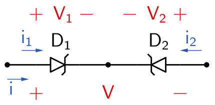

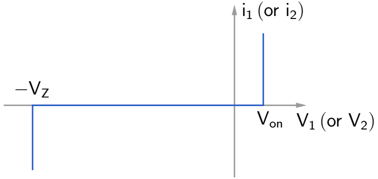

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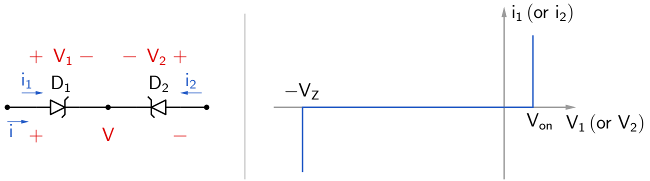
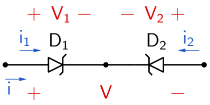


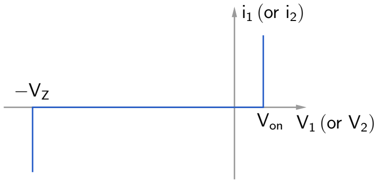
∗ $i > 0 \rightarrow D_1$ in forward conduction, D_2 in reverse conduction
$\rightarrow V_1 = V_{\text{on}},\ V_2 = -V_Z$.
Total voltage drop $V = V_1 - V_2 = V_{\text{on}} + V_Z$.
Example: $V_{\text{on}} = 0.7\,\text{V},\ V_Z = 5\,\text{V} \rightarrow V = 5.7\,\text{V}$.

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

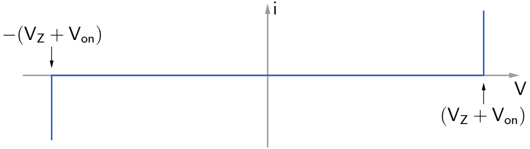
∗ For $-(V_Z + V_{\text{on}}) < V < (V_Z + V_{\text{on}})$, conduction is not possible $\rightarrow i = 0$.

Two Zener diodes connected "back-to-back"

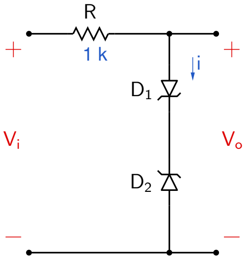




* $i > 0 \rightarrow D_1$ in forward conduction, D_2 in reverse conduction
  $\rightarrow V_1 = V_{\mathrm{on}},\ V_2 = -V_Z$.
  Total voltage drop $V = V_1 - V_2 = V_{\mathrm{on}} + V_Z$.
  Example: $V_{\mathrm{on}} = 0.7\,\mathrm{V},\ V_Z = 5\,\mathrm{V} \rightarrow V = 5.7\,\mathrm{V}$.
* $i < 0 \rightarrow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



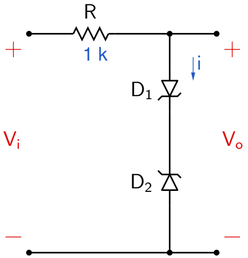
Diode circuit example (voltage limiter)

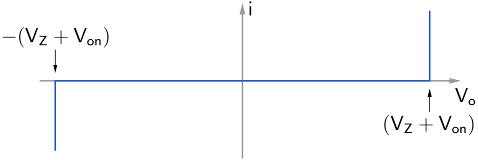


$V_{on} = 0.7$ V, $V_Z = 5$ V.

Plot V_o versus V_i.

Diode circuit example (voltage limiter)

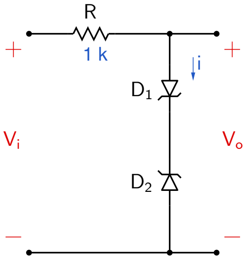


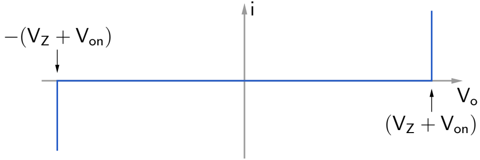


$V_{on} = 0.7$ V, $V_Z = 5$ V.

Plot V_o versus V_i.

Diode circuit example (voltage limiter)



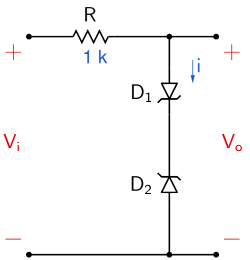


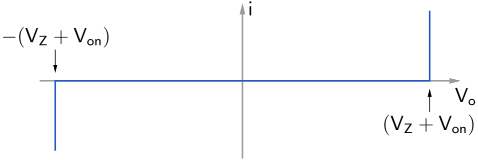
$V_{on} = 0.7$ V, $V_Z = 5$ V.

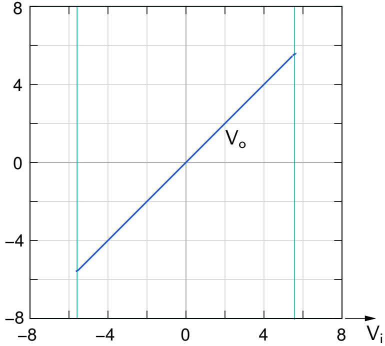
Plot V_o versus V_i.

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

Diode circuit example (voltage limiter)







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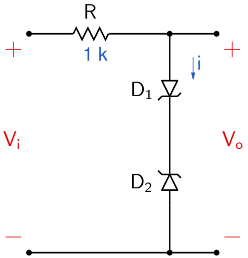
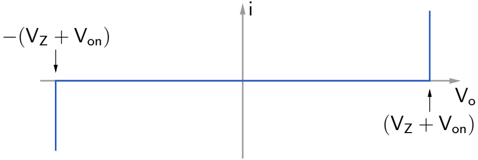
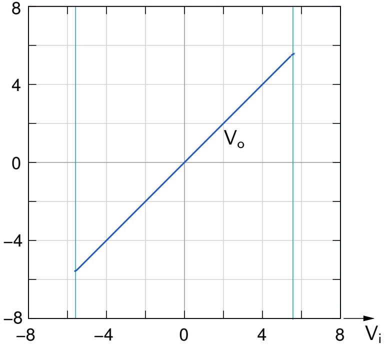


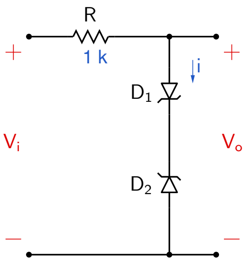


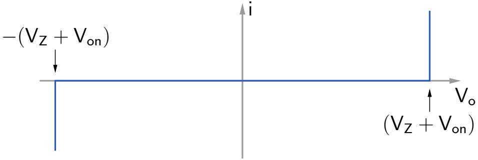


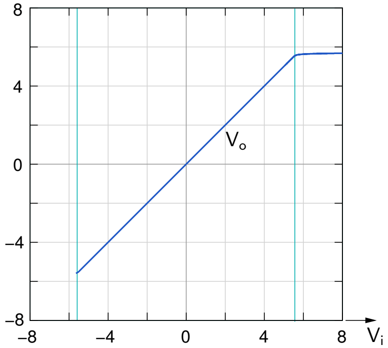
$V_{on} = 0.7$ V, $V_Z = 5$ V.

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 $V_o = (V_{on} + V_Z)$. The excess voltage $(V_i - (V_{on} + V_Z))$ drops across R.







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

Plot V_o versus V_i.

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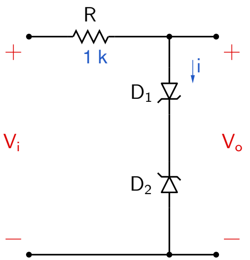
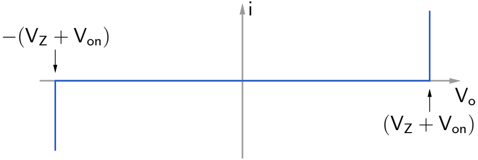
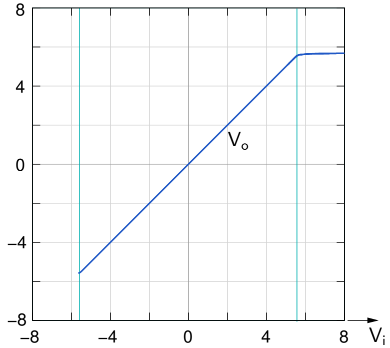
Diode circuit example (voltage limiter)





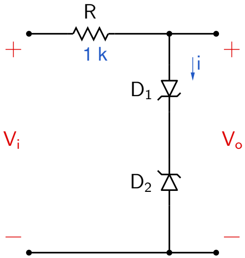


$V_{on} = 0.7$ V, $V_Z = 5$ V.

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 $V_o = (V_{on} + V_Z)$. The excess voltage $(V_i - (V_{on} + V_Z))$ drops across R.
* For $V_i < -5.7\,\text{V}$, 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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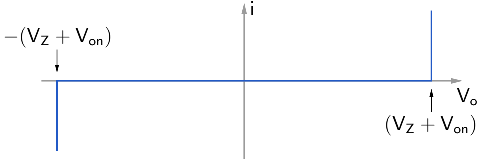

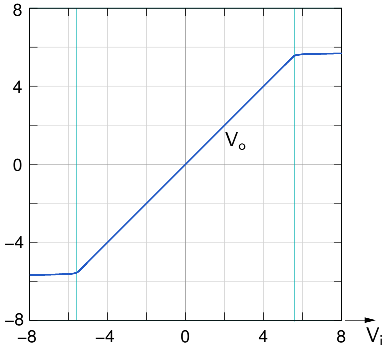

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* For $V_i < -5.7\,\text{V}$, D_2 is forward-biased, D_1 is reverse-biased, and $V_o = -(V_{on} + V_Z)$. The excess voltage $(-V_i - (V_{on} + V_Z))$ drops across R.